Wind Turbine Shutdowns and Upgrades in Denmark: Timing Decisions and the Impact of Government Policy*

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Abstract: For policymakers, an important long-run question related to the development of renewable industries is how government policies affect decisions regarding the scrapping or upgrading of existing assets. This paper develops a dynamic structural econometric model of wind turbine owners' decisions about whether and when to add new turbines to a pre-existing stock, scrap an existing turbine, or replace old turbines with newer versions (i.e., upgrade). We apply our model to owner-level panel data for Denmark over the period 1980-2011 to estimate the underlying profit structure for small wind producers (who constitute the vast majority of turbine owners in the Danish wind industry during this time period), and evaluate the impact of technology and government policy on wind industry development. Our structural econometric model explicitly takes into account the dynamics and interdependence of shutdown and upgrade decisions, and generates parameter estimates with direct economic interpretations. Results from the model indicate that the growth and development of the Danish wind industry were driven primarily by government policies as opposed to technological improvements. We use the parameter estimates to simulate counterfactual policy scenarios in order to analyze the relative effectiveness and cost-effectiveness of the Danish feed-in-tariff and replacement certificate programs. Results show that both of these policies significantly impacted the timing of shutdown and upgrade decisions made by small wind producers and accelerated the development of the wind industry in Denmark. We also find that when compared with the feed-in-tariff; a declining feed-in-tariff; and the replacement certificate program and the feed-in-tariff combined, the replacement certificate program was the most cost-effective policy both for increasing payoffs of small wind producers and also for decreasing carbon emissions.

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1 Introduction

Due to concerns about climate change, local air pollution, fossil fuel price volatility, energy security, and possible fossil fuel scarcity, governments at many levels around the world have begun implementing policies aimed at increasing the production share of renewables in the electricity sector. These support policies have taken several different forms (e.g., Renewable Portfolio Standards, feed-in-tariffs, tax credits, etc.), and proponents argue that they are necessary for these nascent industries to continue to develop technological improvements, achieve economies of scale, and compete with existing industries. Wind energy was one of the earliest renewable generation technologies to be promoted, and its maturity and low costs relative to other renewables have made it a leading option for many countries in the early phases of pursuing climate goals.

For policymakers, an important long-run question related to the development of renewable industries is how government policies affect decisions regarding the scrapping or upgrading of existing assets. How much of the shutdowns and upgrades can be attributed to the policies as opposed to technological progress? How do policies affect the timing of owner decisions and the subsequent path of the industry?

This paper aims to shed some light on these questions by developing a dynamic structural econometric model of wind turbine shutdowns and upgrades in the context of Denmark and using it to estimate the underlying profit structure for turbine owners. In particular, we model wind turbine owners' decisions about whether and when to add new turbines to a pre-existing stock, scrap an existing turbine, or replace old turbines with newer versions (i.e., upgrade). Shutting down and/or upgrading existing productive assets are important economic decisions for the owners of those assets and are also the fundamental decisions that underlie the development of new, growing industries.

To date, empirical research addressing the economics of wind energy has tended to focus on production costs, investment decisions, or policy options for increasing the penetration of wind energy in electricity grids. Engineering studies have regularly calculated the cost of producing electricity from wind turbines and compared it with existing fossil-fuel generators (Darmstadter, 2003; Krohn et al., 2009). Trancik et al. (2015) describe the evolution of wind energy in recent decades, and find that wind energy is now nearly cost-competitive with natural gas- and coal-fired power plants in many regions of the world. Hartley and Medlock (2017) find that until fossil fuels are abandoned, however, the price of energy is insufficient to cover even the operating costs of renewable energy production, let alone provide a competitive return on the capital employed. Krekel and Zerrahn (2017) analyze whether the presence of wind turbines has negative externalities for people in their surroundings, and find that negative externalities exist but are spatially and temporally limited; Lang et al. (2014) find that wind turbines have no statistically significant negative impacts on house prices. Jacobsson and Johnson (2000) come at the problem from a technology innovation and diffusion perspective, and provide an analytical framework for examining the process of technical change in the electricity industry. Hartley (2018) examines the costs of replacing fossil fuels by wind generation and storage, and compares wind power with generation based on nuclear and storage. Oliveira et al. (2019) present an empirical analysis of the displacement of CO_2 emissions associated with wind generation in the Irish electricity market.

Previous studies of scrapping decisions in the electricity industry have been either analytic, numerical, or reduced-form. Fleten et al. (2017) use a numerical real options analysis to study the effects of regulatory uncertainty and cash flow uncertainty on decisions to shut down, start up, and abandon existing peak power plants; we build on the methods used by Fleten et al. (2017) by estimating a dynamic model econometrically. Mauritzen (2014) estimates a reduced-form model of wind turbine scrapping decisions; we build on the work of Mauritzen (2014) by developing and estimating a dynamic structural econometric model, by utilizing additional data, by extending the model to include both shutdown and upgrade decisions, and by analyzing the effects and cost-effectiveness of government policy.

The previous literature on wind policy has been aimed at describing the policies that have been implemented (Allison and Williams, 2010); evaluating different wind energy policies based on their ability to promote new investments (Agnolucci, 2007; May, 2017), wind production (Aldy et al., 2019), or innovation (Covert and Sweeney, 2019); examining whether current policies encourage investments in socially optimal renewable capacity additions (Novan, 2015); or comparing the policies of different countries with emerging wind industries (Klaassen et al., 2005). Hitaj (2013) analyzes the effects of government policies on wind power development in the United States. Ciarreta et al. (2017) compare feed-in-tariffs and tradable green certificates in the Spanish electricity system. Munksgaard and Morthorst (2008) provide an excellent description of the trends in feed-in-tariffs and the market price of electricity in Denmark, and forecast future investments in wind energy based on an estimated internal rate of return. Fell and Linn (2013) use a simulation model to compare the cost-effectiveness of renewable electricity policies, including renewable portfolio standards, production subsidies, and feed-in-tariffs, in the Electricity Reliability Council of Texas (ERCOT) region. Reguant (2019) analyzes the efficiency and distributional implications of large-scale renewable policies, including carbon taxes, feed-in-tariffs, production subsidies, and renewable portfolio standards, using data from the California electricity market.

The "bottom-up" style of modeling we use in this paper is in direct contrast to many previous "top-down" approaches to examining trends in the wind industry, and the structural nature of our model gives insights into key economic and behavioral parameters. Understanding the factors that influence individual decisions to invest in wind energy and how different policies can affect the timing of these decisions is important for policies both in countries that already have mature wind industries, as well as in regions of the world that are earlier in the process of increasing renewable electricity generation (e.g. most of the U.S.).

We apply our dynamic structural econometric model to owner-level panel data for Denmark over the period 1980-2011 to estimate the underlying profit structure for small wind producers (who constitute the vast majority of turbine owners in the Danish wind industry during this time period), and evaluate the impact of technology and government policy on wind industry development. Our structural econometric model explicitly takes into account the dynamics and interdependence of shutdown and upgrade decisions, and generates parameter estimates with direct economic interpretations.

Results from our dynamic structural econometric model indicate that the growth and development of the Danish wind industry were driven primarily by government policies as opposed to technological improvements. We use the parameter estimates to simulate counterfactual policy scenarios in order to analyze the relative effectiveness and cost-effectiveness of the Danish feed-in-tariff and replacement certificate programs. Results show that both of these policies significantly impacted the timing of shutdown and upgrade decisions made by small wind producers and accelerated the development of the wind industry in Denmark. We also find that when compared with the feed-in-tariff; a declining feed-in-tariff; and the replacement certificate program and the feed-in-tariff combined, the replacement certificate program was the most cost-effective policy both for increasing payoffs of small wind producers and also for decreasing carbon emissions.

The balance of our paper proceeds as follows. We describe the Danish wind industry in Section 2. We describe our dynamic structural econometric model in Section 3. We present the results in Section 4. Section 5 concludes.

2 The Danish Wind Industry

For many countries, questions regarding wind turbine shutdown and upgrade decisions will become increasingly relevant in the near future as existing turbines approach the end of their expected lifetimes (usually around 20 years) and technology continues to improve. This is already the case in Denmark, where a concerted effort to transition away from fossil fuels began in the late 1970's soon after the first oil crisis. Since then, the long-term energy goal of the Danish government has been to have 100% of the country's energy supply come from renewable sources.

With a long history of designing turbines that stretches back to the late 19$^{\text{th}}$ century (Heymann, 1998), wind power was Denmark's leading technological choice to offset electricity production from fossil fuels. To this end, the Danish government implemented several policies designed to encourage wind investments throughout the country. As a result of this sustained policy goal, Denmark became a leader in both turbine design and installed wind capacity during the 1980s and 1990s, and has one of the most mature modern wind industries in the world. Denmark has dominated other countries in wind deployment per capita and per GDP, and currently produces the equivalent of roughly 40% of its electricity demand in wind power (Trancik et al., 2015).

We focus on the wind industry in Denmark over the period 1980-2011, and use data from a publicly available database containing all turbines constructed in Denmark during that time period (DEA, 2018). Ownership information for each turbine was obtained from a professional colleague at Energinet.dk so that a panel data set at the owner level could be constructed and used to estimate our dynamic structural econometric model. During our period of study, there were significant improvements in turbine technology as well as changes to government wind policies.

An interesting feature of Danish wind development was that it was not led by a few large firms constructing large, centralized wind farms. Instead, the vast majority of wind turbines in the country were installed and owned by individuals or local cooperatives. In terms of ownership, the Danish wind industry has been remarkably decentralized throughout its history. This decentralized development resulted in 80% of all turbines in Denmark being owned by wind cooperatives in 2001 (Mendonça et al., 2009). Of the roughly 2,900 turbine owners during over the period 1980-2011, the vast majority (~90%) own two or fewer turbines, and these turbine owners owning two or fewer turbines produced the majority (56.5%) of Denmark's wind production output during this time period. In particular, of the 2,924 total turbine owners in the country during our period of study (1980-2011), 2,565 (88%) own two or fewer turbines. We therefore focus on turbine owners who own two or fewer turbines.

Our analysis makes use of several turbine-specific and national level variables that likely have an impact on turbine management decisions. Included in the Energinet.dk data are the capacity of each turbine, the date it was installed, and the location of the turbine. Capacity enters directly into all specifications of our model, while the installation date is used to calculate the age of each turbine throughout the study period. Summary statistics for the capacity and installation date of the turbines we use in our dynamic structural econometric model (i.e., turbines owned by owners with two or fewer turbines over the period 1980 to 2011) are shown in Table 1. We also include variables for government policy and for the state of wind turbine technology, each of which we describe in detail below.

2.1 Government Policy

We focus on two important policies that the Danish government has implemented on the wind industry: (1) the feed-in-tariff for electricity generated by wind turbines, and (2) the replacement certificate scheme for incentivizing turbine owners to scrap old turbines and replace them with new ones.

Since the late 1970s, the Danish government has supported wind development by paying wind turbine owners a feed-in-tariff for electricity generated by wind turbines. A feed-in-tariff is a policy that guarantees a flat price to renewable technologies for each unit of electricity generation, usually over a long period of time, potentially with a changing tariff over time and targeted to specific technologies (Fell and Linn, 2013; Reguant, 2019).

Prior to the liberalization of the power market in 1999,[1] the feed-in-tariff provided by the Danish government to wind turbine owners was a fixed price guaranteed for a significant portion (if not all) of a wind turbine's useful life. After liberalization,[2] the feed-in-tariff was a supplement to be paid to owners on top of the electricity price determined in the competitive wholesale market so that wind turbine owners were guaranteed a maximum total price (feed-in-tariff plus market price). The price guaranteed by the feed-in-tariff is determined by the date a turbine was built, and has been adjusted over time as more wind power came online (see Table 2). Because the feed-in-tariff guarantees the price that wind turbine owners will receive for production, wind turbine owners are insulated from changes in wholesale prices.[3] Thus, the shutdown and upgrade decisions of wind turbine owners are likely to be affected by the price guaranteed by the feed-in-tariff, and not by wholesale prices.

Also beginning in 1999, the government created a replacement certificate program to incentivize the upgrading of older, lower capacity turbines to newer, larger turbines. Eligible turbine owners who scrapped

[1]Before 1999, Danish municipal utilities were vertically integrated and operated as regulated natural monopolies so that the price of electricity for retail customers was set at a level that allowed the utility to recouperate the cost of generating, transmitting, and distributing electricity to its customers.

[2]After liberalization in 1999, Denmark joined the Nordic regional market (NordPool) and began using locational marginal pricing together with a Dutch auction mechanism (2^{nd} price auction) to determine wholesale prices. Because the feed-in-tariff guarantees the price that wind turbine owners will receive for production, however, wind turbine owners are insulated from changes in wholesale prices, including those resulting from changes in Nordpool prices and Danish foreign electricity trade.

[3]Massive increases in wind capacity (and generation) can have an impact on daily wholesale prices. On particularly windy days, the wholesale price can become negative as zero-marginal cost wind becomes the marginal source of generation and the market actually pays buyers to use excess wind production. Rintamäki et al. (2017) find that wind power decreases the daily volatility of prices in Denmark, however, by flattening the hourly price profile.

their turbines during the program received a certificate that would grant an additional price supplement for a new turbine that was constructed (see Table 3). These scrapping certificates were given out through the end of 2011 and could be used by owners to upgrade their turbines (which we define as scrapping an existing turbine they own and subsequently adding a new turbine in the same year), or sold to other prospective turbine owners.

Figure 1 graphs the fraction of all owners of one turbine who scrap, add, and upgrade, respectively, for each year of the data set. Similarly, Figure 2 graphs the fraction of all owners of two turbines who exit, scrap one turbine, and upgrade, respectively, for each year of the data set. In both figures, the dotted vertical lines indicate the years in which the feed-in-tariff was high, medium, and low, respectively. The dashed vertical lines indicate the years when there was no replacement certificate, and the years when the replacement certificate was high, medium, and low, respectively.

As can be seen in both figures, there is variation over time in fraction of turbine owners who scrap, add, and upgrade, and also in the relative frequency of each of these decisions. Also as can be seen in both figures, there is a possible correlation between the decisions of turbine owners and the government policies. In order to more rigorously analyze the effects of government policies on turbine owners' decisions, however, one needs to estimate a dynamic structural model.

From the perspective of turbine owners, the evolution of both of these policies over time was uncertain at the beginning of the study period, due to the democratic nature of lawmaking and uncertainty about the evolution of the Danish wind industry and fuel prices for other forms of electricity generation. Although the basic strategy of reducing the feed-in-tariff over time was likely known by turbine owners, the exact timing and values of either of the support policies could not have been perfectly anticipated. We therefore model future values of these policies as uncertain from the point of view of the turbine owners in any given year of our period of study in our dynamic structural model. In particular, we assume that both of these government policies evolve as a finite state first-order Markov process, and that a turbine owner's expectations of future values of these government policies depend on current values of these policies and on current values of other state variables, including the state of wind turbine technology. We use empirical probabilities to estimate a turbine owner's expectation of future values of these policies conditional on current values of these policies and on current values of other state variables.

2.2 State of Wind Turbine Technology

For our measure of the state of wind turbine technology in Denmark, we use the levelized cost of energy in Denmark. Levelized cost of energy is defined as the total present value cost of a turbine divided by the total amount of electricity it produces in its lifetime. The levelized cost can be thought of as the price that electricity would have to be sold at in order for a new generator to break even over the lifetime of the project. It provides a signal to owners about the costs associated with installing a new turbine that year.

Levelized cost is calculated by summing the present discounted value of the entire stream of total costs of an electricity-generating asset over the course of its expected lifetime, and then dividing by the total amount of electricity the asset is expected to produce. Total costs include initial capital costs, fuel costs, and operation and maintenance costs. Levelized costs are typically calculated over 20-40 year lifetimes, and all costs over this expected lifetime are discounted back to the present.

A general equation for levelized cost *lcoe* is given by:

$$lcoe = \frac{\sum_{t=1}^{T} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{T} E_t}, \quad (1)$$

where, for each time t from $t = 1$ to $t = T$, I_t denotes investment cost, M_t denotes maintenance cost, F_t denotes fuel cost, E_t denotes electricity output at time t, and r is the discount rate. In the case of wind, fuel costs are zero and operation costs are low, so the bulk of the cost is the cost of the turbine itself. Total electricity generation (in kWh) is usually estimated by specifying a capacity factor representing the fraction of time the turbine will actually be producing electricity, and then multiplying that number by the capacity of the turbine (in kW) and the number of hours in a year (which is 8760 hours).

One of the primary purposes of the levelized cost of energy is to allow developers to evaluate potential projects on a prospective basis. Though the actual number is very much dependent on the assumptions that are made, the levelized cost is meant to give an idea of the likelihood of a project breaking even. For example, if the levelized cost of energy for a potential wind project is a lot higher than the current price of electricity, then that project does not look very promising.

For our estimates of the levelized cost of wind energy, we use the estimates of the levelized cost of energy for onshore wind turbines in Denmark from the Danish Energy Agency (DEA, 1999) for each year over the period 1980 to 1999, which were the years when these estimates were available, and we use the lower bound of the remaining estimates in Lantz et al. (2012) for each year over the period 2000 to 2010. We extrapolate the levelized cost for 2011 using data from the years 2004-2010. Figure 3 plots the levelized costs of wind energy used in our model. For comparison, the levelized costs of producing electricity in Denmark from combined-cycle gas turbines and from steam turbine extraction generators, as estimated by Levitt and Sørensen (2014b), are plotted in Figure 3 as well.[4]

As seen in Figure 3, the levelized costs of wind energy are generally declining over the period 1980 to 2003. During this period, as technology improved over time, the cost of generating electricity from wind turbines declined because of economies of scale and learning. Beginning around 2003 and continuing through the latter half of the 2000s, however, wind power capital costs increased, primarily due to rising commodity and raw materials prices, increased labor costs, improved manufacturer profitability, turbine upscaling, and demand growth (Lantz et al., 2012; Trancik et al., 2015). As a consequence, the levelized costs of wind energy increased beginning around 2003 and continuing through the latter half of the 2000s, in spite of continued performance improvements (Lantz et al., 2012).

Because we eventually discretize the levelized cost of energy into three bins for use in our structural model, our results are robust to any imprecision in our estimates of the levelized cost of energy owing to our merging estimates from multiple sources and our extrapolating the values for the year 2011, as any imprecision is unlikely to have large effects on the bin into which the levelized cost of energy in any particular year

[4]The interest rate used to calculate the levelized costs was the effective bond interest rate (series *lwbz*) from the Statistics Denmark Annual Danish Aggregate Model (Statistics Denmark, 2013). These rates date from 1948, providing a consistent set of interest rates. It is likely that these interest rates are a little lower than the financing rates actually offered to finance electricity generation projects (Levitt and Sørensen, 2014a).

falls.

We assume that all turbines built in the same year have the same discretized value of the levelized cost. As Denmark is a small and topographically homogenous country, the spatial variation in annual wind patterns is relatively small, so this is a reasonable assumption for the purposes of measuring the state of technology. According to our preliminary analyses using descriptive reduced-form econometric models of the decisions of small wind producers in Denmark to add, scrap, or upgrade a wind turbine (not shown), wind quality generally does not have a significant effect.

The purpose of including levelized cost of energy in our model is to capture the development of wind turbine technology over time. The idea is that as technology improves, turbine costs will decline and capacity factors will increase, both of which will lead to a lower levelized cost of energy. As long as the levelized cost of energy for each year is calculated using similar methodology and assumptions, then what the levelized cost is capturing is the time path of turbine costs, which is driven by developments in turbine technology. We are assuming that the levelized cost of energy is exogenous from the point of view of a small wind farm owner and that an individual owner's investment decisions do not impact the levelized cost of energy.

We model the future values of technology as uncertain from the point of view of the turbine owners. Moreover, because we are studying the decisions of turbine owners with small numbers of turbines (rather than large energy companies), we argue that the evolution of these variables is taken as given by each individual turbine owner and the owner's decisions have zero impact on the future values of these variables. In particular, we assume that the state of wind turbine technology evolves as a finite state first-order Markov process, and that a turbine owner's expectations of future values of technology depend on the current state of technology and on current values of other state variables, including government policies. We use empirical probabilities to estimate a turbine owner's expectation of future values of technology conditional on current values of technology and on current values of other state variables.

Although we assume that an individual wind turbine owner's investment decisions do not impact either the levelized cost of energy or government policy, we allow government policies to affect the evolution of wind turbine technology, and wind turbine technology to affect the evolution of government policy. In particular, we assume that the state of wind turbine technology evolves as a finite state first-order Markov process, and that a turbine owner's expectations of future values of technology depend on the current state of technology and on current values of other state variables, including government policies. We similarly assume that both of these government policies evolve as a finite state first-order Markov process, and that a turbine owner's expectations of future values of these government policies depend on current values of these policies and on current values of other state variables, including the state of wind turbine technology. We use empirical probabilities to estimate a turbine owner's expectation of future values of government policies and future values of technology, conditional on current values of government policy, wind turbine technology, and other state variables.

3 Dynamic Structural Econometric Model

We model the decision to add, scrap, or upgrade a wind turbine using a dynamic structural econometric model. In particular, we develop and estimate a single agent dynamic structural econometric model using the econometric methods developed in the seminal work of Rust (1987, 1988). These methods have been applied to analyze various topics including bus engine replacement (Rust, 1987), nuclear power plant shutdown decisions (Rothwell and Rust, 1997), water management (Timmins, 2002), air conditioner purchases (Rapson, 2014), agricultural land use (Scott, 2013), copper mining decisions (Aguirregabiria and Luengo, 2016), vehicle scrappage decisions (Li and Wei, 2013), agricultural disease management (Carroll et al., 2019a,b,c), organ transplant decisions (Agarwal et al., 2019), pesticide spraying decisions (Sambucci et al., 2019), vehicle ownership and usage (Gillingham et al., 2016), and the adoption of rooftop solar photovoltaics (Feger et al., 2017; Langer and Lemoine, 2018).[5] To our knowledge, this paper is the first application to the wind industry.

Applying a dynamic structural econometric model to micro-level data allows one to model the decision to shut down or upgrade a wind turbine as a dynamic optimization problem at the individual level and enables one to study the impact of government policies and technological progress on those decisions. This "bottom-up" style of modeling is in direct contrast to many previous "top-down" approaches to examining trends in the wind industry, and the structural nature of our model gives insights into key economic and behavioral parameters. Understanding the factors that influence individual decisions to invest in wind energy and how different policies can affect the timing of these decisions is important for policies both in countries that already have mature wind industries, as well as in regions of the world that are earlier in the process of increasing renewable electricity generation (e.g. most of the U.S.).

There are several advantages to using a dynamic structural model to analyze the shutdown and upgrade decisions of wind turbine owners. First, unlike reduced-form models, a structural approach explicitly models the dynamics of shutdown and upgrade decisions. Wind turbines are long-term productive assets that degrade over time and are costly to replace in terms of money, time, and effort. With an existing turbine, owners are locked into a fixed output capacity and feed-in-tariff. Meanwhile, technology and government policies are changing over time. Because the payoffs from shutting down or upgrading turbines depend on market conditions such as the state of technology and government policies that vary stochastically over time, a turbine owner who hopes to make a dynamically optimal decision would need to account for the option value to waiting before making an irreversible decision to shut down or upgrade a turbine (Dixit and Pindyck, 1994). Using a dynamic model allows an owner's decision to scrap or upgrade a turbine to be based not only on the condition of the existing turbine, but also on the current and expected future states of technology and policy.

A second advantage of the structural model is that with the structural model we are able to estimate

[5] In addition, structural econometric models of dynamic games have been applied to such issues relating to the environment and energy as offshore petroleum production (Lin, 2013), environmental regulation (Ryan, 2012), market-based emissions regulation (Fowlie et al., 2016), utility regulation (Lim and Yurukoglu, 2018), renewable fuel subsidies (Yi et al., 2019), the solar industry (Gerarden, 2019), the world petroleum market (Kheiravar et al., 2019; Kheiravar and Lin Lawell, 2019), ethanol investment (Thome and Lin Lawell, 2019; Yi and Lin Lawell, 2019a,b; Lin Lawell, 2017), climate change policy (Zakerinia and Lin Lawell, 2019), and the coal industry (Jha, 2019).

the effect of each state variable on the expected payoffs from shutting down or upgrading a turbine, and are therefore able to estimate parameters that have direct economic interpretations. Unlike reduced-form models, a dynamic structural model accounts for the continuation value, which is the expected value of the value function next period. With the structural model we are able to estimate parameters in the payoffs from shutting down or upgrading, since we are able to structurally model how the continuation values relate to the payoffs from shutting down or upgrading.

A third advantage of our structural model is that we are able to model the interdependence of the shutdown, addition, and upgrade decisions. In particular, we model the value function for owners of one turbine and the value function for owners of two turbines separately, but allow them to depend on each other. Since an owner of one turbine has the option of becoming an owner of two turbines by adding a new turbine, the value of being an owner of one turbine depends in part on the value of being an owner of two turbines. Similarly, since an owner of two turbines has the option of becoming the owner of one turbine by scrapping one of his turbines, the value of being an owner of two turbines depends in part on the value of being an owner of one turbine.

Modeling the interdependence of the shutdown, addition, and upgrade decisions is particularly important for analyzing the effects of government policy, since part of the effect of government policies may be owing to the interdependence of these decisions. For example, part of the effect of the replacement certificate may be that it increases the shutdown of one turbine by owners of two turbines since it gives them the option of adding a new turbine in the future, and therefore the option of redeeming the replacement certificate they earned by the initial shutdown. Similarly, part of the effect of both the feed-in-tariff and the replacement certificate may be that they increase the addition of a second turbine by owners of one turbine, since doing so gives them the option of shutting down their older turbine and earning a replacement certificate.

A fourth advantage of our structural model is that we can use the parameter estimates from our structural model to simulate various counterfactual policy scenarios. In order to analyze the relative effectiveness and cost-effectiveness of the Danish feed-in-tariff and replacement certificate programs, we use our estimates to simulate the Danish wind industry in absence of government policy, and compare the actual development of the industry in the presence of government policy with this counterfactual development in the absence of policy.

A fifth advantage of using a dynamic structural model to analyze the effects of government policy on shutdown and upgrade decisions of wind turbine owners is that, although other countries have implemented policies aimed at increasing the production share of renewables in the electricity sector, it is not clear that a comparison group exists for any single country that has implemented such policies, and thus a difference-in-differences approach may not be feasible. Moreover, a country's renewable energy policy often consists of multiple policies, and it is valuable to understand which policy in the portfolio is the most influential. A dynamic structural model is thus well-suited for analyzing the the effects of government policy on shutdown and upgrade decisions of wind turbine owners.[6]

[6] A potential drawback of structural econometric models is that they require sources of structure (e.g., from economic theory) and the assumptions underlying these sources of structure may or may not hold in reality. We mitigate these concerns by imposing minimal, parsimonious assumptions in our dynamic structural econometric model of turbine shutdowns and upgrades. As we explain in more detail below, the sources of economic structure in our dynamic structural econometric model are dynamic

Our structural model allows for owners to have up to two turbines at any particular time and the available actions depend on how many turbines are in operation. As mentioned, 88% of turbine owners own two or fewer turbines during the period of study (1980-2011).

We build upon previous structural dynamic models by modeling two interdependent value functions, reflecting interdependent shutdown, adding, and upgrading decisions. The basic idea is to have a model with two "worlds", such that an owner is in the one-turbine world when he/she has one operating turbine, and moves to the two-turbine world if and when a second turbine becomes operational. The interdependence of the shutdown, adding, and upgrading decisions is depicted in Figure 4. We model the decisions of owners beginning in the year in which their first wind turbine was built, conditional on having built a turbine, so that all owners begin in the one-turbine world. Each period (year), an owner of one turbine decides whether to continue producing with a single turbine, add a new turbine, upgrade to a new turbine, or scrap their existing turbine (exit the market). Scrapping a turbine and adding a turbine in the same period constitutes an upgrade. If the owner decides to add, then they move to the two-turbine world in the following period, where they have a slightly different set of possible actions.

In the two-turbine world, owners can either continue producing with two turbines, scrap one of their existing turbines, upgrade one of their existing turbines, or scrap both of their turbines. Scrapping a turbine and adding a turbine in the same period constitutes an upgrade. If an owner of two turbines scraps a single turbine, he/she moves back to the one-turbine world.

Each agent in our model is a turbine owner who owns and operates no more than two wind turbines in any given period. Each discrete time period t represents a year. In each period t, the each turbine owner i choices an action $d_{i,t} \in \{0, 1, 2, ..., 9\}$. The choice set available to agent i depends upon the world that an owner is in during that period, as listed in Table 4. In each period t, an owner of one turbine can decide to continue without any shutdown, addition, or upgrade; add a small turbine; add a medium turbine; add a large turbine; upgrade to a small turbine; upgrade to a medium turbine; upgrade to a large turbine; or scrap his turbine. In each period t, an owner of two turbines can decide to continue without any shutdown or upgrade; upgrade one turbine to a small turbine; upgrade one turbine to a medium turbine; upgrade one turbine to a large turbine; scrap one turbine; or scrap both turbines.

The per-period payoff of each each turbine owner i, which measures the turbine owner i's utility in a given period t, depends on the action $d_{i,t}$ chosen by turbine owner i, the state variables $x_{i,t}$, and turbine owner i's private information shocks $\epsilon_{i,t}$ at time t. The per-period payoff (or utility) of a turbine owner includes anything and everything the turbine owner may care about, including both economic and non-economic sources of utility. Our model therefore captures both economic and non-economic motives for adding, scrapping, or upgrading a wind turbine.

The sources of economic structure in our dynamic structural econometric model are dynamic program-

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programming and our modeling of the interdependence of the scrapping, adding, and upgrading decisions. Aside from dynamic programming and the interdependence of the scrapping, adding, and upgrading decisions, we impose minimal additional assumptions on our model. For example, our specification of the per-period payoff function is agnostic about the actual functional form of the payoff function; the actual functional form of the production function; the actual functional form of the cost function; the actual nature of the constraints; and the actual mechanism by which, for example, the age of the turbine affects wind production, revenue, costs, and/or payoffs; and thus is general enough to capture the reduced-form implications of a number of models of wind production, wind energy market behavior, and electricity market behavior.

ming and our modeling of the interdependence of the scrapping, adding, and upgrading decisions. Since our focus is on annual scrapping, adding, and upgrading decisions, we do not model daily wind production explicitly, and therefore use a reduced-form specification for per-period payoffs. We account for the important factors in a wind turbine owner's annual scrapping, adding, and upgrading decisions by including in the payoff function state variables $x_{i,t}$ that affect wind production, revenue, benefits, and/or costs. We also include shocks $\epsilon_{i,t}$ to the payoff function that may reflect shocks to wind production, revenue, benefits, and/or costs.

We account for the important factors in a turbine owner's profit maximization decision by including in the payoff function state variables that affect wind production; state variables that affect revenue; state variables that affect non-monetary benefits, including any environmental preferences of the turbine owner and/or Danish electricity consumers; state variables that affect costs; and shocks that reflect uncertainty in wind production, revenue, benefits, and/or costs. The per-period payoff function therefore includes terms that are functions of actions, turbine characteristics, economic factors, and government policy. Our specification of the per-period payoff function is agnostic about the actual functional form of the payoff function; the actual functional form of the production function; the actual functional form of the cost function; the actual nature of the constraints; and the actual mechanism by which, for example, the age of the turbine affects wind production, revenue, costs, and/or payoffs; and thus is general enough to capture the reduced-form implications of a number of models of wind production, wind energy market behavior, and electricity market behavior.

The per-period payoff (or utility) of each turbine owner i in each period t depends on state variables $x_{i,t}$ that vary across individuals and/or time. Each state variable is discretized based on observed values in the data. The state variables include the capacity (cap_kw1_i) of the first turbine, the age ($turbine\_age1_{i,t}$) of the first turbine, the price guaranteed by the feed-in-tariff ($orig\_fit1_i$) for the first turbine, the levelized cost ($orig\_lcoe1_i$) of the first turbine, the capacity (cap_kw2_i) of the second turbine, the age ($turbine\_age2_{i,t}$) of the second turbine, the price guaranteed by the feed-in-tariff ($orig\_fit2_i$) of the second turbine, the levelized cost ($orig\_lcoe2_i$) of the second turbine, the current period replacement subsidy ($rep\_subsidy_{i,t}$), and the current period levelized cost ($lcoe_t$).

Owing to state-space and computational constraints, we are limited in the number of state variables we can include in our model. We therefore choose as our state variables those variables that are the most important factors that affect wind production, revenue, non-monetary benefits, and/or costs. Turbine capacity affects wind production, and therefore affects revenue, non-monetary benefits, and costs. Turbine age captures various factors that affect the payoffs from operating an individual turbine that evolve as the turbine ages, including depreciation, whether the turbine investment has been written off and/or paid off, the obsolescence of its older technology, and the costs of operation and maintenance. The price guaranteed by the feed-in-tariff affects the revenue from wind production. The levelized cost of wind energy, our measure of the state of technology, affects the revenue, non-monetary benefits, and costs of both wind production and wind turbine upgrades and additions. The replacement subsidy affects the net benefits from shutdowns and upgrades.

Because the feed-in-tariff guarantees the price wind turbine owners will receive for production, wind turbine owners are insulated from changes in wholesale prices. Thus, the shutdown and upgrade decisions of wind turbine owners are likely to be affected by the price guaranteed by the feed-in-tariff, and not by wholesale prices. As a consequence, since we include the price guaranteed by the feed-in-tariff in the payoff function, there is no need to also include wholesale prices.[7]

We assume that the state variables evolve as a finite state first-order Markov process. We also assume that actions that change an owner's stock of turbines (e.g., add, upgrade, shutdown) take time to complete and therefore do not affect the values of state variables until the following period. This is a standard assumption in discrete time models, and also reflects the reality that wind turbines cannot be added, upgraded, or scrapped instantaneously.

For owners of one turbine, the values of the state variables for the second turbine are set to zero. If and when an owner owning one turbine chooses to add a second turbine, then in the subsequent period, the state variables for the second turbine are set equal to their respective values at the time the second turbine is added. If an owner owning two turbines scraps one of his turbines, which in the data is always the older turbine, then in the subsequent period the state variables for the first turbine take on the values of the state variables for the second turbine and the state variables for the second turbine are again set to zero.

There is a choice-specific shock $\epsilon_{i,t}(d_{i,t})$ associated with each possible action $d_{i,t}$; these choice-specific shocks are observed by owner i at time t, before owner i makes his time-t action choice, but is never observed by the econometrician.

Because the model requires discrete data, we bin the action and state variables. The discrete action choices are explained above and presented in Table 4. The bins used to discretize the state variables are shown in Table 5. We discretize turbine capacity into three sizes: small, medium, and large. We discretize turbine age into three bins: young, middle-aged, and old. The price guaranteed by the feed-in-tariff is binned into its three levels in Table 2: low, medium, and high. The replacement certificate is binned into its three levels in Table 3: low, medium, and high. We discretize the levelized cost of wind energy into three bins: low, medium, and high.

Because the variables in our model have been discretized, there are no meaningful units associated with the variables, payoffs, or value functions; and the payoff and value functions described in the model do not explicitly measure revenue or profit. Nevertheless, the payoff function does include action and state variables that affect wind production, revenue, and/or costs.

Although some information in the data is lost by discretizing the variables, and although there are no meaningful units associated with the variables, payoffs, or value functions, there are several advantages of having to use discretized variables in our structural model. First, by discretizing the levelized cost of energy, our measure of the state of technology, our results are robust to any imprecision in our estimates of the levelized cost of energy owing to our merging estimates from multiple sources and our extrapolating the values for the year 2011, as any imprecision is unlikely to have large effects on the bin into which the levelized cost of energy in any particular year falls.

Second, by discretizing turbine age into three bins, our results are robust to any imprecision in converting

[7]Moreover, data availability and computational constraints unfortunately preclude us from including wholesale electricity prices as an additional state variable.

of the actual turbine age in days to turbine age in years, and any idiosyncratic shocks to the time needed to construct, install, and/or start operating an individual turbine, as any such imprecision or idiosyncratic shocks are unlikely to have large effects on the bin into which the turbine age of any turbine-year falls.

Third, in discretizing the turbine capacity into three sizes (small, medium, large), we base the cutoffs for small and medium turbines on the different eligibility cutoffs for various versions of the replacement certificate policy specified by the Danish government over the time period of our study. This enables us to focus our analysis of turbine capacity on the aspects of turbine capacity relevant for Danish wind policy (i.e., whether or not the turbine capacity exceeds the varying eligibility cutoffs), making our results robust to the exact choice of turbine capacity within our broader size bins, and enabling us to analyze the relative effectiveness and cost-effectiveness of the Danish feed-in-tariff and replacement certificate programs without having to finely model every last detail of every daily or hourly aspect of wind production for each and every individual turbine owner.

Fourth, the wind policies we examine – the Danish feed-in-tariff and replacement certificate programs – each take on three discrete values over the time period of our analysis, and are therefore already discrete. Attempting to extrapolate and make these discrete policy variables continuous would introduce noise and imprecision that may hinder the ability of any empirical analysis to credibly identify the effect of these wind policies.

Thus, the discretization of our state and action variables is not only necessary for our dynamic structural econometric model, but also enables us to best identify and analyze the relative effectiveness and cost-effectiveness of the Danish feed-in-tariff and replacement certificate programs given data availability and computational constraints, and in a manner robust to any additional assumptions or imprecision that may be introduced if we were to instead finely model every last detail of every daily or hourly aspect of wind production for each and every individual turbine owner.

For each owner of one turbine, the per-period payoff function $U^I\left(d_{i,t}, x_{i,t}, \epsilon_{i,t}\,; \theta\right)$, which depends on the action $d_{i,t}$ taken, the state variables $x_{i,t}$, the vector of shocks $\epsilon_{i,t}$ to agent i's payoffs from each possible action, and the parameters θ, is given by:

$$U^I\left(d_{i,t}, x_{i,t}, \epsilon_{i,t}\,; \theta\right) = \begin{cases} \pi^{I,c}(x_{i,t}\,; \theta) + \epsilon_{i,t}^{I,c} & \text{if } d_{i,t} = 1 \text{ (Continue)} \\ \pi^{I,a}(x_{i,t}\,; \theta) + \epsilon_{i,t}^{I,a}(d_{i,t}) & \text{if } d_{i,t} \in \{2,3,4\} \text{ (Add)} \\ \pi^{I,u}(x_{i,t}\,; \theta) + \epsilon_{i,t}^{I,u}(d_{i,t}) & \text{if } d_{i,t} \in \{6,7,8\} \text{ (Upgrade)} \\ \pi^{I,e}(x_{i,t}\,; \theta) + \epsilon_{i,t}^{I,e} & \text{if } d_{i,t} = 9 \text{ (Exit),} \end{cases} \tag{2}$$

where owners of one turbine can choose to add or upgrade to a small, medium, or large turbine and the respective payoff to doing so includes a distinct error term for each of these actions, and where the deterministic components $\pi^{I,j}(\cdot)$ of the per-period payoff functions are given by:

$$
\begin{aligned}
\pi^{I,c}(x_{i,t}\ ;\theta) &= \gamma_{I,1} cap\_kw1_i + \gamma_{I,2} turbine\_age1_{i,t} + \gamma_{I,3} orig\_fit1_i + \gamma_{I,4} orig\_lcoe1_i \\
\pi^{I,a}(x_{i,t}\ ;\theta) &= \gamma_{I,1} cap\_kw1_i + \gamma_{I,2} turbine\_age1_{i,t} + \gamma_{I,3} orig\_fit1_i + \gamma_{I,4} orig\_lcoe1_i + \rho_1 \\
\pi^{I,u}(x_{i,t}\ ;\theta) &= \gamma_{I,1} cap\_kw1_i + \gamma_{I,2} turbine\_age1_{i,t} + \gamma_{I,3} orig\_fit1_i + \gamma_{I,4} orig\_lcoe1_i + \alpha_1 rep\_subsidy_{i,t} + \rho_2 \\
\pi^{I,e}(x_{i,t}\ ;\theta) &= \alpha_1 rep\_subsidy_{i,t} + \alpha_2 lcoe_t + S_{1i}.
\end{aligned}
\tag{3}
$$

We use the term 'deterministic period payoffs' to denote the deterministic components of the per-period payoff functions.

In the deterministic period payoffs $\pi^{I,c}(\cdot)$ to continuing production with a single turbine, the deterministic period payoffs $\pi^{I,a}(\cdot)$ to adding a new turbine, and the deterministic period payoffs $\pi^{I,u}(\cdot)$ to upgrading to a new turbine in Equation (3), we include the following terms to capture the per-period payoffs to operating the turbine: turbine capacity (cap_kw1_i), turbine age ($turbine\_age1_{i,t}$), the price guaranteed by the feed-in-tariff ($orig\_fit1_i$), and the levelized cost of wind energy ($orig\_lcoe1_i$) at the time the turbine was installed. Since we do not have any data on maintenance or operating costs, we assume that all operating and maintenance costs are captured by the capacity of the turbine (cap_kw1_i); the age of the turbine ($turbine\_age1_{i,t}$); and the levelized cost of wind energy ($orig\_lcoe1_i$) when the turbine was built, which is our measure of the state of technology of the turbine. The price guaranteed by the feed-in-tariff ($orig\_fit1_i$) is determined by the date of construction of the turbine.

The deterministic period payoffs $\pi^{I,a}(\cdot)$ to adding a turbine includes not only the terms above representing the per-period payoffs from operating the first turbine, but also an additional ρ_1 term that represents the total discounted cost associated with buying and constructing an additional turbine.

The deterministic period payoffs $\pi^{I,u}(\cdot)$ to upgrading the turbine includes not only the terms above representing the per-period payoffs from operating the first turbine, but also the replacement subsidy (with associated coefficient α_1) as well as a parameter ρ_2 that represents the cost of upgrading.

In the deterministic period payoffs $\pi^{I,e}(\cdot)$ to scrapping and exiting, we include the replacement subsidy; the current period levelized cost of wind energy, which serves as a proxy for (the negative of) the value that could be obtained by selling a replacement certificate; and the scrap value S_{1i} from scrapping the turbine. We expect replacement certificates to be more valuable when turbines are cheaper to build (i.e., low values of $lcoe_t$) and demand for new investments is high. Separate specifications of the model were run using scrap values that are constant ($S_{1i} = \tau_1$) or scrap values S_{1i} that vary by capacity ($S_{1i} = \tau_2 cap\_kw1_i$).

Per-period payoffs $U^{II}(d_{i,t}, x_{i,t}, \epsilon_{i,t}\ ;\theta)$ for owners of two turbines are very similar, except that a slightly different set of options are available – namely, owners of two turbines cannot add a third turbine, but can instead choose to scrap the older of their two turbines:

$$
U^{II}(d_{i,t}, x_{i,t}, \epsilon_{i,t}\ ;\theta) = \begin{cases} \pi^{II,c}(x_{i,t}\ ;\theta) + \epsilon_{i,t}^{II,c} & \text{if } d_{i,t} = 1 \text{ (Continue)} \\ \pi^{II,s}(x_{i,t}\ ;\theta) + \epsilon_{i,t}^{II,s} & \text{if } d_{i,t} = 5 \text{ (Scrap one turbine)} \\ \pi^{II,u}(x_{i,t}\ ;\theta) + \epsilon_{i,t}^{II,u}(d_{i,t}) & \text{if } d_{i,t} \in \{6,7,8\} \text{ (Upgrade)} \\ \pi^{II,e}(x_{i,t}\ ;\theta) + \epsilon_{i,t}^{II,e} & \text{if } d_{i,t} = 9 \text{ (Exit),} \end{cases} \tag{4}
$$

where the deterministic components $\pi^{II,j}(\cdot)$ of the per-period payoffs are defined as:

$$
\begin{aligned}
\pi^{II,c}(x_{i,t}\,;\theta) &= \gamma_{I,1} cap\_kw1_i + \gamma_{I,2} turbine\_age1_{i,t} + \gamma_{I,3} orig\_fit1_i + \gamma_{I,4} orig\_lcoe1_i \\
&\quad + \gamma_{II,1} cap\_kw2_i + \gamma_{II,2} turbine\_age2_{i,t} + \gamma_{II,3} orig\_fit2_i + \gamma_{II,4} orig\_lcoe2_i \\
\pi^{II,s}(x_{i,t}\,;\theta) &= \gamma_{II,1} cap\_kw2_i + \gamma_{II,2} turbine\_age2_{i,t} + \gamma_{II,3} orig\_fit2_i + \gamma_{II,4} orig\_lcoe2_i \\
&\quad + \alpha_1 rep\_subsidy_{i,t} + \alpha_2 lcoe_t + S_{1i} \\
\pi^{II,u}(x_{i,t}\,;\theta) &= \gamma_{I,1} cap\_kw1_i + \gamma_{I,2} turbine\_age1_{i,t} + \gamma_{I,3} orig\_fit1_i + \gamma_{I,4} orig\_lcoe1_i \\
&\quad + \gamma_{II,1} cap\_kw2_i + \gamma_{II,2} turbine\_age2_{i,t} + \gamma_{II,3} orig\_fit2_i + \gamma_{II,4} orig\_lcoe2_i \\
&\quad + \alpha_1 rep\_subsidy_{i,t} + \rho_2 \\
\pi^{II,e}(x_{i,t}\,;\theta) &= \alpha_1 rep\_subsidy_{i,t} + \alpha_3 lcoe_t + S_{2i}.
\end{aligned}
\tag{5}
$$

In the deterministic period payoffs $\pi^{II,c}(\cdot)$ to continuing production with two turbines and the deterministic period payoffs $\pi^{II,u}(\cdot)$ to upgrading one of the owner's existing turbines in Equation (5), we include the following terms to capture the per-period payoffs to operating the first turbine: turbine capacity (cap_kw1_i), turbine age ($turbine\_age1_{i,t}$), the price guaranteed by the feed-in-tariff ($orig\_fit1_i$), and the levelized cost of wind energy ($orig\_lcoe1_i$) at the time the first turbine was installed. Since we do not have any data on maintenance or operating costs, we assume that all operating and maintenance costs for the first turbine are captured by the capacity of the first turbine (cap_kw1_i); the age of the first turbine ($turbine\_age1_{i,t}$); and the levelized cost of wind energy ($orig\_lcoe1_i$) when the first turbine was built, which is our measure of the state of technology of the first turbine. The price guaranteed by the feed-in-tariff ($orig\_fit1_i$) for the first turbine is determined by the date of construction of the first turbine.

The deterministic period payoffs $\pi^{II,c}(\cdot)$ to continuing production with two turbines and the deterministic period payoffs $\pi^{II,u}(\cdot)$ to upgrading one of the owner's existing turbines include not only the terms above representing the per-period payoffs to operating the first turbine, but also the following terms to capture the per-period payoffs to operating the second turbine: turbine capacity (cap_kw2_i), turbine age ($turbine\_age2_{i,t}$), the price guaranteed by the feed-in-tariff ($orig\_fit2_i$), and the levelized cost of wind energy ($orig\_lcoe2_i$) at the time the second turbine was installed. Since we do not have any data on maintenance or operating costs, we assume that all operating and maintenance costs for the second turbine are captured by the capacity of the second turbine (cap_kw2_i); the age of the second turbine ($turbine\_age2_{i,t}$); and the levelized cost of wind energy ($orig\_lcoe2_i$) when the second turbine was built, which is our measure of the state of technology of the second turbine. The price guaranteed by the feed-in-tariff ($orig\_fit2_i$) for the second turbine is determined by the date of construction of the second turbine.

In the deterministic period payoffs $\pi^{II,s}(\cdot)$ to scrapping one of the owner's existing turbines, which in the data is always the older turbine, we include the terms above representing the per-period payoffs to operating the second turbine; as well as the replacement subsidy; the current period levelized cost of wind energy, which serves as a proxy for (the negative of) the value that could be obtained by selling a replacement certificate; and the scrap value S_{1i} from scrapping the first turbine. Separate specifications of the model were run using scrap values that are constant ($S_{1i} = \tau_1$) or scrap values that vary by capacity ($S_{1i} = \tau_2 cap\_kw1_i$).

The deterministic period payoffs $\pi^{II,u}(\cdot)$ to upgrading one of the existing turbines includes not only the terms above representing the per-period payoffs from operating the first turbine and the terms above representing the per-period payoffs from operating the second turbine, but also the replacement subsidy (with associated coefficient α_1) as well as a parameter ρ_2 that represents the cost of upgrading.

In the deterministic period payoffs $\pi^{II,e}(\cdot)$ to scrapping both turbines and exiting, we include the replacement subsidy; the current period levelized cost of wind energy, which serves as a proxy for (the negative of) the value that could be obtained by selling a replacement certificate; and the scrap value S_{2i} from scrapping both turbines. We expect replacement certificates to be more valuable when turbines are cheaper to build (i.e., low values of $lcoe_t$) and demand for new investments is high. In one specification we allow the coefficient α_3 on (the negative of) the value that could be obtained by selling a replacement certificate for owners of two turbines to differ from the coefficient α_2 on (the negative of) the value that could be obtained by selling a replacement certificate for owners of one turbine; in the other specifications we assume that these coefficients are the same. Separate specifications of the model were run using scrap values that are constant ($S_{2i} = \tau_1$) or scrap values that vary by capacity ($S_{2i} = \tau_2 cap\_kw_i + \tau_3 cap\_kw2_i$).

In each period t, each turbine owner i chooses action $d_{i,t}$ to maximize the present discounted value of his entire stream of expected per-period payoffs. Letting $\epsilon_{i,t}$ denote a vector of the time-t shocks for all possible actions $d_{i,t}$ for turbine owner i, and using the payoff functions in Equations (2) and (4), we can write out the value function for the owner of one turbine and the value function for the owner of two turbines, respectively.

The value $V^I(\cdot)$ of owning one turbine depends on the value $V^{II}(\cdot)$ of owning two turbines, and is given by:

$$V^I(x_{i,t}, \epsilon_{i,t}\,; \theta) = \max \left\{ \begin{array}{l} \pi^{I,c}(x_{i,t}\,; \theta) + \epsilon_{i,t}^{I,c} + \beta E[V^I(x_{t+1}, \epsilon_{t+1}\,; \theta) \mid x_t, \epsilon_t, d_{i,t} = 1], \\ \pi^{I,a}(x_{i,t}\,; \theta) + \epsilon_{i,t}^{I,a}(d_{i,t}) + \beta E[V^{II}(x_{t+1}, \epsilon_{t+1}\,; \theta) \mid x_t, \epsilon_t, d_{i,t} \in \{2,3,4\}], \\ \pi^{I,u}(x_{i,t}\,; \theta) + \epsilon_{i,t}^{I,u}(d_{i,t}) + \beta E[V^I(x_{t+1}, \epsilon_{t+1}\,; \theta) \mid x_t, \epsilon_t, d_{i,t} \in \{6,7,8\}], \\ \pi^{I,e}(x_{i,t}\,; \theta) + \epsilon_{i,t}^{I,e} \end{array} \right\}, \tag{6}$$

where β is the discount factor.

Similarly, the value $V^{II}(\cdot)$ of owning two turbines depends on the value $V^I(\cdot)$ of owning one turbine, and is given by:

$$V^{II}(x_{i,t}, \epsilon_{i,t}\,; \theta) = \max \left\{ \begin{array}{l} \pi^{II,c}(x_{i,t}\,; \theta) + \epsilon_{i,t}^{II,c} + \beta E[V^{II}(x_{t+1}, \epsilon_{t+1}\,; \theta) \mid x_t, \epsilon_t, d_{i,t} = 1], \\ \pi^{II,s}(x_{i,t}\,; \theta) + \epsilon_{i,t}^{II,s} + \beta E[V^I(x_{t+1}, \epsilon_{t+1}\,; \theta) \mid x_t, \epsilon_t, d_{i,t} = 5], \\ \pi^{II,u}(x_{i,t}\,; \theta) + \epsilon_{i,t}^{II,u}(d_{i,t}) + \beta E[V^{II}(x_{t+1}, \epsilon_{t+1}\,; \theta) \mid x_t, \epsilon_t, d_{i,t} \in \{6,7,8\}], \\ \pi^{II,e}(x_{i,t}\,; \theta) + \epsilon_{i,t}^{II,e} \end{array} \right\}. \tag{7}$$

We make the following conditional independence assumption:

$$Pr(x_{i,t+1}, \epsilon_{i,t+1} \mid d_{i,t}, \theta) = Pr(x_{i,t+1} \mid x_{i,t}, d_{i,t}, \theta)\, Pr(\epsilon_{i,t+1} \mid \theta)\,. \tag{8}$$

A standard assumption in many dynamic structural models, our conditional independence assumption implies that the evolution of the observed state variables $x_{i,t}$ does not depend on the particular realization of the idiosyncratic shocks $\epsilon_{i,t}$ to the payoffs of individual owners from each possible action choice regarding upgrading, scrapping, adding, exiting, or continuing.

For turbine age and turbine capacity, the conditional independence assumption makes sense since a turbine ages will increment by one more year each year regardless of any unobservable idiosyncratic shock to the individual turbine owner, and since the turbine capacity is chosen by the turbine owner. Moreover, since we have discretized turbine age and turbine capacity into three bins each, our results are robust to any imprecision in converting of the actual turbine age in days to turbine age in years, to the exact choice of turbine capacity within our broader size bins, and to any idiosyncratic shocks to the time needed to construct, install, and/or start operating an individual turbine, as any such imprecision or idiosyncratic shocks are unlikely to have large effects on the bin into which the turbine age or turbine capacity of any turbine-year falls.

For the levelized cost of wind energy, the price guaranteed by the feed-in-tariff, and the replacement certificate, it is reasonable to assume that shocks to any particular individual turbine owner are unlikely to affect how industry-level technology and nation-wide government policy evolves at the aggregate level for all turbine owners.

The transition probabilities $Pr\left(x_{i,t+1} \mid x_{i,t}, d_{i,t}, \theta\right)$ are estimated non-parametrically from the data for all possible state and action combinations. For turbine age, we kept track of actual age and increment it deterministically each year, then determine which discretized bin the actual age falls into. We assume that each shock in $\epsilon_{i,t}$ is i.i.d. extreme value (type 1) across owners i, actions $d_{i,t}$ and time t.

We set the discount factor β to 0.90. Since we focus on small-scale wind turbine owners who own at most two turbines at any one time in our data set, and do not model larger wind farms, we use the same discount rate for all turbine owners in our analysis.

As derived in more detail in Appendix A, the probability of a given action conditional on the realization of a particular combination of state variables is given by the following choice probabilities:

$$Pr\left(d_{i,t} = \tilde{d} \mid x_{i,t}, \theta\right) = \frac{\exp\left(\delta^{j,\tilde{d}}\left(x_{i,t}, \tilde{V}^{\ddagger}\right)\right)}{\sum_{d} \exp\left(\delta^{j,d}\left(x_{i,t}, \tilde{V}^{\ddagger}\right)\right)} \quad \text{for } j = I, II, \tag{9}$$

where:

$$\delta^{j,d}\left(x_{i,t}, \tilde{V}^{\ddagger}\right) = \pi^{j,d} + \beta \int \tilde{V}^{\ddagger}(x_{i,t+1}) dPr\left(x_{i,t+1} \mid x_{i,t}, d, \theta\right) \quad \text{for } j = I, II, \tag{10}$$

and where, as explained in more detail in Appendix A, the ex ante value function $\tilde{V}^{\ddagger}$ next period used to calculate the continuation value is either the ex ante value function $\tilde{V}^{I}(x_{i,t+1})$ for owners of one turbine next period or the ex ante value function $\tilde{V}^{II}(x_{i,t+1})$ for owners of two turbines next period, depending upon the world that an owner is in this period and the action taken this period, and is given by:

$$\tilde{V}^{j}(x_{i,t+1}) = \int V^{j}(x_{i,t+1}, \epsilon_{i,t+1}; \theta) dPr(\epsilon_{i,t+1} \mid \theta) = E_{\epsilon}\left[V^{j}(x_{i,t+1}, \epsilon_{i,t+1}; \theta)\right] \quad \text{for } j = I, II. \tag{11}$$

After obtaining the model predictions for the choice probabilities as functions of the state variables and the unknown parameters θ, the parameters θ can then be estimated using nested fixed point maximum likelihood estimation (Rust, 1987, 1988). The likelihood function is a function of the choice probabilities, and therefore a function of the ex ante value functions $\tilde{V}^j$ for $j = I, II$. Solving for the parameters θ via maximum likelihood thus requires an inner fixed point algorithm to compute the ex ante value functions $\tilde{V}^j$ for $j = I, II$ simultaneously as rapidly as possible and an outer optimization algorithm to find the maximizing value of the parameters θ. In other words, a simultaneous fixed point calculation to compute the ex ante value functions $\tilde{V}^j$ for $j = I, II$ simultaneously is nested within a maximum likelihood estimation (MLE). From Blackwell's Theorem, the fixed point for each $\tilde{V}^j$ is unique.

Identification of the parameters θ comes from the differences between per-period payoffs across different action choices, which in infinite horizon dynamic discrete choice models are identified when the discount factor β and the distribution of the choice-specific shocks ϵ_{it} are fixed (Abbring, 2010; Magnac and Thesmar, 2002; Rust, 1994). In particular, the parameters in our model are identified because each term in the deterministic components $\pi^{I,j}(\cdot)$ and $\pi^{II,j}(\cdot)$ of the per-period payoffs given in Equations (3) and (5) for the one- and two-turbine worlds, respectively, depends on the action $d_{i,t}$ being taken at time t, and therefore varies based on the action taken; as a consequence, the parameters do not cancel out in the differences between per-period payoffs across different action choices and are therefore identified. For example, the coefficient $\gamma_{I,1}$ on the capacity (cap_kw1_i) of the first turbine in deterministic components $\pi^{I,j}(\cdot)$ of the per-period payoff in the one-turbine world in Equation (3) is identified in the difference between the per-period payoff from choosing to exit and the per-period payoff from any other action choice $d_{i,t}$.

Standard errors are formed by a non-parametric bootstrap. Turbine owners are randomly drawn from the data set with replacement to generate 100 independent panels each with the same number of turbine owners as in the original data set. The structural model is run on each of the panels. The standard errors are then formed by taking the standard deviation of the estimates from each of the random samples.

The parameter estimates are then used to simulate counterfactual policy scenarios in order to analyze the relative effectiveness and cost-effectiveness of the Danish feed-in-tariff and replacement certificate programs.

4 Results

4.1 Structural Parameters

We estimate three specifications of our dynamic structural econometric model. The three specifications vary in the way they model new turbine costs, scrap values, and the value of selling a replacement certificate. Specification 1 includes the cost of adding a new turbine costs, the cost of upgrading, and the scrap value from exiting. Specification 2 allows for the value of replacement certificates to be different for owners of one turbine and owners of two turbines. Specification 3 assumes that scrap values are proportional to the size of the turbine.[8]

[8]State-space and computational constraints unfortunately limit the number of parameters we are able to estimate in each specification, and therefore preclude us from considering alternative combinations of these modeling assumptions that involve

The parameter estimates for these three specifications of our dynamic structural econometric model are reported in Table 6. Because the state variables are discretized, the estimates are not interpretable as marginal effects, but should instead be interpreted as relative contributions to the profits of turbine owners. Our estimated coefficients in the per-period payoffs therefore give us a sense of the sign and relative impacts of different variables on the profits of wind turbine owners and the importance of the policies put into place by the Danish government.

The positive sign on the coefficient $\gamma_{I,1}$ in the per-period payoff on the capacity (small, medium, or large) of the first turbine indicates that higher profits are generated by turbines with higher capacity. The negative sign on the coefficient $\gamma_{I,2}$ on the age of the first turbine indicates that the profitability of a turbine declines with as the turbine gets older. The positive sign on the coefficient $\gamma_{I,3}$ in the per-period payoff on the price guaranteed by the feed-in-tariff for the first turbine indicates that higher guaranteed prices yield higher profits. The negative sign on the coefficient $\gamma_{I,4}$ on the levelized cost of energy of the first turbine indicates that the profits are higher if the state of wind turbine technology is better and the levelized cost is lower. Parameters for owners of one turbine are estimated much more precisely likely due to fact that there is a relatively small sample of owners owning two turbines.

The positive coefficient α_1 in the per-period payoffs on the replacement certificate indicates that the deterministic period payoffs from upgrading or scrapping are higher when the replacement certificate is greater. The negative coefficients α_2 and α_3 on levelized cost of energy in the (the negative of) the value that could be obtained by selling a replacement certificate in some specifications provide some evidence that, as expected, replacement certificates are more valuable when turbines are cheaper to build (i.e., low values of $lcoe_t$) and demand for new investments is high.

We find that there are costs to adding new turbines and to upgrading a turbine that are both statistically significant and large in magnitude. Comparing the magnitudes of the costs of adding (ρ_1) and upgrading (ρ_2), we find that upgrading is the more costly of the two actions.

One way to assess the relative importance of government policies as opposed to technological improvements is to compare the relative effects of changes in the discretized values of the government policies and the state of technology, respectively. Since each of the policy and technology variables has been discretized into three bins each, changes in their discretized values (e.g., from low to medium, or from medium to high) reflect comparable changes across the respective distributions of each state variable.

In all specifications, the price guaranteed by the feed-in-tariff is a significant source of revenues. A change in the price guaranteed by the feed-in-tariff (e.g., from low ($0.06/kWh) to medium ($0.08/kWh), or from medium ($0.08/kWh) to high ($0.11/kWh)) has approximately 1.5 to 2 times the effects on per-period payoffs as a decrease in the level of the levelized cost of energy, the indicator of technology (e.g., from high (> $100/MWh) to medium ($76-100/MWh), or from medium ($76-100/MWh) to low ($0-75/MWh)), where the levels are determined by the bins in Table 5.

Likewise, replacement certificates comprise a significant share of the payoffs to scrapping or upgrading existing turbines in all three specifications. A change in the level of the replacement certificate (e.g., from low ($0.01/kWh) to medium ($0.02/kWh), or from medium ($0.02/kWh) to high ($0.03/kWh)) has approx-

estimating additional parameters.

imately 7 to 9.5 times the effects on per-period payoffs as a decrease in the level of the levelized cost of energy, the indicator of technology (e.g., from high to medium, or from medium to low).

Our results therefore indicate that the growth and development of the Danish wind industry were driven primarily by government policies as opposed to technological improvements.

To assess the goodness of fit of our models, Table 6 also reports the log likelihood from each of the three specifications. Our preferred specification is Specification 1, which has the highest log likelihood among our three specifications.

4.2 Policy Simulations

One of the primary benefits of estimating a structural model is that it enables us to simulate counterfactual policy scenarios to analyze the relative effectiveness and cost-effectiveness of the Danish feed-in-tariff and replacement certificate programs. We use our estimates to simulate the Danish wind industry in absence of government policy, and compare the actual development of the industry in the presence of government policy with this counterfactual development in the absence of policy.

The particular counterfactual policy scenarios we simulate are the following. In the first counterfactual policy scenario, we remove the replacement certificate program (but make no changes to the feed-in-tariff). In the second counterfactual policy scenario, we modify the feed-in-tariff so that the price guaranteed by the feed-in-tariff declines as a turbine ages as shown in Table 7, instead of remaining flat through the lifetime of the turbine (but make no changes to the replacement certificate program). In the third counterfactual policy scenario, we remove the feed-in-tariff (but make no changes to the replacement certificate program). In the fourth counterfactual policy scenario, we remove both the replacement certificate program and the feed-in-tariff.

For each counterfactual policy scenario, we use Specification 1 of the model (our preferred specification) to simulate the effects of the counterfactual policy on wind turbine shutdown and upgrade decisions and the evolution of the Danish wind industry over the time period of our data set (1980-2011). For the parameter values in our counterfactual simulations, we use the values of the parameter estimates from Specification 1 for parameters that are significant at a 5% level; and we set the values of the parameters in Specification 1 that are not significant at a 5% level, and therefore do not have a significant effect on wind turbine owners' payoffs or decisions, to 0.

Each simulation in each counterfactual simulations was run as follows. We first modify the relevant state variables and transition densities to reflect the counterfactual policy being simulated. Beginning with the first observed value of the remaining state variables for each owner from the actual data, we simulate the action for that period by drawing from the choice probabilities and the state variables for the next period by drawing from the transition probabilities. Based on the state variables drawn for the next period, we then simulate the action for that period and the state variables for the subsequent period, and so on until the last year of our data set (2011).

Once the simulated data is created, we calculate various summary statistics for comparison to what actually happened when both policies were in place. These statistics of interest include the discounted payoffs (or utility) of small wind producers (i.e., the present discounted value of the entire stream of payoffs over the period 1980-2011 for each turbine owner, summed over all owners of two or fewer turbines), the number of new turbines added, the number of turbines that were scrapped, the number of upgrades made, the average age of turbines scrapped, and the number of replacement certificates issued over the period 1980-2011. We also calculate, for the turbines in the final year of the data set (2011), the average age of these turbines and the distribution of these turbines' capacities.

For each counterfactual policy scenario, we run 100 independent simulations. The means and standard deviations are then calculated over the 100 independent simulations for each of the summary statistics. These means and standard deviations are reported in Table 8.

Examining the results in Table 8, there are several noticeable differences between the policy simulations and what actually happened when both policies were in place. First, discounted payoffs (or utility) of small wind producers are significantly higher when both policies are in place than in any of the simulations. This result suggests that both the replacement certificate policy and feed-in-tariff provided windfall gains to small wind producers. In particular, discounted payoffs (or utility) of small wind producers would have been 70% lower if there were no replacement certificate and 95% lower if there were no feed-in-tariff. In the absence of both policies, discounted payoffs (or utility) of small wind producers would have been 96% lower.

A second result is that in all policy simulations, owners choose to scrap more and add fewer turbines under the counterfactual scenarios than they do when both policies are in place. This is likely because the value of owning turbines and the value associated with waiting for future periods before scrapping are significantly lower in the absence of these policies, since both the replacement certificates and feed-in-tariff have positive values for turbine owners. As a consequence, many owners scrap their turbines and exit the industry, rather than add new turbines.

We examine the evolution of the Danish wind industry under the different counterfactual policy scenarios. Figure 5 shows the number of small (< 450 kW), medium (450 - 750 kW), and large (> 750 kW) wind turbines that existed in each year from 1980-2011 under each policy simulation. Overall, fewer turbines exist in the simulations except for rapid growth in the number of medium-sized turbines during the boom years of the industry between 1990-2000.

Our simulation results show that both the replacement certificate policy and feed-in-tariff increased the discounted payoffs (or utility) of small wind producers. To analyze the relative effectiveness and cost-effectiveness of the Danish feed-in-tariff and replacement certificate programs, we conduct back-of-the-envelope calculations to estimate the costs of each of the policies to the Danish government (and therefore to Danish taxpayers) and well as the carbon emissions benefits of each of the policies, and then compare the benefits with the costs.

We also calculate the cost-effectiveness of each policy as the cost to the Danish government (and therefore to Danish taxpayers) per percentage point increase in discounted payoffs (or utility) of turbine owners, as well as the cost to the Danish government (and therefore to Danish taxpayers) per million tonne CO_2 emissions avoided. This parsimonious analysis of costs and benefits thus enables us to compare the cost-effectiveness of each policy in achieving two possible objectives of wind policy – increasing payoffs of turbine owners, and decreasing greenhouse gas emissions – without having to make possibly subjective assumptions about the relative importance of these objectives, the external costs of carbon emissions, and/or the marginal cost of public funds.[9] As explained in more detail below, we also use our back-of-the-envelope estimates of costs and benefits to calculate the minimum threshold discounted payoffs per wind turbine producer needed in the absence of any policy in order for each policy to be efficient, and the minimum threshold discounted payoffs per wind turbine producer needed in the absence of any policy in order for each policy to be socially efficient. Table 9 summarizes our back-of-the-envelope estimates of benefits, costs, cost-effectiveness, and efficiency of each policy.[10]

The details of the calculations underlying our back-of-the-envelope estimates of benefits, costs, cost-effectiveness, and efficiency of each policy in Table 9 are as follows.

We estimate both a lower bound and an upper bound to the total cost to the Danish government of the replacement certificates it issued to small wind producers during the time period of our data set. We calculate a lower bound to the total cost to the Danish government of the replacement certificates it issued to small wind producers during the time period of our data set by calculating the total cost to the Danish government of the replacement certificates it issued to all the owners of two or fewer turbines who upgraded their turbine in our data set during the time period of our data set. Our estimated lower bound is \$1.84 million US dollars.

To estimate an upper bound to the total cost to the Danish government of the replacement certificates it issued to small wind producers during the time period of our data set, we also estimate what the total cost to the Danish government of the replacement certificates would be if all the owners of two or fewer turbines who scrapped (but did not upgrade) their turbines immediately sold their replacement certificates to someone else who then built a large turbine that operated from the date the scrapped turbine was scrapped to the end of the time period of our data set. To do this, we first estimate the production from a large turbine in each year by using the average production of turbines larger than 750 kW for all owners in our data set (not just the owners with two or fewer turbines we model with our dynamic structural model). We then calculate an upper bound to the total cost to the Danish government of the replacement certificates to all the owners of two or fewer turbines who scrapped (but did not upgrade) their turbines as the replacement subsidy value times the average production for every year from the date the scrapped turbine was scrapped to the end of the time period of our data set. Under these assumptions, the cost comes to \$112 million US dollars.

We then calculate an upper bound to the total cost to the Danish government of the replacement certificates it issued to small wind producers during the time period of our data set by adding the total cost to the Danish government of the replacement certificates it issued to all the owners of two or fewer turbines who upgraded their turbine in our data set during the time period of our data set (our lower bound estimate of the total cost to the Danish government of the replacement certificates), plus the total cost to the Danish

[9]The marginal cost of public funds measures the loss incurred by society in raising additional revenues to finance government spending due to the distortion of resource allocation caused by taxation (Dahlby, 2008).

[10]As discussed above, the discretization of our state and action variables is not only necessary for our dynamic structural econometric model, but also enables us to best identify and analyze the relative effectiveness and cost-effectiveness of the Danish feed-in-tariff and replacement certificate programs given data availability and computational constraints, and in a manner robust to any additional assumptions or imprecision that may be introduced if we were to instead finely model every last detail of every daily or hourly aspect of wind production for each and every individual turbine owner. Thus, while our estimates of the costs and carbon emissions benefits of each of the policies are back-of-the-envelope calculations, and as there are no meaningful units associated with the our estimates of turbine owner payoffs because the variables in our model have been discretized, our qualitative results on the relative effectiveness and cost-effectiveness of the Danish feed-in-tariff and replacement certificate programs are likely to be robust to any additional assumptions or more detailed modeling.

government of the replacement certificates to all the owners of two or fewer turbines who scrapped (but did not upgrade) their turbines if all these owners immediately sold their certificates to someone else who then built a large turbine that operated from the date the scrapped turbine was scrapped to the end of the time period of our data set. Our upper bound estimate of the total cost of the replacement certificate program is $114 million US dollars.

We therefore estimate that the total cost to the Danish government of the replacement certificates it issued to small wind producers during the time period of our data set ranges from $1.84 million US dollars to $114 million US dollars.

Thus, at a cost of $1.84 million US dollars to $114 million US dollars, the replacement certificate program nearly tripled the discounted payoffs (or utility) of small wind producers (from the normalized welfare in Table 8 of 34.2 in the no replacement certificate scenario, to the normalized welfare of 100 in when both policies are in place, with the feed-in-tariff assumed to be in place in both cases). The cost per percentage point increase in discounted wind producer payoffs is $27,808 US dollars to $1.73 million US dollars.

We also estimate the total cost to the Danish government of the feed-in-tariffs it paid to all the owners of two or fewer turbines in our data set during the time period of our data set. Using the turbine level data, we estimate that $3.547 billion US dollars was paid out to all the owners of two or fewer turbines in our data set for the entire duration of our study. Thus, at a cost of $3.547 billion US dollars, the feed-in-tariff increased discounted payoffs of small wind producers by approximately 20-fold (from the normalized welfare of 5.03 in the no feed-in-tariff scenario, to the normalized welfare of 100 when both policies are in place, with the replacement certificate program assumed to be in place in both cases). The cost per percentage point increase in discounted wind producer payoffs is $37.34 million US dollars.

Combining the costs for both the replacement certificate policy and feed-in-tariff, we find that at a cost of $3.549 billion US dollars to $3.661 billion US dollars, the replacement certificate program and the feed-in-tariff increased discounted payoffs of small wind producers by approximately 25-fold (from the normalized welfare of 4.05 in the no replacement certificate and no feed-in-tariff scenario, to the normalized welfare of 100 when both policies are in place). The cost per percentage point increase in discounted wind producer payoffs is $36.99 million US dollars to $38.16 million US dollars.

We also estimate the total cost to the Danish government of a declining feed-in-tariff. In the declining feed-in-tariff scenario, the amount of the subsidy (and thus the cost to the government) depends on how old a particular turbine is as well as how much electricity it produces each year. We therefore use the number of turbines in each age-size combination in each year, averaged over 100 simulations, from the declining feed-in-tariff scenario. We estimate the production of a turbine in a each year by calculating the average production (kWh) for each size bin in the real data. Then, for each combination of size and age, we multiply the number of turbines by the appropriate production estimate for that year (based on size) and then by the appropriate feed-in-tariff amount (based on age). We estimate the cost to the Danish government of the declining feed-in-tariff to be: $1.114 billion US dollars.

Thus, at a cost of $1.114 billion US dollars, the declining feed-in-tariff increased discounted payoffs of small wind producers approximately 7.6 times (from the normalized welfare of 5.03 in the no feed-in-tariff scenario, to the normalized welfare of 38.4 in the declining feed-in-tariff scenario, with the replacement certificate program assumed to be in place in both cases). The cost per percentage point increase in discounted wind producer payoffs is $33.41 million US dollars.

As external, uncompensated benefits associated with reduced greenhouse gas emissions potentially serve as an important justification for renewable energy policies (Callaway et al., 2018), we also calculate the benefits of each policy in terms of carbon emissions avoided. To do so, we first estimate the marginal emissions that would be displaced by wind generation. Since Denmark does not have any nuclear or hydro capacity and minimal solar and bioenergy production, we assume that all non-wind production would otherwise have come from fossil generation.[11] We therefore argue that if there were fewer wind turbines in Denmark, the energy that would have been supplied by the wind turbines would instead have been supplied by natural gas or coal. Thus, in the absence of either the replacement certificate program or the feed-in-tariff, or both, there would have been fewer wind turbines and higher levels of carbon emissions. We therefore estimate the marginal emissions that would be displaced by wind energy as the average carbon emission per unit capacity of the non-wind energy mix in Denmark. For each year, we divide the total annual carbon emissions in Denmark (DEA, 2013) by the total fossil generation in Denmark for each year (EIA, 2015) to get annual values for the average carbon emission per unit capacity of the non-wind energy mix.

We calculate the additional wind capacity that resulted from each policy as follows. For each counterfactual policy scenario (which removes one or both of the policies), we subtract the number of small turbines under that scenario in 2011 from the number of actual small turbines in 2011, and multiply the difference by the average capacity of a small turbine. Similarly, we subtract the number of medium turbines under that scenario in 2011 from the number of actual medium turbines in 2011, and multiply the difference by the average capacity of a medium turbine. Likewise, we subtract the number of large turbines under that scenario in 2011 from the number of actual large turbines in 2011, and multiply the difference by the average capacity of a large turbine. We then sum up the values for the three turbine sizes to get the capacity of energy that would have to be supplied by non-wind energy in that policy scenario (when compared with the actual data, when both policies are in place). We multiply this capacity by the marginal emissions that would be displaced by wind energy. This is the additional carbon emissions (compared to the actual data, when both policies are in place) resulting from the policy scenario (which removes one or both of the policies), and thus the carbon emissions avoided when the policy is in place.[12]

[11] Potential exceptions to this would be if the wind capacity were replaced by imported Norwegian hydro power or if wind power was actually on the margin during extremely low load hours.

[12] A more detailed analysis of the carbon emission avoided would finely model every last detail of every daily or hourly aspect of wind production for each and every individual turbine owner. Since our focus is on annual scrapping, adding, and upgrading decisions, we do not model daily wind production explicitly. In addition, as discussed above, we base the cutoffs for small and medium turbines on the different eligibility cutoffs for various versions of the replacement certificate policy specified by the Danish government over the time period of our study. This enables us to focus our analysis of turbine capacity on the aspects of turbine capacity relevant for Danish wind policy (i.e., whether or not the turbine capacity exceeds the varying eligibility cutoffs), making our results robust to the exact choice of turbine capacity within our broader size bins, and enabling us to analyze the relative effectiveness and cost-effectiveness of the Danish feed-in-tariff and replacement certificate programs without having to finely model every last detail of every daily or hourly aspect of wind production for each and every individual turbine owner. Thus, while our estimates of the carbon emissions benefits of each of the policies are back-of-the-envelope calculations, our qualitative results the relative effectiveness and cost-effectiveness of the Danish feed-in-tariff and replacement certificate programs are likely to be robust to any additional assumptions or more detailed modeling. We hope to pursue more detailed modeling of wind production and carbon emissions benefits in future work.

Our results show that, over the 32-year period from 1980 to 2011, when considering small wind producers (who constitute the vast majority of turbine owners in the Danish wind industry during this time period), the replacement certificate program reduced carbon emissions by 52.5 million tonnes of CO_2, with a cost per million tonne CO_2 avoided of $34,972 US dollars to $2.17 million US dollars. The feed-in-tariff reduced carbon emissions by 57.4 million tonnes of CO_2, with a cost per million tonne CO_2 avoided of $61.80 million US dollars. The replacement certificate program and the feed-in-tariff combined reduced carbon emissions by 57.4 million tonnes of CO_2, with a cost per million tonne CO_2 avoided of $61.84 million US dollars to $63.80 million US dollars. The declining feed-in-tariff would have reduced carbon emissions by 5.8 million tonnes of CO_2 (compared to the no feed-in-tariff scenario), with a cost per million tonne CO_2 avoided of $192.16 million US dollars.

We also use our back-of-the-envelope estimates of costs to calculate the minimum threshold discounted payoffs per wind turbine producer needed in the absence of any policy in order for each policy to be efficient. In particular, for each policy we analyze, we calculate the minimum threshold discounted payoffs per wind turbine producer needed in the absence of any policy (i.e., in the absence of either the feed-in-tariff or the replacement certificate) in order for the total costs of that policy to the Danish government to be less than or equal to the total benefits to the turbine owners of that policy. We calculate the benefits to the turbine owners of a particular policy as the increase in their discounted payoffs under that policy relative to the case of no policy. For the costs of a particular policy, we use our upper bound estimate of the total cost of that policy to the Danish government.

Similarly, we use our back-of-the-envelope estimates of costs and our back-of-the-envelope estimates of the benefits of each policy in terms of carbon emissions avoided to calculate the minimum threshold discounted payoffs per wind turbine producer needed in the absence of any policy in order for each policy to be socially efficient. In particular, for each policy we analyze, we calculate the minimum threshold discounted payoffs per wind turbine producer needed in the absence of any policy (i.e., in the absence of either the feed-in-tariff or the replacement certificate) in order for the total costs of that policy to the Danish government to be less than or equal to the social benefits of the policy, where the social benefits are the private benefits to the turbine owners of that policy (in terms of an increase in their discounted payoffs relative to the case of no policy) plus the external benefits of the carbon emissions avoided. For the costs of a particular policy, we use our upper bound estimate of the total cost of that policy to the Danish government. To calculate the external benefits of the carbon emissions avoided, we apply the central value of the social cost of carbon in 2010, a year towards the end of the time period of our analysis, of $21 US dollars per ton of CO_2 emissions from Greenstone et al. (2013) to our back-of-the-envelope estimates of the benefits of each policy in terms of carbon emissions avoided. While the value of the social cost of carbon we use is lower than more recent estimates used in the United States based on global benefits (Auffhammer et al., 2016; Metcalf and Stock, 2017), it is higher than social cost of carbon estimates based on domestic U.S. benefits (Tol, 2008; Metcalf and Stock, 2017), is higher than the negative country-level social cost of carbon recently that has recently been estimated for Northern Europe (Ricke et al., 2018), and is moreover a value from 2010, a year towards the end of the time period of our analysis, and therefore serves as a reasonable value for a conservative lower bound to the social cost of carbon to use for Denmark. We also repeat the analysis using a higher social cost of carbon estimate of $50 US dollars per ton of CO_2 emissions.

As seen in Table 9, when compared with the feed-in-tariff; a declining feed-in-tariff; and the replacement certificate program and the feed-in-tariff combined, the replacement certificate program had the lowest cost per percentage point increase in discounted wind producer payoffs (or utility), and also the lowest cost per million tonne CO_2 avoided. Thus, the replacement certificate program was the most cost-effective policy both for increasing payoffs of small wind producers and also for decreasing carbon emissions.

For the replacement certificate program, the benefits to turbine owners of the policy would have exceeded its costs to the Danish government over the period 1980-2011 as long as the average present discounted value of the entire stream of payoffs over that period to each wind turbine owner owning two or fewer turbines would have been at least $2,740 US dollars in the absence of any policy. In contrast, for each of the other counterfactual policy scenarios (feed-in-tariff; a declining feed-in-tariff; and the replacement certificate program and the feed-in-tariff combined), the minimum threshold discounted payoffs per wind turbine producer needed in the absence of any policy in order for the policy to be efficient is much higher. For the feed-in-tariff, for example, the minimum threshold discounted payoffs per wind turbine producer needed in the absence of any policy in order for the feed-in-tariff to be efficient is $58,970 US dollars.

Moreover, when also considering the external benefits of the carbon emissions avoided as well as the private benefits to wind turbine owners, and when using a social cost of carbon of $21 US dollars per ton of CO_2 emissions, the replacement certificate program would have been socially efficient over the period 1980-2011 even if the discounted payoffs to turbine owners in the absence of any policy would have been negative, as long as on average each wind turbine owner owning two or fewer turbines would have lost less than $23,720 US dollars in present discounted value over that period in the absence of any policy. In contrast, for each of the other counterfactual policy scenarios (feed-in-tariff; a declining feed-in-tariff; and the replacement certificate program and the feed-in-tariff combined), the minimum threshold discounted payoffs per wind turbine producer needed in the absence of any policy in order for the policy to be socially efficient is much higher, and positive rather than negative. For the feed-in-tariff, for example, the minimum threshold discounted payoffs per wind turbine producer needed in the absence of any policy in order for the feed-in-tariff to be socially efficient is $38,930 US dollars. When using a higher social cost of carbon estimate of $50 US dollars per ton of CO_2 emissions, the minimum threshold discounted payoffs per wind turbine producer needed in the absence of any policy in order for the policy to be socially efficient is still negative for the replacement certificate program, and still much higher and positive for all the other counterfactual policy scenarios.

5 Discussion and Conclusion

This paper develops a dynamic structural econometric model of wind turbine ownership that is used to estimate a profit structure for small wind energy producers in Denmark over the period 1980-2011 and evaluate the impact of technology and government policy on wind industry development. Results from the model indicate that the growth and development of the Danish wind industry were driven primarily by government policies as opposed to technological improvements. Results from policy simulations show that both the replacement certificate and feed-in-tariff policies generated windfall profits for small wind producers (who constitute the vast majority of turbine owners in the Danish wind industry during this time period) and resulted in more turbine additions and upgrades than would have otherwise occurred. Both of these policies significantly impacted the timing of shutdown and upgrade decisions made by small wind producers and accelerated the development of the wind industry in Denmark.

Without the policies, the benefits to owning a turbine would have been significantly reduced. In particular, discounted payoffs (or utility) of small wind producers would have been 70% lower if there were no replacement certificate and 95% lower if there were no feed-in-tariff. In the absence of both policies, discounted payoffs (or utility) of small wind producers would have been 96% lower. Without these policies, most small-scale wind turbine owners would have exited the industry before the end of 2011.

We also find that when compared with the feed-in-tariff; a declining feed-in-tariff; and the replacement certificate program and the feed-in-tariff combined, the replacement certificate program was the most cost-effective policy both for increasing payoffs of small wind producers and also for decreasing carbon emissions.

The results from the policy simulations can be used to assess Denmark's wind policies from several different perspectives. The driving forces behind renewable energy development in Denmark for 35 years have been energy security and green growth that have manifested themselves in a series of energy and climate goals (Energinet.dk, 2010; Meyer, 2004). To these ends, the feed-in-tariff was the primary tool chosen by the Danish government to incentivize new investments in wind turbines, while the replacement certificate program was created to allow the expansion of wind power to take place along with the decommissioning of older, lower capacity wind turbines.

Evaluated on the basis of their stated goals, the feed-in-tariff and replacement certificate policies have been a rousing success, though their ability to achieve other objectives is not quite as clear. Our results show that, due to the fixed nature of feed-in-tariff incentives over the lifetime of a turbine, the policy became increasingly expensive for the government as the number of turbines grew throughout the 1980s and 1990s. We also find that implementing a declining feed-in-tariff would have reduced government expenditures, but would also have resulted in the addition of fewer turbines. We find in contrast that, when compared with the feed-in-tariff; a declining feed-in-tariff; and the replacement certificate program and the feed-in-tariff combined, the replacement certificate program was the most cost-effective policy both for increasing payoffs of small wind producers and also for decreasing carbon emissions.

Although our paper is the first to our knowledge to compare the cost-effectiveness of the Danish feed-in-tariff and replacement certificate policies, our results that the replacement certificate program was more cost-effective than the feed-in-tariff are consistent with previous studies of feed-in-tariffs in other areas of the world that show that feed-in-tariffs can be inefficient (Reguant, 2019) and costly (Ciarreta et al., 2017), and that feed-in-tariffs are not necessarily the most cost-effective renewable electricity policy (Fell and Linn, 2013).

The intuition for why the replacement certificate program may be more cost-effective than the feed-in-tariff is similar to the trade-off between production subsidies and investment subsidies described and analyzed in Yi et al. (2019), and is as follows. A drawback of the feed-in-tariff, which one can view as an implicit production subsidy, is that the Danish government would need to pay the production subsidy implicit in the price guaranteed by the feed-in-tariff for every unit of wind energy that is produced, including wind energy produced by older, smaller turbines that are neither replaced nor upgraded, as well as any other inframarginal units of wind energy that would still have been produced even in absence of the feed-in-tariff. Thus, government payments to these inframarginal units of production are wasted from the point of view of encouraging expanded wind energy production.

In contrast, with the replacement certificate, the Danish government would only need to pay the additional price supplement if a turbine were scrapped and a new turbine were constructed. Thus, the Danish government would only need to pay the additional price supplement from the replacement certificate for a subset of wind turbines, and for fewer inframarginal units of wind production. As a consequence, in the replacement certificate program, there are fewer government payments to inframarginal units of production that are wasted from the point of view of encouraging expanded wind energy production. Thus, it is possible that the replacement certificate can be more cost-effective than the feed-in-tariff, and our empirical results show that this is indeed the case.

In their analysis of the U.S. ethanol industry, Yi et al. (2019) similarly find that while historically the U.S. federal government has used production subsidies to support ethanol, investment subsidies and entry subsidies are more cost-effective than production subsidies for inducing investment that otherwise would not have occurred.

Over the period 1980 to 2010, observed annual CO_2 emissions from electricity production declined on net from 23.8 million tonnes in 1980 to 17.7 million tonnes in 2010 (DEA, 2017). During this time, annual wind consumption for electricity production increased from 38 TJ in 1980 to 28,114 TJ in 2010 (DEA, 2017). Thus, in the year 2010 alone, observed annual CO_2 emissions from electricity production were 6.1 million tonnes lower than were observed annual CO_2 emissions from electricity production in 1980. Similarly, in the year 2010 alone, annual wind consumption for electricity production was orders of magnitude higher than what it was in 1980.

Our results show that, over the 32-year period from 1980 to 2011, when considering small wind producers (who constitute the vast majority of turbine owners in the Danish wind industry during this time period), the replacement certificate program reduced carbon emissions by 52.5 million tonnes of CO_2, and that the replacement certificate program and the feed-in-tariff combined reduced carbon emissions by 57.4 million tonnes of CO_2. In other words, we find that, in the absence of the replacement certificate program, total CO_2 emissions over the 32-year period from 1980 to 2011 would have been 52.5 million tonnes higher.

As observed annual CO_2 emissions from electricity production were 6.1 million tonnes lower than were observed annual CO_2 emissions from electricity production in 1980 in one year – the year 2010 – alone, our results that, in the absence of the replacement certificate program, total CO_2 emissions over the entire 32-year period from 1980 to 2011 would have been 52.5 million tonnes higher for small wind producers (who constitute the vast majority of turbine owners in the Danish wind industry during this time period) seem reasonable.

Since historically the vast majority of wind turbines in Denmark were installed and owned by individuals or local cooperatives, we focus on turbine owners who own two or fewer turbines. This trend has changed in more recent years as more utility-scale wind projects have come online. Because our sample only contains those turbine owners who operate a maximum of two turbines at any one time and because installed wind capacity continued to grow in Denmark through the 2000s, the results of the policy simulations suggest that new installations in the absence of government policy would have been dominated by investments in larger wind farms from new entrants as opposed to decentralized investments made by small-scale turbine owners. This is to say, over time the Danish wind industry would have shifted toward larger wind farms that were owned by fewer numbers of people. Without the feed-in-tariff and replacement certificate program, it is likely that nearly all early turbine owners would have exited the industry by the end of 2011.

Other relevant economic questions include whether or not the policies improved welfare from a social standpoint and understanding any equity impacts. We have seen that the welfare of owners with small numbers of turbines was improved by the policies, but, as we focus on turbine owners who own two or fewer turbines, the effects on larger owners and electricity consumers could not be estimated. Thus, our results may not necessarily generalize beyond the small wind producers we focus on in our study. In future work we hope to analyze the effects of wind policy on larger wind farms as well.

The focus of our paper is on the shutdown, addition, and upgrade decisions of existing turbine owners, as shutting down and/or upgrading existing productive assets are important economic decisions for the owners of those assets and are also the fundamental decisions that underlie the development of new, growing industries. We do not model the original entry decision for an owner, but instead condition upon it. Because the location of turbines are pre-determined by municipal wind plans (DEA, 2009), we can plausibly argue that the probability of entry was driven by factors exogenous to the Danish feed-in-tariff and replacement certificate programs, and therefore that our estimates of the effects of the Danish feed-in-tariff and replacement certificate programs are not biased towards zero even though we condition upon entry. If the entry decision is affected by the Danish feed-in-tariff and replacement certificate programs, however, it is likely to be affected in a positive direction (i.e., the government policies leads to more entry than there would have been otherwise), in which case our estimates of the effects of these policies on discounted wind producer payoffs are a lower bound on the total benefits of the policies and the actual benefits of these policies may be even greater than what we estimate. In this case, the large lower bound values for the total benefits of the policies that we estimate are still meaningful since they suggest that the actual benefits of these policies may be at least as large. We hope to model the entry decision in future work.

The dynamic structural econometric model we develop in this paper can be applied to any set of interdependent shutdown and upgrade decisions. Our application to the Danish wind industry has important implications for the design of renewable energy policies worldwide.

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Table 1: Summary Statistics for Turbines Owned by Owners with Two or Fewer Turbines, 1980-2011

	Number of Turbines	**Mean**	**Std. Dev.**	**Min.**	**Max.**
Capacity (kW)	6,410	487.9	507	10	6000
Installation Date	6,410	Aug. 13, 1994	6.46 years	Jan. 1, 1978	Oct. 17, 2011

Table 2: Danish Feed-in-Tariff Policies

Date Range	**Price Guaranteed By Feed-in-Tariff**	
	Value	Bin
Before Jan. 1, 2000	$0.11/kWh	high
Jan. 1, 2000 – Dec. 31, 2002	$0.08/kWh	med
Jan. 1, 2003 – present	$0.06/kWh	low

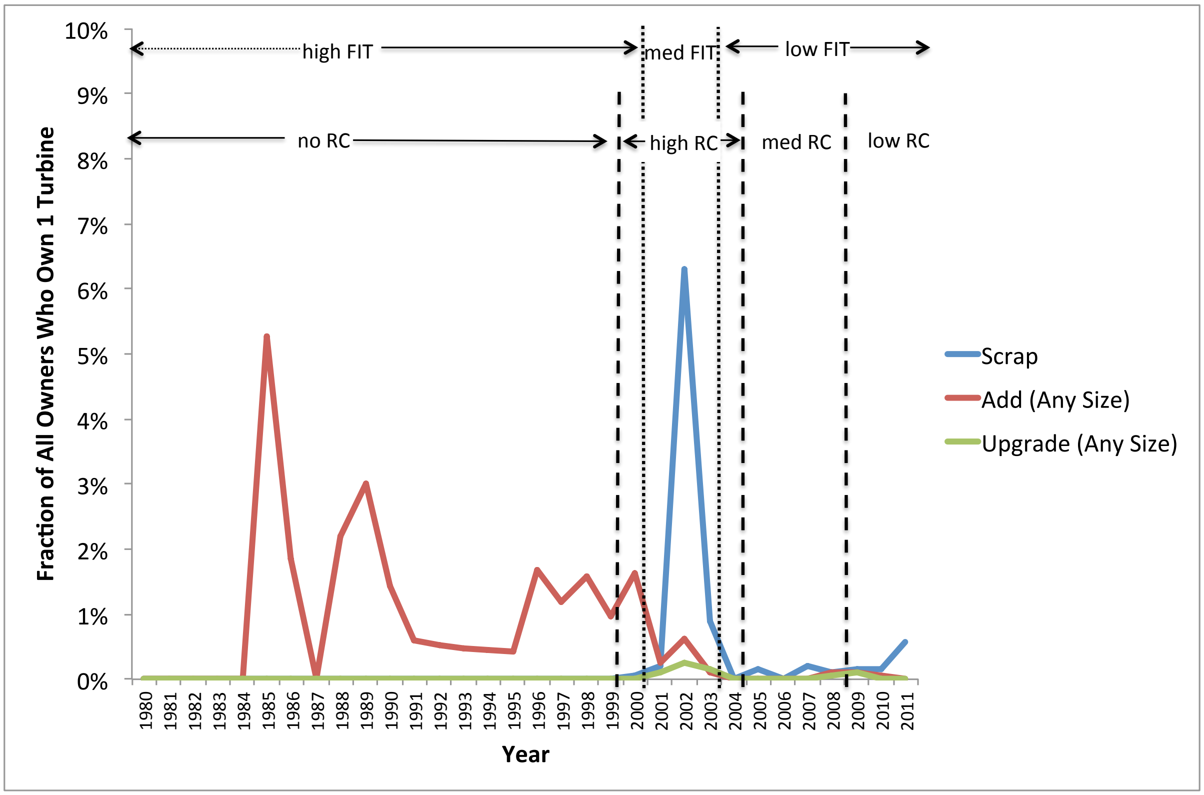
Note: Values in Danish krone (DKK) are converted to US dollars using the 2010 DKK to USD exchange rate of 0.1782575, which is calculated as the average of the monthly DKK to USD exchange rates during 2010 in OFX (2018). From January 1, 2003 to the present, the price guaranteed by the feed-in-tariff was a maximum of $0.06/kWh, and the feed-in-tariff was a maximum of $0.02/kWh.
Sources: Act no. 1392 (2008); IEA (2009); Mauritzen (2014)

Table 3: Danish Replacement Certificate Program

Date Range for Scrapping	Eligible Capacities	Scrapping Certificate	
		Value	Bin
Mar. 3, 1999 – Dec. 31, 2003	< 150 kW	$0.03/kWh	high
Dec. 15, 2004 – Feb. 20, 2008	< 450 kW	$0.02/kWh	med
Feb. 21, 2008 – Dec. 31, 2011	< 450 kW	$0.01/kWh	low

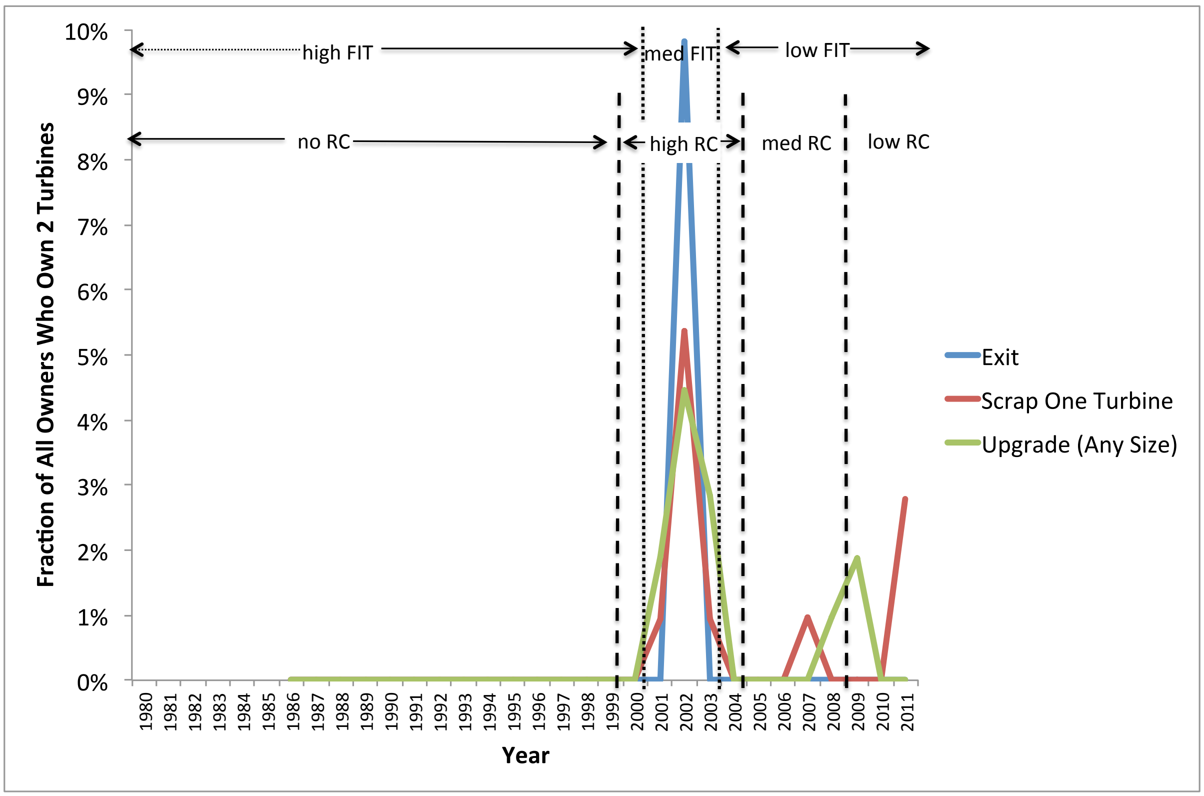
Note: Values in Danish krone (DKK) are converted to US dollars using the 2010 DKK to USD exchange rate of 0.1782575, which is calculated as the average of the monthly DKK to USD exchange rates during 2010 in OFX (2018).
Source: Act no. 1392 (2008)

Figure 1: Observed Decisions of Owners with One Turbine



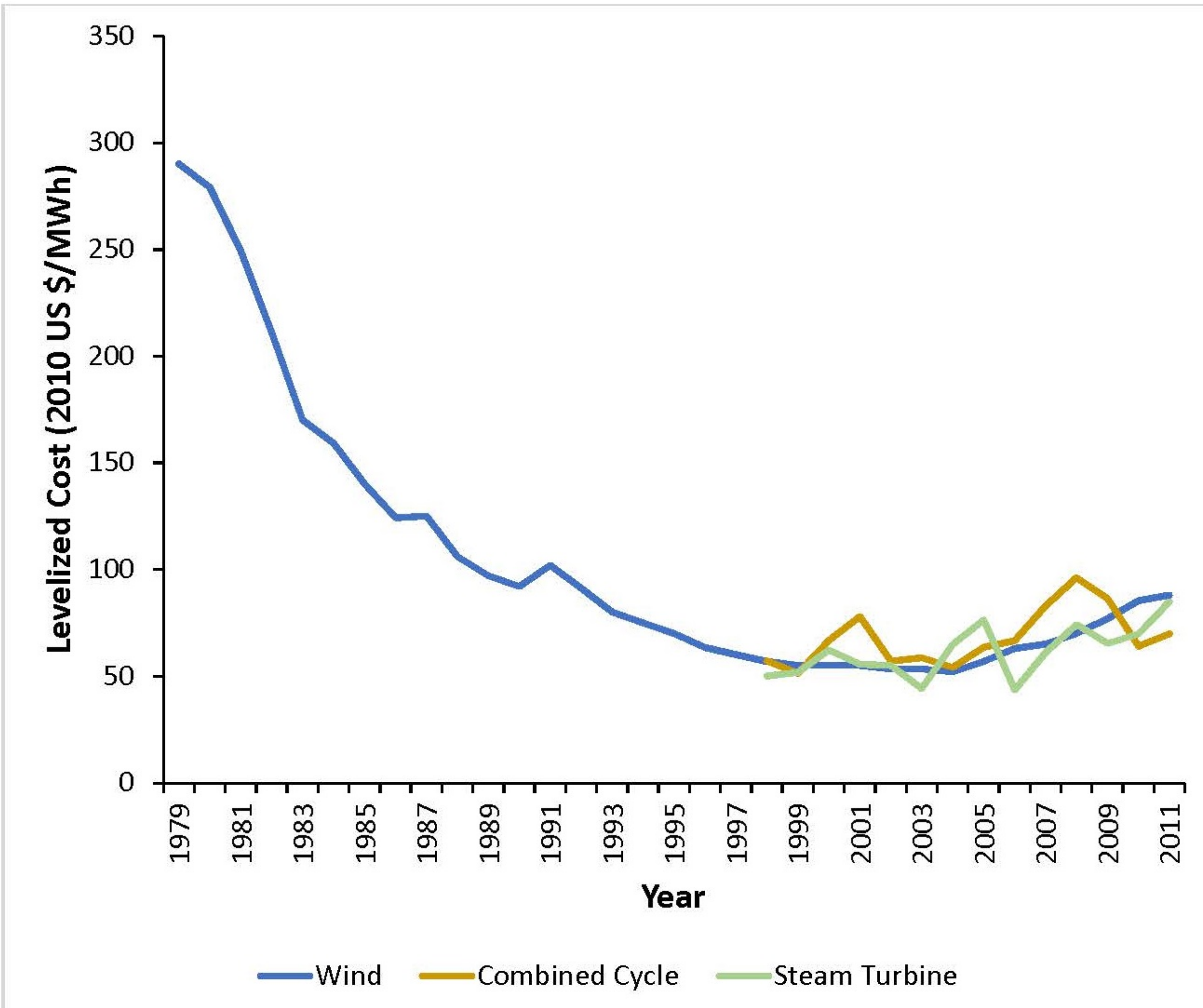
Notes: FIT = feed-in-tariff. RC = replacement certificate.

Figure 2: Observed Decisions of Owners with Two Turbines



Notes: FIT = feed-in-tariff. RC = replacement certificate.

Figure 3: Levelized Cost of Wind Energy



Note: This graph plots the levelized costs of wind energy used in our model. For comparison, the levelized costs of producing electricity in Denmark from combined-cycle gas turbines and from steam turbine extraction generators are plotted as well. Values in Danish krone (DKK) are deflated to 2010 DKK using the GDP deflator from the World Bank (World Bank, 2018) and then converted to US dollars using the 2010 DKK to USD exchange rate of 0.1782575, which is calculated as the average of the monthly DKK to USD exchange rates during 2010 in OFX (2018).

Sources: DEA (1999); Lantz et al. (2012); Levitt and Sørensen (2014b)

Figure 4: Interdependence of Scrapping, Adding, and Upgrading Decisions

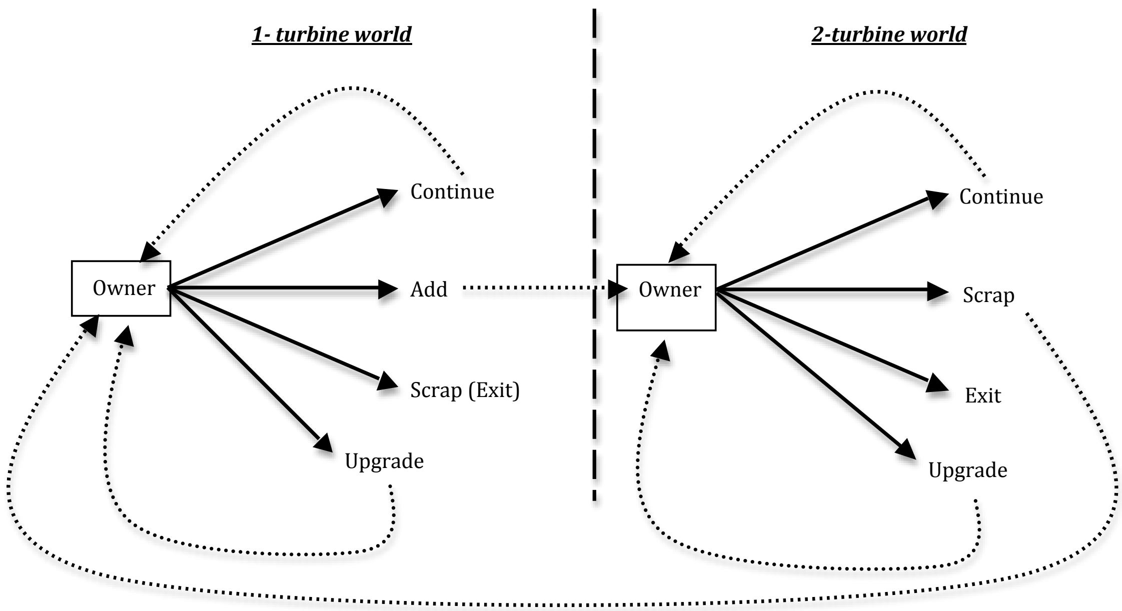


Table 4: Actions Available to Turbine Owners Owning One and Two Turbines

Action	**One-turbine world**	**Two-turbine world**
Continue ($d_{i,t}$ = 1)	x	x
Add small turbine ($d_{i,t}$ = 2)	x	
Add medium turbine ($d_{i,t}$ = 3)	x	
Add large turbine ($d_{i,t}$ = 4)	x	
Scrap only one turbine ($d_{i,t}$ = 5)		x
Upgrade to small turbine ($d_{i,t}$ = 6)	x	x
Upgrade to medium turbine ($d_{i,t}$ = 7)	x	x
Upgrade to large turbine ($d_{i,t}$ = 8)	x	x
Scrap all turbines (exit) ($d_{i,t}$ = 9)	x	x

Table 5: Discretized Values for State Variables in Structural Model

Variable	Value Range	Bin	Discrete Value
Capacity (kW)	0-450	small	1
	451-750	medium	2
	>750	large	3
Turbine age	0-9	young	1
	10-19	middle-aged	2
	>19	old	3
Price guaranteed by feed-in-tariff ($/kWh)	0.06	low	1
	0.08	medium	2
	0.11	high	3
Replacement certificate ($/kWh)	0.01	low	1
	0.02	medium	2
	0.03	high	3
Levelized cost of wind energy ($/MWh)	0-75	low	1
	76-100	medium	2
	>100	high	3

Table 6: Results of Dynamic Structural Econometric Model

Parameter		*Coefficient in per-period payoffs on:*	(1)	(2)	(3)
$\gamma_{I,1}$	*cap_kw*1	Capacity of turbine 1	0.166***	0.184***	0.152
			(0.036)	(0.038)	(0.128)
$\gamma_{I,2}$	*turbine_age*1	Age of turbine 1	-0.066	-0.059	-0.156**
			(0.036)	(0.038)	(0.056)
$\gamma_{I,3}$	*orig_fit*1	Price guaranteed by feed-in-tariff for turbine 1	0.224***	0.248***	0.326*
			(0.045)	(0.044)	(0.130)
$\gamma_{I,4}$	*orig_lcoe*1	Levelized cost of energy for turbine 1	-0.154***	-0.152***	0.073
			(0.022)	(0.022)	(0.068)
$\gamma_{II,1}$	*cap_kw*2	Capacity of turbine 2	0.012	-0.011	-0.131***
			(0.046)	(0.042)	(0.032)
$\gamma_{II,2}$	*turbine_age*2	Age of turbine 2	0.037	0.064	0.213*
			(0.106)	(0.096)	(0.087)
$\gamma_{II,3}$	*orig_fit*2	Price guaranteed by feed-in-tariff for turbine 2	0.011	-0.005	-0.180 ***
			(0.052)	(0.046)	(0.039)
$\gamma_{II,4}$	*orig_lcoe*2	Levelized cost of energy for turbine 2	0.019	-0.003	-0.072
			(0.043)	(0.041)	(0.048)
α_1	*rep_subsidy*	Replacement certificate	1.123***	1.014***	0.169
			(0.290)	(0.201)	(1.032)
α_2	$lcoe_t$	(Negative of) value of replacement certificate	-0.467	-1.400*	1.781
			(0.811)	(0.654)	(1.312)
α_3	$lcoe_t$	(Negative of) value of replacement certificates for owners of 2 turbines		-2.011*	
				(0.972)	
ρ_1	constant	(Negative of) cost of adding new turbine	-6.148***	-5.394***	
			(0.835)	(0.529)	
ρ_2	constant	(Negative of) cost of upgrading	-9.068***	-8.678***	
			(2.046)	(1.572)	
τ_1	constant	Scrap value from exiting	-2.286	0.033	
			(2.407)	(1.358)	
τ_2	*cap_kw*1	Scrap value of turbine 1			0.103
					(1.378)
τ_3	*cap_kw*2	Scrap value of turbine 2			-1.439***
					(0.328)
Log likelihood			-1,649.7	-1,663.7	-2,611.3
Number of observations			40,636	40,636	40,636
Number of turbines			6,410	6,410	6,410

Notes: Standard errors are in parentheses. Significance codes: *** p<0.001, ** p<0.01, * p<0.05.

Table 7: Simulated Declining Feed-in-Tariff Policy

Turbine Age	**Feed-in-Tariff**
0 to 8 years	$0.11/kWh price guarantee
9 to 16 years	$0.08/kWh price guarantee
>16 years	$0.06/kWh maximum price guarantee (Feed-in-tariff up to $0.02/kWh)

Table 8: Results of Simulations of Counterfactual Policy Scenarios, 1980-2011

	Both Policies in Place	No Replacement Certificate	Declining Feed-In-Tariff	No Feed-In-Tariff	No Replacement Certificate + No Feed-In-Tariff
Discounted wind producer payoffs (% of actual)	100	34.2	38.4	5.03	4.05
		(0.51)	(0.52)	(0.21)	(0.17)
Number of turbines scrapped	214	2,342.6	2,333.7	2,350.8	2,350.6
		(8.21)	(8.59)	(6.43)	(5.81)
Number of turbines upgraded	13	1.63	1.85	0.75	0.77
		(1.32)	(1.24)	(0.83)	(0.85)
Number of turbines added	129	31.55	30.84	16.77	16.98
		(5.88)	(5.77)	(4.20)	(3.71)
Number of turbines scrapped by owners of 1 turbine	180	2,296.7	2,288.7	2,325.9	2,325.7
		(7.08)	(7.74)	(4.85)	(4.57)
Number of turbines scrapped by owners of 2 turbines	34	45.96	44.96	24.93	24.91
		(9.12)	(9.07)	(6.56)	(6.01)
Average age of turbines scrapped	16	2.92	3.00	2.10	2.11
		(0.04)	(0.04)	(0.03)	(0.03)
Number of replacement certificates issued	213	NA	101.09	66.95	NA
			(8.46)	(7.39)	
Average age of turbines in 2011	13	5.03	4.99	2.00	2.00
		(0.44)	(0.37)	(0.32)	(0.33)
Number of small turbines in 2011	423	3.52	2.38	1.56	2.06
		(1.34)	(1.10)	(0.70)	(0.83)
Number of medium turbines in 2011	1291	17.71	16.59	1.78	1.79
		(4.27)	(4.05)	(1.24)	(1.38)
Number of large turbines in 2011	472	61.93	70.67	50.50	49.68
		(3.97)	(5.16)	(2.88)	(2.94)

Notes: The table reports, for each policy scenario, the means and standard deviations over 100 simulations. Standard deviations are in parentheses. Discounted wind producer payoffs are defined as the present discounted value of the entire stream of payoffs over the period 1980-2011 for each turbine owner, summed over all owners of two or fewer turbines.

Figure 5: Evolution of Wind Industry Under Different Policy Scenarios

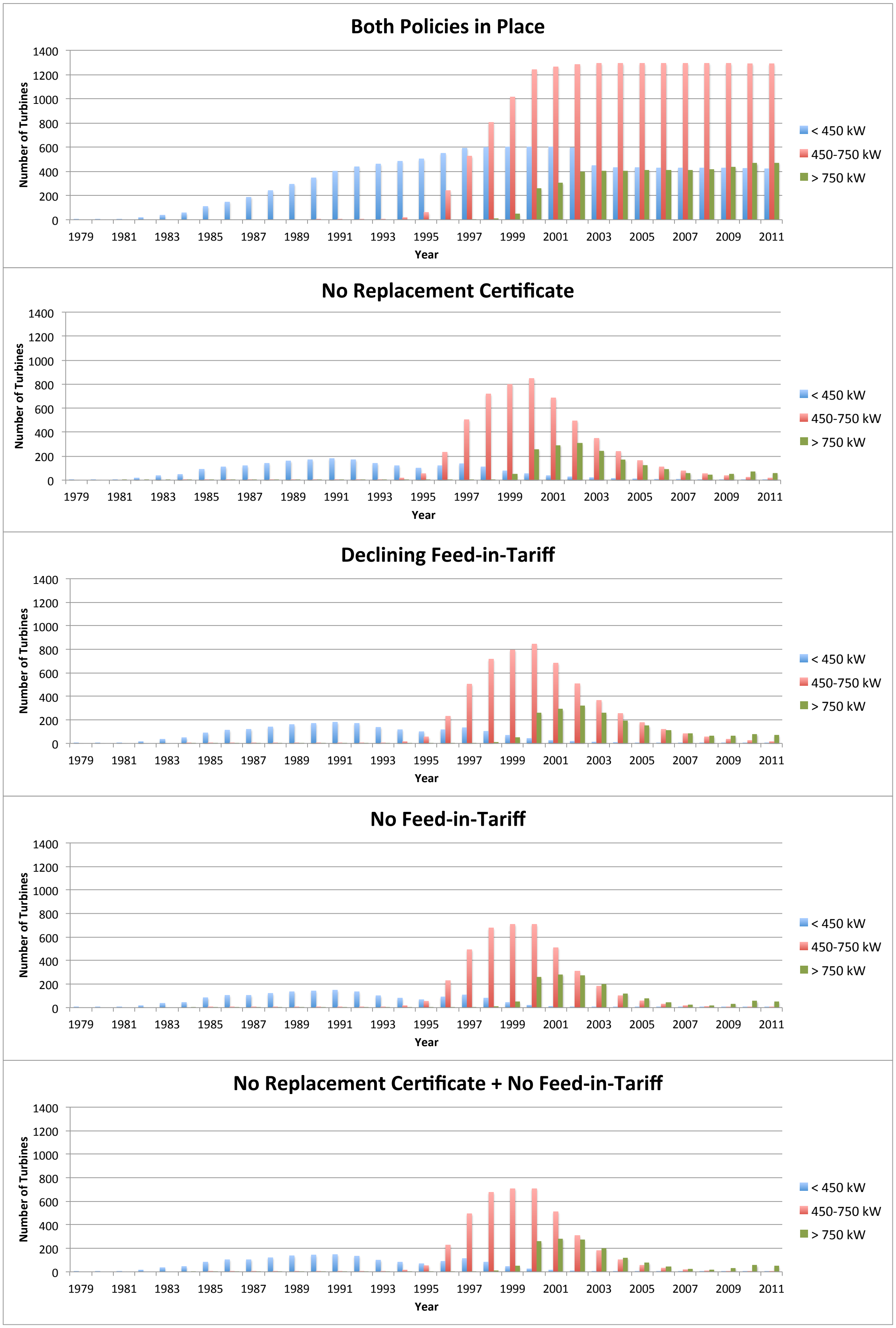


Table 9: Back-of-the-Envelope Estimates of Benefits, Costs, Cost-Effectiveness, and Efficiency of Various Wind Policies, 1980-2011

	Replacement Certificate	Declining Feed-In-Tariff	Feed-In-Tariff	Replacement Certificate + Feed-In-Tariff
Benefits				
Percentage point increase in discounted wind producer payoffs	65.8	33.37	94.97	95.95
Total avoided carbon emissions (million tonnes CO_2)	52.5	5.8	57.4	57.4
Costs				
Total cost to Danish government (million US $)	1.84 to 114.12	1,114	3,547	3,549 to 3,661
Cost-Effectiveness				
Cost per percentage point increase in discounted wind producer payoffs (million US $)	0.028 to 1.73	33.41	37.34	36.99 to 38.16
Cost per million tonne CO_2 avoided (million US $)	0.035 to 2.17	192.16	61.80	61.84 to 63.80
Efficiency				
Minimum threshold average discounted payoffs per wind producer (thousand US $) needed in absence of any policy in order for policy to be ...				
... Efficient	2.74	52.71	58.97	60.25
... Socially efficient when social cost of carbon is $21 US dollars per ton of CO_2	-23.72	46.95	38.93	40.41
... Socially efficient when social cost of carbon is $50 US dollars per ton of CO_2	-60.25	38.99	11.26	13.02

Notes: Benefits and costs are calculated over the 32-year period from 1980 to 2011 for owners of two or fewer turbines (who constitute the vast majority of turbine owners in the Danish wind industry during this time period). Discounted wind producer payoffs are defined as the present discounted value of the entire stream of payoffs over the period 1980-2011 for each turbine owner, summed over all owners of two or fewer turbines.

Appendix A. Details of Dynamic Structural Econometric Model

In this Appendix, we explain and derive the choice probabilities in Equation (9) in more detail.

Substituting the conditional independence assumption in Equation (8) into the value functions in Equations (6) and (7) yields:

$$V^{I}\left(x_{i,t},\epsilon_{i,t}\,;\theta\right)=\max\left\{\begin{array}{l}\pi^{I,c}(x_{i,t}\,;\theta)+\epsilon_{i,t}^{I,c}+\beta\int\tilde{V}^{I}(x_{i,t+1})dPr\left(x_{i,t+1}\mid x_{i,t},d_{i,t}=1,\theta\right),\\ \pi^{I,a}(x_{i,t}\,;\theta)+\epsilon_{i,t}^{I,a}(d_{i,t})+\beta\int\tilde{V}^{II}(x_{i,t+1})dPr\left(x_{i,t+1}\mid x_{i,t},d_{i,t}\in\{2,3,4\},\theta\right),\\ \pi^{I,u}(x_{i,t}\,;\theta)+\epsilon_{i,t}^{I,u}(d_{i,t})+\beta\int\tilde{V}^{I}(x_{i,t+1})dPr\left(x_{i,t+1}\mid x_{i,t},d_{i,t}\in\{6,7,8\},\theta\right),\\ \pi^{I,e}(x_{i,t}\,;\theta)+\epsilon_{i,t}^{I,e}\end{array}\right\}\quad\text{(A.1)}$$

for owners of one turbine, and:

$$V^{II}\left(x_{i,t},\epsilon_{i,t}\,;\theta\right)=\max\left\{\begin{array}{l}\pi^{II,c}(x_{i,t}\,;\theta)+\epsilon_{i,t}^{II,c}+\beta\int\tilde{V}^{II}(x_{i,t+1})dPr\left(x_{i,t+1}\mid x_{i,t},d_{i,t}=1,\theta\right),\\ \pi^{II,s}(x_{i,t}\,;\theta)+\epsilon_{i,t}^{II,s}+\beta\int\tilde{V}^{I}(x_{i,t+1})dPr\left(x_{i,t+1}\mid x_{i,t},d_{i,t}=5,\theta\right),\\ \pi^{II,u}(x_{i,t}\,;\theta)+\epsilon_{i,t}^{II,u}(d_{i,t})+\beta\int\tilde{V}^{II}(x_{i,t+1})dPr\left(x_{i,t+1}\mid x_{i,t},d_{i,t}\in\{6,7,8\},\theta\right),\\ \pi^{II,e}(x_{i,t}\,;\theta)+\epsilon_{i,t}^{II,e}\end{array}\right\}\quad\text{(A.2)}$$

for owners of two turbines, where the ex ante value functions $\tilde{V}^{j}(\cdot)$ are given by:

$$\tilde{V}^{j}(x_{i,t+1})=\int V^{j}(x_{i,t+1},\epsilon_{i,t+1};\theta)dPr(\epsilon_{i,t+1}\mid\theta)=E_{\epsilon}\left[V^{j}(x_{i,t+1},\epsilon_{i,t+1};\theta)\right]\quad\text{for } j=I,II.\quad\text{(A.3)}$$

Making the assumption that each shock in $\epsilon_{i,t}$ is i.i.d. extreme value (type 1) across owners i, actions $d_{i,t}$ and time t, we can then write the expressions for the ex ante value functions $\tilde{V}^{j}(x_t)$ as:

$$\tilde{V}^{I}(x_{i,t})=\ln\left(\sum_{d}\exp\left(\delta^{I,d}\left(x_{i,t},\tilde{V}^{\ddagger}\right)\right)\right)\quad\text{(A.4)}$$

and:

$$\tilde{V}^{II}(x_{i,t}) = \ln\left(\sum_d \exp\left(\delta^{II,d}\left(x_{i,t}, \tilde{V}^{\ddagger}\right)\right)\right), \tag{A.5}$$

where:

$$\delta^{j,d}\left(x_{i,t}, \tilde{V}^{\ddagger}\right) = \pi^{j,d} + \beta \int \tilde{V}^{\ddagger}(x_{i,t+1}) dPr\left(x_{i,t+1} \mid x_{i,t}, d, \theta\right) \quad \text{for } j = I, II, \tag{A.6}$$

and where the ex ante value function $\tilde{V}^{\ddagger}$ next period used to calculate the continuation value is either the ex ante value function $\tilde{V}^{I}(x_{i,t+1})$ for owners of one turbine next period or the ex ante value function $\tilde{V}^{II}(x_{i,t+1})$ for owners of two turbines next period, depending upon the world that an owner is in this period and the action taken this period (similar to Equations (A.1) and (A.2)).

The probability of a given action conditional on the realization of a particular combination of state variables is given by the following choice probabilities:

$$Pr\left(d_{i,t} = \tilde{d} \mid x_{i,t}, \theta\right) = \frac{\exp\left(\delta^{j,\tilde{d}}\left(x_{i,t}, \tilde{V}^{\ddagger}\right)\right)}{\sum_d \exp\left(\delta^{j,d}\left(x_{i,t}, \tilde{V}^{\ddagger}\right)\right)} \quad \text{for } j = I, II, \tag{A.7}$$

which are a function of the ex ante value functions $\tilde{V}^{\ddagger}$ for $\ddagger = I, II$.