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

Jonathan A. Cook

Department of Agricultural and Resource Economics
University of California, Davis

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Optimal Investments, Technology Adoption Spillovers and Turnover

If we had everything priced perfectly (we don’t), would we make the right energy investments?
Optimal Investments, Technology Adoption Spillovers and Turnover

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- Even with a first-best pricing policy, knowledge spillovers could lower future costs
Optimal Investments, Technology Adoption Spillovers and Turnover

- If we had everything priced perfectly (we don’t), would we make the right energy investments?
- Even with a first-best pricing policy, knowledge spillovers could lower future costs
- Policies designed to encourage new investments may have adverse impacts on long-run turnover
Modern Danish wind industry dates back to late 1970’s following the 1st global oil crisis
Why Denmark?

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- More than 5,000 turbines currently in operation that produce approximately 25% of Denmark’s electricity
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- More than 5,000 turbines currently in operation that produce approximately 25% of Denmark’s electricity
- Turbines are owned by individuals and cooperatives – 88% of owners have fewer than three turbines from 1977-2011
Improvements in Turbine Technology

The chart illustrates the evolution of wind turbine technology from 1980 to 2005. The turbines have increased in size and power output over time. For example, the 1980 turbine had a power output of 50 kW and a hub height of 24 m, while the 2005 turbine had a power output of 5000 kW and a hub height of 114 m. This demonstrates significant advancements in turbine technology and the growth of wind power in Denmark.
Danish government made an early commitment to supporting wind power using price-based policies.
Danish Wind Policies

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  - Feed-in-tariff – Long-term price guarantee for electricity produced by wind turbines
Danish government made an early commitment to supporting wind power using price-based policies

1. **Feed-in-tariff** – Long-term price guarantee for electricity produced by wind turbines
2. **Replacement Certificate program** – Extra subsidy for scrapping small, older turbines and replacing them with newer, larger and more efficient turbines
Danish Wind Policies

- Danish government made an early commitment to supporting wind power using price-based policies
  1. *Feed-in-tariff* – Long-term price guarantee for electricity produced by wind turbines
  2. *Replacement Certificate program* – Extra subsidy for scrapping small, older turbines and replacing them with newer, larger and more efficient turbines

- Long-run energy goals
  - 50% wind by 2020
  - 100% renewable energy system by 2050
## Feed-in-Tariff

<table>
<thead>
<tr>
<th>Date Range</th>
<th>Level of Subsidy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Jan 1, 2000</td>
<td>DKK (.60/kWh) price guarantee for 10 years, DKK (.10/kWh) price guarantee for next 20 years</td>
</tr>
<tr>
<td>Jan 1, 2000 – Dec 31, 2002</td>
<td>DKK (.43/kWh) price guarantee for 22,000 load hours</td>
</tr>
<tr>
<td>Jan 1, 2003 – Feb 20, 2008</td>
<td>Feed-in-tariff up to DKK (.10) over market price with maximum payment of DKK (.36/kWh)</td>
</tr>
<tr>
<td>Feb 21, 2008 – present</td>
<td>Feed-in-tariff of DKK (.25/kWh) for 22,000 load hours</td>
</tr>
</tbody>
</table>

*Source: Johannes Mauritzen. The decision to scrap a wind turbine: Opportunity cost, timing and policy. SSRN eLibrary, 2011.*
## Replacement Certificate Program

<table>
<thead>
<tr>
<th>Date Range for Scrapping</th>
<th>Eligible Capacities</th>
<th>Value of Scrapping Certificate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar 3, 1999 – Dec 31, 2003</td>
<td>&lt; 150 kW</td>
<td>DKK .17/kWh over market price for 12,000 peak-load hours with maximum price of DKK .60/kWh</td>
</tr>
<tr>
<td>Dec 15, 2004 – Feb 20, 2008</td>
<td>&lt; 450 kW</td>
<td>DKK .12/kWh over market price for 12,000 peak-load hours with maximum price of DKK .48/kWh</td>
</tr>
<tr>
<td>Feb 21, 2008 – Dec 31, 2011</td>
<td>&lt; 450 kW</td>
<td>DKK .08/kWh over market price for 12,000 peak-load hours with maximum price of DKK .38/kWh</td>
</tr>
</tbody>
</table>

Research Questions of Interest

1. What is the profit structure for wind turbine owners in Denmark?
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2. How have policies impacted the timing of investment and scrapping decisions?
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2. How have policies impacted the timing of investment and scrapping decisions?
3. How do policies affect the turnover of old turbines and the long-run path of the industry?
Available Data

- Danish Energy Agency Register of Wind Turbines (2012)
  - Dates for new turbine installations and scrapping of old turbines
  - Turbine characteristics including capacity, hub height and location
- Ownership information used to create owner-level panel for 1977-2011
- Panel supplemented with values of policy variables and state of technology (levelized cost)
Dynamic Discrete Choice Framework

- Agent is a turbine owner who can operate no more than two turbines in a given period
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- Payoffs in each period depend on the characteristics of an owner’s turbines and the values of applicable policy variables
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- Payoffs in each period depend on the characteristics of an owner’s turbines and the values of applicable policy variables.
- Agents assumed to choose actions that dynamically optimize a discounted stream of payoffs.
Other Assumptions of the Model

- All costs associated with owning and operating turbines is correlated with either the turbine’s age or level of technology (levelized cost proxy)
- Replacement certificates that are not used by an owner are sold to another owner in the period they were received
Conceptual Depiction of Structural Model

1-turbine world

- Owner
  - Continue
  - Add
  - Scrap (Exit)
  - Upgrade

2-turbine world

- Owner
  - Continue
  - Scrap
  - Exit
  - Upgrade
Model Specifications

1. New turbine costs and scrap value vary with capacity and all replacement certificates have the same value within a given period.
2. New turbine costs and scrap value vary with capacity, but value of replacement certificates allowed to differ if multiple turbines scrapped in the same period.
3. New turbine costs and scrap value are constant and all replacement certificates have same value.
### Parameter Estimates of Interest from Structural Model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Description</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_1$</td>
<td>$\text{cap_{kw}}$</td>
<td>Capacity of Turbine 1</td>
<td>0.6817</td>
<td>0.6815</td>
<td>0.1662**</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.4145)</td>
<td>(0.4176)</td>
<td>(0.0363)</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>$\text{turbine_{age}}$</td>
<td>Age of Turbine 1</td>
<td>-0.0832*</td>
<td>-0.0833*</td>
<td>-0.0656</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.0408)</td>
<td>(0.0409)</td>
<td>(0.0356)</td>
</tr>
<tr>
<td>$\gamma_3$</td>
<td>$\text{orig_{fit}}$</td>
<td>Feed-in-tariff for Turbine 1</td>
<td>0.3158*</td>
<td>0.3159*</td>
<td>0.2234**</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.1362)</td>
<td>(0.1372)</td>
<td>(0.0450)</td>
</tr>
<tr>
<td>$\gamma_4$</td>
<td>$\text{lcoe_{orig}}$</td>
<td>LCOE for Turbine 1</td>
<td>-0.1530**</td>
<td>-0.1530**</td>
<td>-0.1537**</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.0255)</td>
<td>(0.0256)</td>
<td>(0.0217)</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>$\text{rep_{subsidy}}$</td>
<td>Replacement Certificate</td>
<td>1.4664**</td>
<td>1.4668**</td>
<td>1.1213**</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.1137)</td>
<td>(0.1154)</td>
<td>(0.2902)</td>
</tr>
<tr>
<td>$\rho_1$</td>
<td>constant</td>
<td>Cost of adding new turbine</td>
<td>-6.1502**</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(0.8350)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho_2$</td>
<td>constant</td>
<td>Net cost of upgrading</td>
<td>-9.0635**</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2.0459)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho_3$</td>
<td>constant</td>
<td>Scrap value of exiting</td>
<td>-2.2851</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(2.4072)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Significance codes:** * = 5%, ** = 1%

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Wind Turbine Upgrades in Denmark
Policy Simulations

- Can simulate counterfactual policy scenarios using structural parameter estimates (in progress)
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  1. How would scrapping/upgrade decisions have changed if there was no replacement certificate program?
Policy Simulations

Can simulate counterfactual policy scenarios using structural parameter estimates (in progress)

1. How would scrapping/upgrade decisions have changed if there was no replacement certificate program?
2. What would Danish wind industry look like today if there was no feed-in-tariff?
Conclusions

- Policies had a significant impact on investment decisions
  - Feed-in-tariff subsidy accounts for 30-50% of revenue for turbine owners
  - Replacement certificate subsidy dominates payoff for scrapping
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  - Feed-in-tariff subsidy accounts for 30-50% of revenue for turbine owners
  - Replacement certificate subsidy dominates payoff for scrapping
- Fixed feed-in-tariff delays turbine turnover
Questions?