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Wind turbines, solar farms, and house prices☆

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ABSTRACT

This paper examines the effect of wind turbines and solar farms on house prices. Using detailed data from the Netherlands between 1985 and 2019, the results show that tall wind turbines have considerably stronger effects on house prices, as compared to small turbines. For example, a tall turbine (>150m) decreases house prices within 2 km by 5.4%, while a small turbine (<50m) has an effect of maximally 2% and the effect dissipates after 1 km. Further results indicate that solar farms lead to a decrease in house prices within 1 km of about 2.6%. By comparing the overall impact on house prices, we show that the external effects of solar farms per unit of energy output are comparable to those of wind turbines. Thus, building solar farms instead of wind turbines does not seem to be a way to avoid the external effects of renewable energy production.

1. Introduction

Renewable energy is on the rise. While global demand is still strongly increasing, the demand for fossil fuels has actually strongly declined (IEA, 2020). Furthermore, the current Covid-19 crisis has made clear the downsides of fossil fuels: the effective use of fossil fuels depend heavily on storage capacity and transportation (Science, 2020). Instead, renewable energy is typically produced locally and could be a viable alternative to fossil fuels. Two important sources of renewable energy production are wind turbines and commercial solar farms.

Renewable energy production may have external effects on local residents (Meyerhoff et al., 2010; Groth and Vogt, 2014). Wind turbines make noise, cast shadows, and create flickering. Moreover, turbines can visually pollute the landscape, particularly if they are tall. Solar panels can reflect sound and sunlight and are also usually not considered to be aesthetically pleasing. In line with a large literature on hedonic pricing, we would expect that such externalities capitalize into house prices. Increasing our understanding of these external effects is policy-relevant for at least two reasons. First, it provides insight in what could be a more efficient allocation of renewable energy production facilities (Rodman and Meentemeyer, 2006). Second, because the effects of wind turbines and solar farms are local, the effect on house prices is indicative that the burden of renewable energy production is not necessarily distributed equally within society.

The aim of this paper is to examine the effect of wind turbines and solar farms on house prices. We employ a quantitative revealed-preferences approach to measure this effect. We contribute to the existing literature in several ways. First, this paper explicitly focuses on the role of turbine height on house prices. In particular, we investigate whether tall turbines have a larger effect on house prices *and* at a larger distance. Given the substantial increase in wind turbine height in the last years, we would expect heterogeneity in the effect of turbines of different heights on house prices. This is important for spatial policies regarding the placement of wind turbines.[1]

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[1] Some studies find effects of turbines up to 14%, while others do not find any effect (see Appendix A.1 for an extensive review). One potential explanation is that previous studies did not take into account that large turbines may lead to larger decreases in housing values. A notable exception is Dröes and Koster (2016), who show that in the Netherlands turbines larger than 100m lead to an additional price decline of 2.2%. However, Dröes and Koster (2016) only analyze a handful of tall turbines and it remains unclear whether the spatial extent of negative externalities for turbines of different heights is the same.

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Second, to identify a causal effect of renewable energy production facilities on house prices is not straightforward, as turbines and solar farms are mostly located in sparsely populated areas with lower house prices. That is, the placement of renewable energy production sites is not random. To mitigate endogeneity concerns many studies use a differences-in-differences design based on comparison with a local control group (Gibbons, 2015; Dröes and Koster, 2016; Jensen et al., 2018). A key identifying assumption is that there are *parallel trends* between treated and control areas. This assumption may be restrictive and is hard to test.[2] Instead, we exploit *temporal variation* in the openings of turbines and solar farms. That is, we employ a hedonic regression design that compares price changes in areas that have received a wind turbine or solar farm; to areas that will receive a turbine or solar farm in the future. By examining the causal effect on *house prices* we aim to measure the (revealed) preferences of households regarding the placement of wind turbines and solar farms.[3]

Third, to the best of our knowledge, we are among the first to investigate the impact of solar farms on house prices. For solar farms, we use essentially the same identification strategy as for wind turbines. However, the effects of solar farms are expected to be more local than those of wind turbines, as visual pollution is likely to be more localized. Additionally, we compare the results of solar farms to those of wind turbines. Many previous studies only focus on a single type of renewable energy production facility.

This paper relies on detailed housing transactions data from the Netherlands between 1985 and 2019, which we combine with data on all wind turbines and solar farms that have been placed during this period. The Netherlands is typically seen as a fairly urbanized country and thus provides an ideal study area to examine the external effects of wind turbines and solar farms on house prices.[4]

The results in this paper show that the construction of a wind turbine leads to a decrease in local house prices of 1.8%. In particular, we find that a turbine taller than 150m decreases prices within 2 km by 5.4%, while the effect of small turbines (<50m) is statistically indistinguishable from zero. Also, the effect of tall wind turbines does not extend much beyond 2 km, but we do find evidence that the impact radius is smaller (<1 km) for low wind turbines. Various additional robustness checks support the main findings. Regarding solar farms, we find that house prices decrease by about 2.6% after opening. The effect is confined to 1 km, so it is more localized than that of wind turbines.

Finally, we show that the total loss in housing values as a result of the placement of wind turbines is about €5 billion, while solar farms imply a total loss of €800 million. Yet, 1% of the turbines cause almost 50% of the total loss in housing values. These are turbines that are placed too close to residential areas. The median loss per installed megawatt-hour (MWh) is €53, with taller turbines having a much lower median loss per MWh (*i.e.* €277 for a turbine <50m versus €11 for a turbine >150m). Hence, it seems much more efficient to build taller, more powerful, turbines. We further find that the average loss per MWh for a solar farm is of the same order of magnitude as that of a wind turbine.

From a policy perspective, our results thus imply that building solar farms instead of wind turbines will not mitigate the external effects of renewable energy production. Our results further highlight the importance of avoiding the placement of wind turbines and solar farms near urban areas.

The remainder of this paper is structured as follows. Section 2 provides a discussion of the international and Dutch policy context. Section 3 discusses the data, while the methodology is discussed in Section 4. Section 5 highlights the regression results and Section 6 concludes.

2. Policy context

Wind turbines are an important source of renewable energy with 30% of its capacity located in Europe and 17% in the U.S. in 2018. Especially China has invested heavily in wind energy, overtaking the E.U. already in 2015 as being the largest producer of wind energy. Currently, 36% of worldwide capacity is located in China (GWEC, 2019). Many other Western and Asian countries have been increasing their capacity over the past decades as well. Technological change fueled by an increased demand for energy has led wind turbines to become taller over time (as taller turbines produce more energy). Where turbines in the 1980s were still around 30m, the newest generation of wind turbines is currently well above 100m.[5]

A relatively new phenomenon is the commercial production of renewable energy via solar farms, which are large fields of solar panels. The first solar farm was constructed in 1982 in California. Yet, with advances in technology, it has become attractive to commercially exploit solar farms only in the last decade or so. Many countries, like India, China, and the United States have heavily invested in very large solar farms.[6]

In 2019, the renewable energy capacity captured 27% of total electricity production with solar photovoltaics capturing only 2.8% of the total production, about half that of wind turbines. Hydropower is still one of the largest contributors. By contrast, last year's growth in solar photovoltaics capacity was about twice that of wind turbines (REN21, 2020). Whether the current surge in the construction of tall wind turbines and solar farms will continue remains to be seen, but some countries have already suggested that the economic recovery after Covid-19 should be a green one (Associated Press, 2020).

In this study, we focus on the Netherlands (which is an E.U. member state). The E.U. has extended its energy efficiency directive in 2018 posing new targets for 2030. According to the national energy and climate plans of the different member states, many European countries will rely on wind and solar energy to meet those targets. In 2013, the Dutch government reached an energy agreement with many central stakeholders in the Dutch society (*i.e.* labor unions, environmental organizations, financial institutions) to reduce CO_2 emissions by 2020–2023. An important pillar of this agreement is to construct about 1300 wind turbines on land (SER, 2013).[7]

In 2019, this ambition was extended and a National Climate Agreement was reached to reduce CO_2 emissions by 49% in 2030 compared to 1990. To achieve this goal, about 50% of renewable energy production should be realized on land (35 of the 84 TWh), while the remainder will be produced offshore. Furthermore, a large-scale subsidy program is now in operation and 30 Dutch regions are required to develop energy production plans. From this, it is clear that wind and solar energy produced on land will play a major role in reaching the renewable energy goals (National Climate Agreement, 2019). Although the Dutch government aims to ensure the participation of local residents in developing renewable energy production sites, there have been a lot of protests, particularly against tall wind turbines (Telegraaf, 2020). Our study is

[2] For a more elaborate discussion, see Bertrand et al. (2004); Abadie (2005), and Donald and Lang (2007).

[3] More specifically, house prices are a useful monetary measure of household preferences (Rosen, 1974).

[4] The Netherlands (an E.U. member state) is more than twice the size of the San Francisco Bay Area (U.S.) but has a comparable population density (430/km^2 versus 488/km^2 for San Francisco).

[5] The average power a turbine <50m generates is 0.14 MW, while it is 4.15 MW for a turbines >150m. These are large differences in potential energy output.

[6] Currently, the largest solar farm in the world is 40 km^2, located in Bhadla, India.

[7] In 2019, the Dutch government lost a major court case against the non-profit environmental organization *Urgenda* because it did not fulfill its climate goals set for 2020. This event created a precedent for other related court cases in other E.U. member states (Supreme Court, 2019), and has created a sense of urgency to increase renewable energy production more quickly.

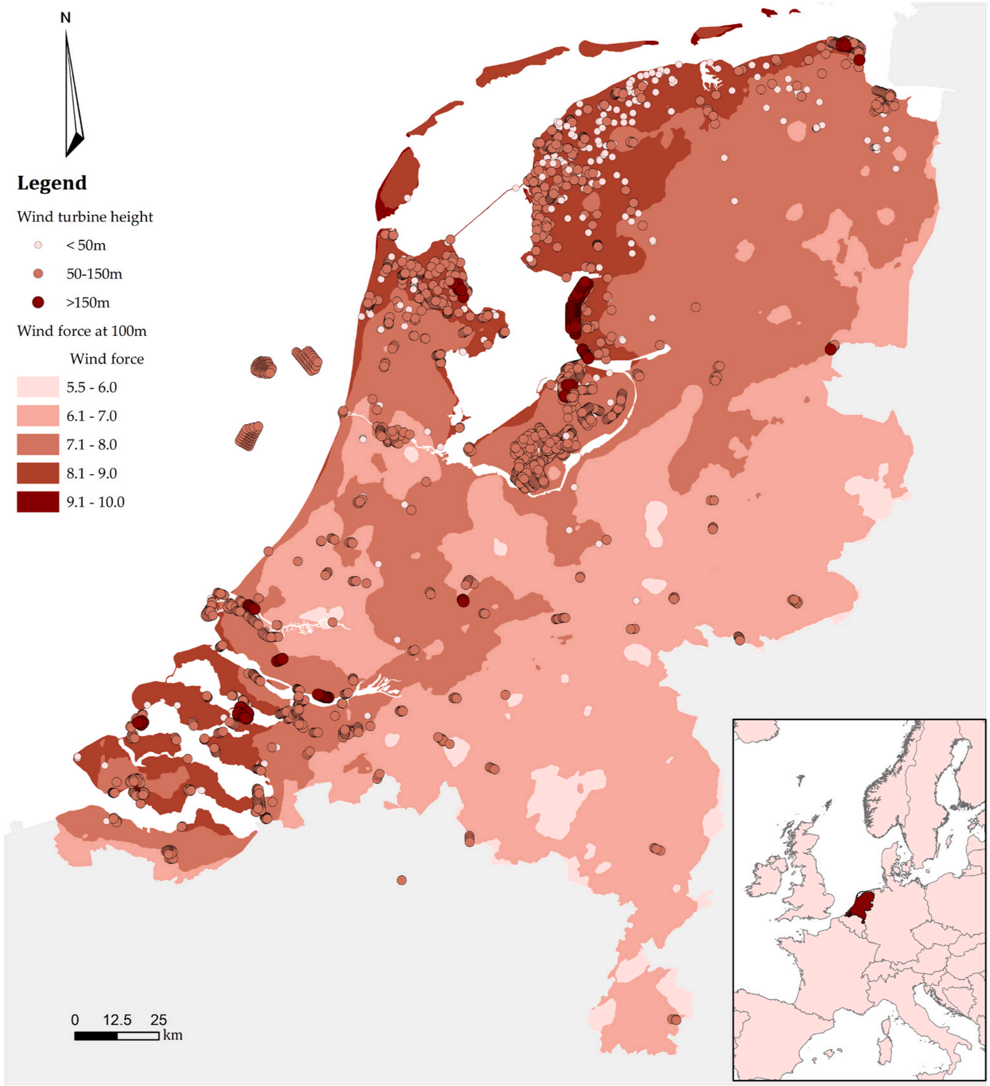


Fig. 1. The location of wind turbines
Notes: We obtain data on solar farms from windstats. Data on wind speeds is from the KNMI. The map is compiled by the authors.

therefore very societally relevant.

3. Data

3.1. Data on wind turbines and housing values

The locations of wind turbines, as well as the axis height, diameter of the blades, and the power (MW) of the turbine come from www.windstats.nl. We define *turbine height* as the axis height plus half the diameter of the rotor blades (*i.e.* the so-called tip height).[8] There is a very high correlation ($\rho = 0.918$) between height of the turbine and the power it generates. For example, a turbine of 3 MW (with a height of about 150m) produced 6.5 million kWh, while a turbine of 2 MW (115m) only provides 4.5 million kWh.

The total number of wind turbines up to and including mid-2019 is $2,695$. This study focuses on the $2,406$ turbines that have been built on land.[9] Of the turbines that have been built on land, 614 were built after 2011. Many of these new turbines are close to the locations where wind turbines have previously been installed. Fig. 1 shows the locations of wind turbines. The map highlights that wind turbines are often concentrated in coastal areas (which have a lot of wind). Fig. 2 shows that there is clearly an upward trend in the height of turbines. In 2000 the average height of new turbines was still around 80m. Towards the end of the sample period, the average height is about 140m with a maximum of 200m. Interestingly, the trend seems to stabilize as of 2016. Currently, low turbines (<50m) account for about 10% of the turbines, medium-sized (50–150m) for about 80% and tall turbines (>150) for the remaining 10%.

The dataset concerning house prices has been provided by Brainbay. The data cover approximately 70% of the market.[10] The data contain

[8] Dröes and Koster (2016) use axis height and the diameter of rotor blades separately, but the effect of these are difficult to measure as height and diameter of the blades are highly correlated (*i.e.* there are 'no high turbines' with tiny blades).

[9] The *Princess Amalia*, *Egmond aan Zee*, *Luchterduinen*, and *Gemini* offshore wind farms are therefore not included in our analysis, *Gemini* is missing from the map shown here because it is far from the coast.

[10] The sales that are not included are by real estate agents that are not a member of the NVM real estate organization, but most of them are.

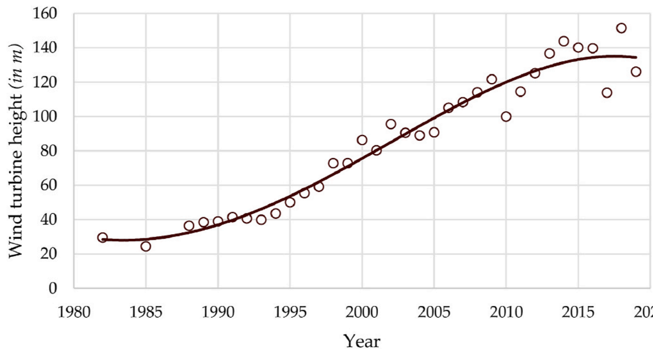


Fig. 2. Average height of new wind turbines
Notes: We obtain data on the height of wind turbines from Windstats. The solid line indicates the non-linear trend line.

sales of existing properties between 1985-(mid)2019. In addition to property prices, the dataset includes information on many different property features. Based on this, we can calculate the distance to the nearest existing wind turbine for each (transacted) home in our sample. The descriptive statistics are reported in Table 1.

The average house price between 1985 and 2019 is €214.178. This is based on more than 3 million transactions (2.7 million homes). The average house price is slightly lower (€206.658) within 2 km of an existing wind turbine, suggesting there is a slight tendency to built turbines in areas with lower prices. In Appendix A.2 we provide more details on differences between treated and control areas.

Finally, the average distance of properties to wind turbines in 2019 is 8.7 km. This distance has been decreasing for years; in 1995 for example the distance was still 26.6 km. However, for many households, wind turbines are still relatively far away. Only 5.1% of the housing transactions between 1985 and 2019 occur within 2 km wind turbines *after* they have become operational. Yet, the total number of transactions near all wind turbines present in 2019 is 290,002 (238,164 houses).

3.2. Data on solar farms and housing values

The data on solar farms come from Zon op Kaart, compiled by ROM3D. We have double-checked these data through OpenStreetMap. Furthermore, using OpenStreetMap, we geocode the data so that we have exact information on the size and geographic demarcation of solar farms. The number of solar farms (107) included in the analysis is much lower than the number of wind turbines.[11]

Fig. 3 shows the location and opening year of solar farms in the Netherlands until mid-2019. The first solar farm in our dataset is *Ecopark Waalwijk* (4.2 thousand panels) which opened in 2004. The locations of the solar farms are not randomly distributed in the Netherlands. As solar farms are land-intensive, many solar farms are located in areas with a low population density because of land availability.

The largest solar farm currently is located in Vlagtwedde (Groningen) and consists of $320,000$ solar panels (approximately 1 km^2) with a total nominal peak power of 109 MWP.[12] It appears that new solar farms generally contain more panels, so the size of solar farms has increased over time. Using the data on property transactions, we calculate the distance of each property to the edge of the nearest solar farm.

Although the first solar farm was opened in 2004 we do not observe transactions within 1 km after the opening of this solar farm. 97 solar farms were opened in 2017, 2018, and 2019. Because almost all solar farms have been opened in recent years, we use the transactions data from the last 10 years (*i.e.* from 2009 to 2019). The descriptive statistics are reported in Table 2.

Table 1
Descriptives: house prices and wind turbines.

	(1) Mean	(2) St.dev.	(3) Min	(4) Max
Transaction price (€)	214,180	121,704	25,000	1,000,000
Wind turbine, <2 km	0.0506	0.2192	0	1
House size in m^2	117.9	37.71	26	250
Number of rooms	4.384	1.340	1	25
Terraced	0.317	0.465	0	1
Semi-detached	0.281	0.449	0	1
Detached	0.128	0.334	0	1
Garage	0.331	0.471	0	1
Garden	0.976	0.154	0	1
Maintenance state is good	0.866	0.341	0	1
Central heating	0.891	0.312	0	1
Listed building	0.00618	0.0784	0	1
Construction year 1945–1959	0.0717	0.258	0	1
Construction year 1960–1970	0.150	0.357	0	1
Construction year 1971–1981	0.169	0.374	0	1
Construction year 1981–1990	0.138	0.345	0	1
Construction year 1991–2000	0.126	0.332	0	1
Construction year >2000	0.109	0.311	0	1

Notes: The number of observations is 3,389,903. The data covers the period 1985-(mid)2019. Apartments are the reference group for the type of residence. Houses built before 1945 are the reference category for the building year.

The average property price between 2009 and mid-2019 is €$249,586$. The other descriptive statistics regarding housing characteristics are almost identical to those of wind turbines. The number of transactions in the Netherlands between 2009 and 2019 is about 1.5 million. Yet, there are not that many observations nearby solar farms. In particular, within 1 km there are 1,736 transactions *after* the placement of a solar farm (0.118% of the data). Fortunately, the total number of transactions within 1 km of all solar farms that are present in 2019 is 12,650 (11,843 houses).

Similarly to wind turbines, house prices within 1 km of a solar farms are lower (€226,000) than the sample average. These, and other descriptive statistics, are discussed in more detail in Appendix A.2.

4. Methodology

4.1. Measuring the price effect of wind turbines

To measure the effect of wind turbines on house prices, we employ a difference-in-differences hedonic price method in which house price developments nearby wind turbines are compared with house price developments further away. In particular, we estimate:

$$\log P_{it} = \beta w_{it-1} + \gamma X_{it} + \lambda_j + \lambda_t + \varepsilon_{it}, \tag{1}$$

where P_{it} is the transaction price of property i sold in year t, w_{it-1} is an indicator that is 1 if a property is sold within 2 km in all years *after* placement of a wind turbine (for now we focus on the nearest wind turbine), X_{it} are housing characteristics, λ_j are location fixed effects at the postcode 6-digit level (containing about a half a street and on average just over 20 households, but fewer in rural areas), λ_t are month and year time dummies that control for overall price trends and seasonality, ε_{it} contains characteristics of properties or locations that are unobserved. These are assumed to be uncorrelated with the placement of

[11] Importantly, we disregard solar panels on roofs of industrial or agricultural buildings and only consider land-based solar farms.

[12] This solar farm produces about $0.85 \times 1,000,000 \times 109 = 92$ million kWh per year (see Tenten Solar, 2019). For comparison purposes, an (average) wind turbine of 3 MW delivers around 8 million kWh; the park is therefore roughly equal to 14 wind turbines.

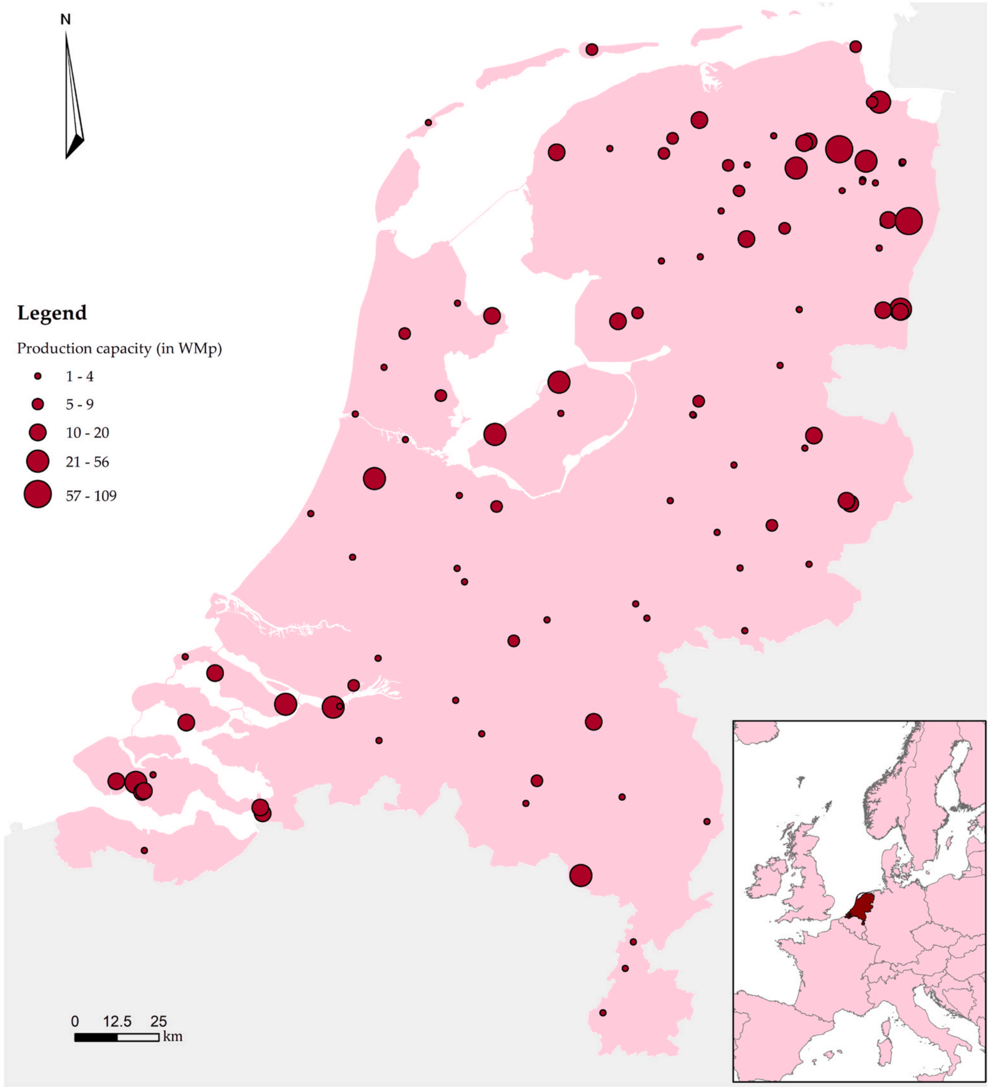


Fig. 3. The locations of solar farms (until mid-2019)
Notes: We obtain data on solar farms from ZonopKaart. The first solar farm was built in 2004. The map is compiled by the authors.

a turbine.[13]

We control for any time-constant price difference across locations. This is important as differences in prices may arise because amenities may differ between locations (for example, the presence of schools, etc.). To alleviate the concern that the location fixed effects are not detailed enough we will also show robustness using a repeat sales approach, completely absorbing time-invariant property and location characteristics. We use 2 km around turbines as treatment areas, as most of the noise (<500m), flickering (<1000m), and landscape pollution (< 2000m) typically falls within this area (Dröes and Koster, 2016). Nevertheless, we will also explicitly investigate whether the effect reaches beyond 2 km.

We are particularly interested in β, which measures *the percentage change in property value relative to a (local) control group*. We start our analysis by using transactions in the rest of the Netherlands as the control group and subsequently examine the effect using 3–5 km and 2–3 km as control group areas.

Still, one may be concerned that properties that are further away than 2 km may have different price trends. For example, they may be located closer to city centers, which are prone to relatively strong price increases due to inelastic housing supply and gentrification. Our preferred specification therefore only keeps observations within 2 km of a (future) wind turbine, implying that we only use the variation in the opening dates of wind turbines. We are then comparing the price development in areas in which wind turbines are opened to locations where they will be opened in the future. This is possible because there is variation in the opening date of wind turbines.

This approach is a version of a difference-in-differences strategy, but one in which unobserved price trends are much more likely to be very similar in treatment and control areas, and much less restrictive than the standard parallel trend assumption between spatially differentiated treatment and control groups that is usually applied in standard differences-in-differences methodologies. In particular, in Appendix A.3 we show that this is equivalent to a model with *non-parallel trends* (*i.e.* we implicitly control for differences in income, unemployment trends, etc.) between control and treatment groups.

Finally, it is important to control for housing characteristics because certain types of homes are more often located closer to wind turbines. A possible decrease in value could then mistakenly be attributed to the

[13] Note that the location fixed effects capture time-invariant price differences between control and treatment areas (*e.g.* the selection effect of wind turbines being placed in low-priced areas). The time fixed effects capture time trends, such as general economic trends affecting house prices. Time fixed effects also absorb any difference between real and nominal prices.

Table 2
Descriptives: house prices and solar farms.

	(1)	(2)	(3)	(4)
	Mean	St.dev.	Min	Max
Transaction price *(€)*	249,586	124,274	25,000	1,000,000
Solar farm <1 km	0.00118	0.0343	0	1
House size in m^2	116.8	37.70	26	250
Number of rooms	4.453	1.398	1	24
Terraced	0.313	0.464	0	1
Semi-detached	0.277	0.448	0	1
Detached	0.122	0.327	0	1
Garage	0.314	0.464	0	1
Garden	0.970	0.170	0	1
Maintenance state is good	0.867	0.340	0	1
Central heating	0.881	0.323	0	1
Monumental status	0.00636	0.0795	0	1
Construction year 1945–1959	0.0704	0.256	0	1
Construction year 1960–1970	0.133	0.339	0	1
Construction year 1971–1981	0.139	0.346	0	1
Construction year 1981–1990	0.114	0.317	0	1
Construction year 1991–2000	0.119	0.324	0	1
Construction year > 2000	0.203	0.402	0	1

Notes: The number of observations is 1,470,808. The data is as of 2009. Apartments are the reference group for the type of residence. Houses built before 1945 are the reference category for the building year.

placement of a wind turbine. We will show various robustness tests showing the validity of our research design.

Furthermore, we are particularly interested to examine heterogeneity in the impact of wind turbines by allowing the price effect to differ between low (<50m), medium-sized (50–150m), and tall (>150) turbines. The specification to be estimated is then:

$$\log P_{it} = \sum_{h=1}^{3} \beta_h w_{iht-1} + \gamma X_{it} + \lambda_j + \lambda_t + \varepsilon_{it}, \tag{2}$$

where w_{iht-1} is a dummy that equals one when the nearest turbine falls in height category h and is within 2 km in $t-1$, and β_h are the coefficients to be estimated for each height category. We will also examine whether the impact radius differs for turbines with different heights.

4.2. Measuring the price effect of solar farms

For solar farms we initially assume an impact radius of 1 km, which we realize is somewhat arbitrary. We will therefore also investigate the spatial extent of the effect. To measure the impact of the opening of a solar farm on property values, we use the same methodology as that for wind turbines. We estimate the following equation:

$$\log P_{it} = \zeta s_{it-1} + \gamma X_{it} + \lambda_j + \lambda_t + \eta_{it}, \tag{3}$$

where P_{it} is again the transaction price of property i sold in year t, s_{it-1} is an indicator that is 1 if a property is sold within 1 km in all years after opening of a solar farm (again we look at the nearest solar farm), X_{it} are property characteristics, λ_j are postcode fixed effects, λ_t are month dummies, and η_{it} again captures unobserved heterogeneity.

We are particularly interested in ζ. This coefficient measures the percentage change in property values due to the placement of a solar farm relative to a (local) control group. The initial control group consists of transactions from the whole of the Netherlands. We improve on this by selecting transactions within 2–5 km and 1–2 km. As there are much fewer solar farms as compared to wind turbines, we expect that just using temporal variation in the opening of solar farms (*i.e.* only using observations within 1 km of a solar farm) will lead to somewhat imprecise estimates.

5. Results

5.1. Baseline estimates: wind turbines and house prices

Table 3 shows the regression results based on equation (1). In column (1) we use the whole dataset. The results suggest that the opening of a wind turbine within 2 km of the property is associated with a house price decrease of 1.9% ($= (e^{-0.0192} - 1) \times 100\%$). This effect is statistically significant at the 1% significance level. Using the whole of the Netherlands as a control group is unlikely to yield unbiased results, as price trends between rural areas (where turbines are often placed) and urban areas are most likely different.[14]

In columns (2) and (3) we change the control group to include transactions within 3–5 km and 2–3 km of a wind turbine, respectively. The effect becomes a bit higher(2.5%) using the 3–5 km control group and -2.1% in case of the 2–3 km control group. The fact that the effect we find is relatively robust and remains statistically significant even with a substantially smaller sample and different control groups suggests that it is plausible we are capturing a causal effect of the opening of wind turbines on house prices.

Finally, we estimate a version of equation (1) that is based on the sample of transactions within 2 km of all existing wind turbines in 2019. That is, we measure the effect conditional on the placement of wind turbines in particular areas. This should capture any selection effect concerning the location of wind turbines. The regression estimate in column (4) shows that house prices within 2 km of a wind turbine decrease by 1.8% *relative* to areas in which a wind turbine has not yet been constructed. The effect is statistically significant at the one percent significance level. We consider this to be strong evidence that wind turbines affect nearby house prices.[15]

5.2. Robustness checks

In Appendix A.3, we discuss several sensitivity analyses concerning the results. First, we estimate a repeat sales model, which conditions out all time-invariant housing and location characteristics by differencing prices between pairs of consecutive transactions of the same house. The estimated coefficient is still very close to the baseline estimate suggesting that the detailed location fixed effects we have used before seem to capture unobserved housing and location characteristics well.

Second, we test whether *anticipation effects* are important. Such anticipation effects may arise because house prices already adjust before the construction of a turbine, *e.g.* because the planning phase may take several years. We show that the treatment effect *controlling for any anticipation effects* is -2.1%. The effect is still statistically significant at the one percent significance level. Prices start to decline about 3 years before the opening of a turbine.

Third, we investigate whether regional trends may be correlated with the placement of turbines. We estimate a specification with travel-to-work-area (TTWA) fixed effects interacted with time trends. The treatment effect remains very stable (*i.e.* it is -2.1%).

Fourth, we examine wind turbine removals and show that house

[14] Yet, the equation including controls and fixed effects seems to capture a considerable amount of the variation in house prices, as we can explain 93% of the variation in house prices. This high fit is mainly due to the inclusion of highly detailed PC6 fixed effects.

[15] In principle, this specification is equivalent to a difference-in-differences model that allows for non-parallel trends between the control and treatment groups. In Appendix A.3 we show that a classical difference-in-differences (DID) model based on the model estimated in column (3) (2–3 km control group), but allowing for such non-parallel trends indeed yields identical point estimates. Only the standard errors are (marginally) smaller as they are (artificially) lowered by adding the control group transactions. We, therefore, prefer the results reported in Table 3, column (4).

Table 3
Average effect of wind turbines on house prices.

(Dependent variable: the logarithm of house prices)				
	(1)	(2)	(3)	(4)
	Full sample	*Control group (3–5 km)*	*Control group (2–3 km)*	*Temporal variation only*
Wind turbine placed, <2km	−0.0192***	−0.0256***	−0.0214***	−0.0183***
	(0.0041)	(0.0045)	(0.0048)	(0.0068)
Housing characteristics	✓	✓	✓	✓
Postcode fixed effects	✓	✓	✓	✓
Year and month fixed effects	✓	✓	✓	✓
Observations	3,389,780	1,488,276	710,703	290,002
R^2	0.92	0.92	0.92	0.92

Notes: This table is based on data between 1985 and 2019. Standard errors are clustered at the neighborhood level and are in parentheses. Significance levels: ***p<0.01, **p<0.05, *p<0.10.

prices increase by 1.1% if a turbine is removed. However, due to a low number of removed turbines, the estimate is somewhat imprecise and not statistically significant at conventional levels.

Fifth, we study the effect of multiple turbines. We show that it is particularly the first turbine that has an effect on house prices. When more turbines are built within 2 km turbines, the additional turbines generally have a negative effect but the effect is less than 1% and statistically insignificant. From a policy perspective, these results imply that to reduce external effects on house prices it is best to cluster turbines in wind farms.

Finally, one may be concerned that the perception regarding wind turbines may have changed. We, therefore, test whether the willingness to pay to live nearby turbines is constant across the study period. It appears that we cannot reject the null hypothesis that the effect is constant over time.

5.3. Demography and sorting

One may wonder what type of households are the most affected by the placement of wind turbines. We explore this in Appendix A.4, where we gather data from Statistics Netherlands on various demographic characteristics at a very spatially disaggregated postcode 6-digit level. The results do confirm that turbines are built in sparsely populated areas with about 30% lower population densities. Interestingly, we find that the median income is only 2% lower within 2 km of a turbine. Hence, the households that are affected are not necessarily those at the lower end of the income distribution. Moreover, the share of people receiving income assistance is the same between treated and untreated areas.

Finally, we further investigate whether preference-based sorting occurs after the placement of a wind turbine. We find small changes in population density, household size, and the share of foreigners after a wind turbine is placed. Although statistically significant, these effects are economically small. Hence, we do not find evidence that the demographic composition changes considerably after turbine construction.

5.4. Wind turbine height

Up until now, we have ignored the effect of turbine height and assumed that the effect of turbines is confined to 2 km. As shown, turbines have become taller over time, which may, in turn, have exacerbated visual pollution, as well as the potential reach of noise pollution, flickering and shadow. We would expect that this increases the treatment effect and also affects the overall impact radius.[16] We, therefore, estimate several regression based on equation (2), using temporal variation only (see Table 3, column (4)), and show the results in several figures.[17]

In Fig. 4a we show that taller turbines indeed have a larger effect on house prices. Small turbines (<50m) on average have an effect of less than -1%. while this effect is not statistically significant. For a medium-sized turbine (50–150m) the effect is around 2% and statistically significant.[18] For turbines taller than 150m the effect is around 5% and also statistically significant, even though the confidence bands are a bit wider due to a lower number of observations.[19] The effect ranges between 3 and 7% and it is clear that the effect is considerably stronger than the effect of low turbines.

In Fig. 4b, we control for time-varying effects of turbines, as to control for any potential changes in perception over time. We find very similar effects for small, medium and tall wind turbines. The effect of a medium-sized turbine is now about − 3% and the effect of a tall turbine is also a bit larger and − 5.4%. These effects are still statistically significant, but note that the confidence bands are now somewhat wider.

5.5. Impact area of turbines

Distance to a wind turbine is likely an important factor in determining the possible decrease in prices. Within 5 times the axis height there is a possible effect of sound and for the average turbine up to 1 km there is also possible shadow. Up to 2 km (and beyond), there is potentially visual pollution.

In Fig. 5 we, therefore, show a specification where we interact the effect of turbines by 250m distance band dummies. Hence, we estimate the treatment effect for different distance bands. The number of observations increases as we now include housing transaction prices within 2.5 km of a (future) turbine. Fig. 5 shows that within 500m the confidence bands are large because the number of observations is low. Hence, we cannot precisely determine the effect of the opening of a wind turbine on transaction prices within short distances. Between 500 and 750m the effect is about − 3%. The effect gradually decreases until at 2500m the effect is small and indistinguishable from zero. Hence, the impact area of turbines seems to be maximally 2250m.

Although the average effect across all turbine heights is of interest, it is important to investigate whether the impact area is different for tall turbines. Therefore, we re-estimate the regression but now allow the effects to vary by wind turbine height *and* distance. Even with this large dataset, the number of observations for tall turbines is small. Hence, we aggregate the distance bins for the tallest turbines by 500m instead of 250m. The results are depicted in Fig. 6. Small turbines only have a statistically significant effect of about 2% at 1 km and the effect is essentially zero beyond 1 km. At 500m and 750m the effects are imprecisely measured.

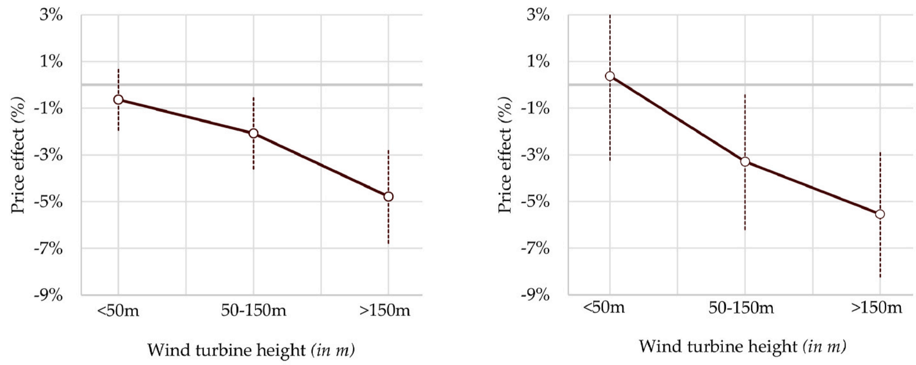
A turbine with a height between 50 and 150m yields a statistically significant effect of -3.4% at 750m. The effect decreases over distance, but at a relatively low rate. At 2500m the effect is no longer statistically

[16] For example, at a distance of 2 km a turbine of 100m in height has a perceived height of 5cm. Instead, a 200m high turbine at that distance has already a perceived height of 10cm. The view of such a turbine might well be less obscured by features of the (urban) landscape.

[17] The underlying regression table is reported in Appendix A.3.

[18] We also considered splitting this category up even further but did not find statistically significant differences between those turbines.

[19] In the Netherlands, turbines larger than 150m also need to have a flashing light (white during the day, red during the night). This might increase the experienced nuisance and visibility of those wind turbines.



(A) UNCONDITIONAL EFFECT OF HEIGHT (B) CONTROLLING FOR TIME-VARYING EFFECTS

Fig. 4. Price effects for different turbine heights
Notes: The dotted lines represent the 95% confidence intervals. These regressions include observations within 2 km of a (future) turbine and control for housing characteristics, postcode fixed effects, as well as year and month fixed effects. The number of observations is 290,002 and the R^2 in both regressions is 0.92.

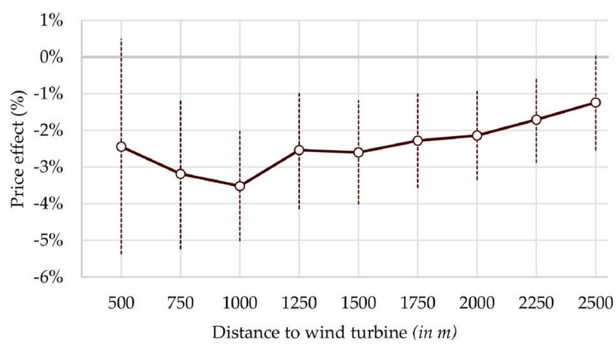


Fig. 5. Wind Turbines: Price effects at different distances (1985–2019)
Notes: The dotted lines represent the 95% confidence intervals. This regression includes observations within 2.5 km of a (future) turbine and controls for housing characteristics, postcode fixed effects, as well as year and month fixed effects. The number of observations is 491,337 and the R^2 is 0.92.

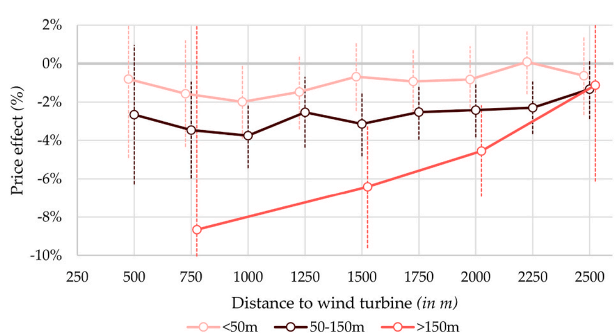


Fig. 6. Distance and wind turbine height
Notes: The dotted lines represent the 95% confidence intervals. This regression includes observations within 2.5 km of a (future) turbine and controls for housing characteristics, postcode fixed effects, as well as year and month fixed effects. The number of observations is 491,337 and the R^2 is 0.92.

significant. For the tallest wind turbines, the effect is again larger than for small turbines. At 750m the effect is -8.3%, albeit very imprecise due to the low number of observations (within 500m of a turbine exceeding 150m there are even no transactions available). The effect again decreases with distance, but more rapidly, and the effect is small and no longer statistically significant at 2500m. Note that the confidence bands for different heights are overlapping in most cases, except when comparing the largest and smallest turbines, which suggests that measuring the effect of height and distance to a turbine demands a lot from the data.

Overall, our results imply that taller turbines have higher effects on house prices and we find evidence that the effect also reaches just beyond 2 km, up to 2250m, but not beyond 2.5 km. Moreover, we show that low turbines (<50m) have a small impact on house prices that is confined to about 1 km.

5.6. Solar farms and house prices

In Table 4 we report results regarding solar farms, based on equation (3). Column (1) shows the effect of the opening of a solar farm within 1 km of a home using the full extent of our data. This effect is -3.7% ($=(e^{-0.0380}-1)\times 100\%$) and statistically significant at the 1% significance level. However, this specification does not take into account local price trends that may be correlated with the placement of solar farms. Moreover, it is not a priori clear that the effect is confined to 1 km.

To take these issues into account, a specification is estimated in column (2) in which the control group are transactions that take place within 2–5 km of a solar farm. The effect now becomes -4.6% and it is still highly statistically significant. Finally, in column (3) we decompose the effect for 500m distance bands. In Fig. 7 we show that the effect within 500m is -5.9%. It is -3.8% up to 1 km and it approaches zero and is no longer statistically significant beyond 1 km.

Next, we undertake some robustness checks. In column (4) we consider a more local control group by only including observations within 2 km of a (future) solar farm. The estimated coefficient is somewhat smaller: house prices decrease on average by 2.6% after the opening of a solar farm. The effect is highly statistically significant. We consider this estimate as our preferred estimate as it is rather conservative and the control group is more local.

Furthermore, it could be argued that the effect of solar farms picks up the effect of wind turbines, because they might be located close to each other. Hence, we add a dummy indicating whether there is a wind turbine within 2 km in column (5). The effect of solar farms is still -2.6%. This is not too surprising as the correlation between wind turbine locations within 2 km and solar farms within 1 km is only 0.005. The negative effect of wind turbines is statistically insignificant because the sample only includes very few turbines.

Finally, we identify the effect based on variation in the opening dates of solar farms only. The result is reported in column (6). In this case, the point estimate is still -1.5% but the effect is no longer statistically significant. This is not surprising as we include just 12,650 observations in the regression. More importantly, given the standard error, this estimate is not statistically significantly different from our preferred estimate.

We interpret these findings as robust evidence that property values decrease within 1 km of solar farms. The coefficient estimates range

Table 4
Average effects of solar farms on property prices (2009–2019).

	(Dependent variable: the logarithm of house prices)					
	(1)	(2)	(3)	(4)	(5)	(6)
	Whole	*Control group*	*Distance*	*Control group*	*+ Wind turbine*	*Temporal*
	Netherlands	*2-5 km*	*profile*	*1-2 km*	*treatment*	*variation only*
Solar farm placed <1 km	−0.0380***	−0.0469***	see Fig. 7	−0.0263***	−0.0263***	−0.0156
	(0.0093)	(0.0099)		(0.0090)	(0.0090)	(0.0253)
Wind turbine placed <2 km					0.0018	
					(0.0166)	
Housing characteristics	✓	✓	✓	✓	✓	✓
Postcode fixed effects	✓	✓	✓	✓	✓	✓
Year and month fixed effects	✓	✓	✓	✓	✓	✓
Observations	1,470,808	355,235	405,164	62,579	62,579	12,650
R^2	0.90	0.90	0.90	0.89	0.89	0.90

Notes: This table is based on data between 2009 and 2019. Standard errors are clustered at the neighborhood level and are within parentheses. ***p< 0.01, **p< 0.05, *p<0.10.

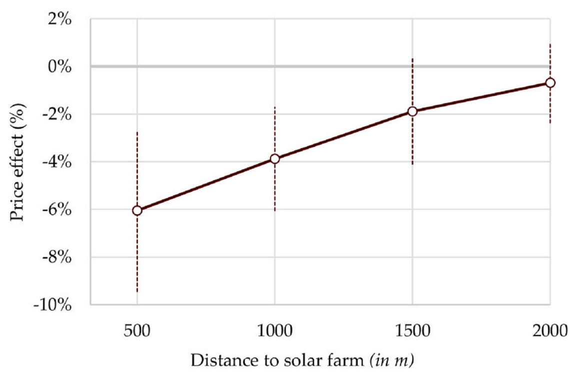


Fig. 7. Price effects at different distances, solar farms (2009–2019)
Notes: The dotted lines represent the 95% confidence intervals. This regression includes observations within 5 km of solar farms present in 2019 and controls for housing characteristics, postcode fixed effects, as well as year and month fixed effects. The number of observations is 405,164 and the R^2 is 0.90.

between -1.5% and -5.9%, depending on the specification. Again, we see the results in column (4) as our preferred model estimate: it takes into account possible unobserved trends and includes enough observations to accurately estimate the effect. The effect is of the same order of magnitude as for turbines, but more localized.

5.7. Overall losses in property values

Given the regression estimates, we can calculate the 'back-of-the-envelope' total loss in housing values as a result of the construction of wind turbines and solar farms in the Netherlands. For wind turbines, we use the estimates that discriminate between the height of a turbine and the distance of a property to the nearest turbine reported in Fig. 6. For solar farms, we rely on the estimate reported in column (4) in Table 4.

Using data from BAG (*i.e.* the Building Register) we calculate the number of residential properties in each distance band from each wind turbine and solar farm. Furthermore, we calculate real average house prices (in 2019 prices) within 2 km of a wind turbine and 1 km of each solar farm using the NVM data. We then multiply the estimated price effects with real prices and the number of residential properties around each turbine or solar farm. Before we move to the results, we caution that the numbers should be interpreted as back-of-the-envelope calculations as we have to make several simplifying assumptions. First, we assume that the relative price decrease estimated for the owner-occupied housing market carries over to the rental market. Second, we

Table 5
Wind turbines and solar farms: total effects on house prices.

	(1)	(2)	(3)	(4)	(5)
	Wind turbines				Solar farms
	All	≤50m	50-150m	≥150m	All
Total loss in € *(in millions)*	4993	427	3789	777	800
Average loss in € per turbine/ farm	4,153,672	2,102,069	4,271,443	6,939,494	7,477,965
Average loss in € per MWh	953.14	2191.89	1033.84	763.82	835.59
Median loss in € per turbine/ farm	140,175	250,599	114,562	116,652	1,901,138
Median loss in € per MWh	53.41	276.96	34.15	11.30	364.80

Notes: We assume that a wind turbine of 1 MW delivers $365 \times 24 \times 0.304 = 2,663$MWh, where 0.304 represents the capacity factor, which we obtain from the Energey Information Agency. A solar farm with a nominal peak power of 1 MWh delivers $0.85 \times 1,000,000 \times 1 = 0.85$ million kWh.

assume that the average price effects of turbines and solar farms apply to properties throughout the Netherlands; so we abstract from any heterogeneity in the price effect other than the heterogeneity in distance to and height of the wind turbine. The results are still informative as they point towards the overall economic magnitude of the effect.

The results for wind turbines, reported in Table 5 show that the total loss in housing value is about €5 billion, which is substantial.[20] Because there are so few properties within 500m of a turbine, only 0.7% of the total loss accrues to properties within 500m of a turbine, while 10% of the loss is borne by properties within 1 km of a turbine. The average loss per turbine built on land is €4.1 million. The average loss per MWh is about €1 thousand. These results suggest that when placing wind turbines it is important to take into account the additional external costs.

However, the average loss per turbine may be somewhat misleading

[20] For comparison purposes, the Dutch GDP was about 725 billion in 2017.

as most of the total loss is due to a few turbines that are close to residential neighborhoods. More specifically, it appears that just 25 turbines account for almost 50% of the total loss. This shows that it is very important to build turbines not too close to residential properties. Indeed, the median loss per turbine is much lower and about €140 thousand, or about €53 per MWh. Given the construction costs of about €1.27 million per MW, we calculate the median loss in housing values as 16.5% of the construction costs.[21]

Note that the median loss per MWh varies considerably across turbines of different heights. For example, because tall turbines generate more power, the median loss per MWh is about €11, while it is €277 for low turbines. Hence, despite the smaller effects of low turbines, the loss in power does not make it more efficient to build low turbines.

Let us now consider the impact of solar farms. Because there are yet much fewer solar farms constructed, the total loss is just over €800 million. The *average loss* per solar farm is of the same order magnitude as the external costs of wind turbines. Here it also seems more informative to look at the median loss of a solar farm, which amounts to about €2 million, which is considerably larger than the median loss for one turbine. However, this is mainly because solar farms are generally larger and generate more energy. In addition, the median loss per MWh is €365, which is also considerably larger than the median loss of a wind turbine. The reason is that solar farms are often large so that it is hardly avoidable to have a solar farm that is not close to residential properties. Indeed, the median number of properties within 1 km is 178, while this is just 3 properties for wind turbines.[22]

These results seem to suggest that – even though the impact area is smaller – building solar farms does not mitigate the external effects of renewable energy production in comparison to wind turbines, at least given the current spatial distribution and available technology. Still, the large differences between the average and median loss per turbine/solar farm strongly confirm that choosing sparsely populated areas to build turbines/solar farms is important. For solar farms, these areas may be easier to find, as the impact area of solar farms seems to be confined to 1 km instead of about 2 km for turbines. On the other hand, the land beneath solar farms cannot be used for other purposes, while land close to turbines can be used for crops or livestock farming.

6. Conclusions and policy implications

Producing energy sustainably is an important step towards a climate-neutral economy with net-zero greenhouse gas emissions. Wind and solar energy are important sources of renewable energy. However, while reductions in CO_2 emissions benefit the whole population, external effects are borne only by households living close to production sites. Hence, insights into these external effects is paramount for renewable energy policy as the size of external effects is informative on whether there is local support for the opening of production sites, such as wind turbines and solar farms. In this study, a panel dataset on house prices between 1985 and 2019 from the Netherlands is used to measure the effect of the proximity of wind turbines and solar farms on property values.

Our results suggest that the opening of a wind turbine decreases local house prices by 1.8%. The impact of turbines does not reach beyond 2250m. It is particularly the first turbine that reduces house prices; hence to mitigate external effects, turbines should be concentrated in wind farms. Moreover, we are particularly interested in the effects of turbine height, as turbines have become much taller over time. For a turbine taller than 150m we find that the effect is on average -5.4%. The impact area is about 2 km. Instead, a small turbine below 50m has only a small effect which at most distances is statistically insignificant and quickly dissipates beyond 1 km. Thus, turbine height is an important source of heterogeneity in the effect of turbines on property values.

This study also investigates the impact of solar farms on house prices. Due to possible noise disturbance, the reflection of the sun, but also visual pollution, a solar farm can have a negative impact on property values. The effects of this are expected to be more local because these solar farms are less visible than wind turbines; and noise reflection also probably does not reach that far. We find evidence of a decrease in property values of about 2.6% after the placement of a solar farm. This effect is confined to 1 km.

Our back-of-the-envelope calculations document that the total loss in house value as a result of wind turbines is about €5 billion, which is about equal to the replacement costs. Interestingly, 1% of the turbines account for almost 50% of the loss in housing values. This confirms that the choice where to build turbines is key; to mitigate losses in housing values turbines should be placed in sparsely populated areas. The median loss per MWh produced is €53, but this varies considerably across turbines of different heights. For example, for tall turbines, the median loss per MWh is about €11. This suggests that it is worthwhile to build tall turbines. The median loss per MWh for solar farms is €365, which is much higher than the median loss for wind turbines (but note that the average losses are about the same). Hence, building solar farms instead of wind turbines will not mitigate the external effects of renewable energy production.[23]

The results in this paper highlight that careful placement of wind turbines and solar farms is paramount as the total loss in housing wealth can quickly increase if turbines and solar farms are built too close to residential properties. We argue that the external costs of wind turbines and solar farms should be taken into account when constructing such renewable energy production facilities and this study clarifies what those potential costs are. However, whether and to what extent homeowners should be compensated for the loss in housing values is a political question. Currently, the Dutch government compensates homeowners for losses in housing values due to area redevelopment exceeding 2% and this will be increased to 4% in 2022. Homeowners are only compensated for a loss in housing value over and above the threshold. We showed that only close to turbines or solar farms, the loss in housing values exceeds 4%, so that this compensation scheme, at least for most homeowners, will be of limited use in the future.

CRediT authorship contribution statement

Martijn I. Dröes: Methodology, Conceptualization, and, Formal analysis. **Hans R.A. Koster:** Methodology, Conceptualization, and, Formal analysis.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2021.112327.

[21] For each turbine, we calculate the loss per MW. We then take the median of this loss.

[22] Within 2 km of a turbine, the median number of properties is 15.5. This stark difference is also due to regulations that prohibit wind turbine construction close to residential properties.

[23] For future research and renewable energy policy, it would be useful to also compare the results with the potential negative external effects of other (non-renewable) energy production alternatives.

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