Intra Firm Diffusion of Process Technologies: Wind Turbine Generators

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October 4, 2009

Work in progress. Please do not cite.

Abstract

The environmental challenge and the systematic robust relationship between growth in output and productivity suggest that technological change is critical if social welfare is to be maintained. Power generation is the largest single contributor of greenhouse gas emissions, so the sector has a responsibility to make a significant contribution to emissions reductions. Furthermore, technological change is increasingly shaping the competitive landscape in which firms operate, so investments in new technologies can be legitimately considered an element of corporate strategy.

A period of low investment in generation capacity but rising demand for electricity proves to have been an uncomfortable combination given the planned plant retirements due to, for example the nuclear phase out in Germany and the Large Plant Directive. The emergence of supply gaps in member states of the EU is a real prospect, and accordingly, 83% of respondents to the PricewaterhouseCoopers (2009) survey of global utilities claim that their competitive strategy includes making large or medium investments in generation capacity, but it is not clear which technologies will be adopted.

Comprehensive models of diffusion, as distinct from more general analysis of innovation, are rare and most existing studies offer at best a partial analysis of the phenomenon. This may be an important shortcoming if they form the justification for costly public policy interventions.

This study is based on Battisti and Stoneman's (2003) study of the intra firm diffusion of a new process innovation The model is tested empirically on firm level data on a sample of leading power generators based in the EU. In 2008 the overall diffusion of wind turbines was 5%, which can be decomposed as follows; approximately 70% of firms have adopted the technology, but the average intensity of wind in firms' total capacity mix is a mere 5%. We

find that multinational firms are more likely to fall into the intense adopters category, and that the absence of monopoly in the firm's member state of origin may be important. Factors contributing to the variance in the time firms delay first use of the technology and the speed with which they intensify that use are considered, and some insights into potential investment strategies offered.
JEL: L13, L25, L94
Keywords: intra firm diffusion; wind turbines; dynamic competition

1 Introduction

The impact of technological change [1] on social welfare is well documented (see for example, Romer, 1990): there a systematic robust relationship between growth in output and productivity. Despite a longstanding recognition that social benefits are fully realised only when new technologies are widely adopted or diffused throughout the economy (Fudenberg and Tirole, 1985), the vast majority of academic research has focussed on one or other of two themes. First, the analysis of innovation in general in which the distinction between the different stages of technological change[2] is not drawn (see for example, Geroski, 2000, Gilbert, 2006). The second major theme concers research and development (R&D). Despite its clear importance, the analysis of diffusion is under developed (Hall, 2004) and is the subject of this study.

There are two aspects of diffusion; the number of firms using the technology *inter* firm diffusion, and the intensity with which adopting firms use it, *intra* firm diffusion. Research efforts devoted to diffusion have focussed on inter firm diffusion and much progress has been made through both theoretical and empirical analysis since the seminal early work of Griliches (1957) and Mansfield (1963). Mansfield (1963) was the first to explore intra firm diffusion, and examined the idea that the same factors may determine both types of diffusion, but until recently it has remained a largely neglected topic.

Public support for technological change is at least implicitly based on the perception that it is driven by scientific discoveries. However, if as Schmookler argued, new technologies emerge in response to "the recognition of a costly problem to be solved or a potentially profitable opportunity to be seized" (Schmookler, 1966, p.199), then the adoption of new process technologies can be considered as a strategic decision in the sense developed by (Porter, 1996), and as an outcome of Schumpeterian (dynamic) competition (). Indeed Schmookler's recognition of the strategic importance of innovation appears to be consistent with the prevailing opinion in at least one important industrial sector. In a recent survey, the leaders of global utility firms report the view that "technology will be central to future growth and competitive advantage" (PricewaterhouseCoopers, 2009, p.3).

[1] Throughout this paper the terms technological change and innovation are synonymous.

[2] *Invention*, the creation of new ideas and knowledge, *R&D*, the introduction of new methods or knowledge, and finally *diffusion* when the new technology is adopted on a widespread basis Schumpeter (see 1994)

Power generation is the largest single contributor to greenhouse gas emissions, so the sector has both the potential and a responsibility to make a large reductions in emissions. The EU has experienced a period in which investment in generation capacity was low while demand for has electricity increased, which proves to be an uncomfortable combination given the planned plant retirements due to, for example the nuclear phase out in Germany and the Large Plant Directive. The emergence of supply gaps in EU member states is a real prospect, and accordingly, 83% of respondents to the PricewaterhouseCoopers survey claim that their competitive strategy includes making large or medium investments in generation capacity.

However, it is not clear which technologies the utilities will invest in. The transition to a low carbon economy, and more specifically, meeting the various targets resulting from the Kyoto protocol, for example for electricity generation from renewable sources, are predicated on innovation. However the analysis of innovation in power generation reflects the dominant approaches outlined above. In particular the literature focussing on the diffusion of low carbon technologies is very limited, and is restricted to the analysis of overall diffusion. For example, Diaz-Rainey (2009) considers patterns of adoption of wind turbines across member states when diffusion is induced by interventions such as support mechanisms or targets. This approach is highly relevant given binding commitments under Kyoto. The model is one of inter firm diffusion though Diaz-Rainey's data actually measures overall diffusion. This conflation of between and within firm diffusion is potentially misleading if there are marked differences between the two components.

The absence of empirical research on intra firm diffusion is important for at least three reasons. First, the observation that overall diffusion, and in this case the implied emissions reductions associated with substituting conventional generation technologies for low carbon technologies, is a function of *both* the number of firms that adopt the technology *and* the intensity with which they use it, and that these outcomes are the result of investment decisions made by firms, *not* governments. Second, recent research suggests that the decision to adopt a new technology is independent of the decision to intensify use of it (Battisti and Stoneman, 2003, Hollenstein and Woerter, 2008), which means that interventions which have the effect of increasing the number of users may have little impact on the overall use of the technology and finally, interventions based on the analysis of inter firm diffusion alone are likely to fail to meet their objectives and perhaps even risk jeopardising the achievement of emissions reduction targets, since such analysis by definition addresses only part of the problem.

The objectives of this study are two fold. First, to find out if we can map certain firm specific characteristics to a particular intensity of use of WTG. Given current concerns regarding the anthropogenic nature of climate change, and the emphasis on innovation as a major part of the solution, this may have important policy implications. Second, to demonstrate the importance of decomposing overall diffusion into its constituent parts based on an application to the diffusion of wind turbine generators (WTG) among leading generators based in the EU. The remainder of the study is structured as follows. In the next section we examine the patterns of adoption of wind turbines across and within firms and the industry. In section 3 we develop a model of diffusion and specify the econometric methodology and present preliminary results in section 4. Section 5 concludes the paper with a discussion of potential policy implications and the next steps for the research.

2 Patterns in the adoption of wind turbines

This section is organised in the following way. Data availability on the extent to which firms use a particular technology is notoriously poor, so first the data on which the empirical analysis is based is discussed, and a very brief history of the industry supplying the technology is provided. The focus of this paper is intra firm diffusion, but in order to achieve the second objective it is necessary to calculate the full extent of overall diffusion across the industry; we next present and discuss descriptive statistics on inter firm diffusion. Finally we focus on the intra firm diffusion of WTG.

2.1 Data

There is no compelling reason for firms in most industries to report their technology mix[3] which makes measuring intra firm diffusion very difficult, and probably underlies the paucity of empirical analysis of the topic. However the importance attached to corporate social responsibility and height-

[3]The technology mix is the combination of plant types used in production. For example, 50% nuclear reactors, 30% coal fired power stations and 20% hydro.

ened public and political commitment to measures aimed at tackling climate change, means that electricity generators are keen to publicise their "green" credentials, including, in most cases, their capacity mix by generating technology. The data released into the public domain as a result has enabled the measurement of the intra firm diffusion of a specific low carbon technology, wind turbines. Given the essentially dynamic nature of diffusion, ideally we would wish to observe changes in diffusion over time. However the resources available for data collection were limited, so the example offered by Battisti and Stoneman (2005) and Hollenstein and Woerter (2008) has been followed and we estimate the model on a cross section of data for 2008. This can be regarded as a pilot study.

Firm level data on 40 firms have been collected from their annual reports, websites and through correspondence where necessary. The database includes, for each adopting firm, data on a number of firm specific characteristics for the year ending December 2008, and importantly, the year in which firms that have adopted the technology first reported generating power from WTG. This facilitates both the generation of an inter firm diffusion curve between 1983, the year the first firm in the sample adopted, and 2008, and the intensity with which adopting firms are using the new technology 26 years after its commercial debut.

2.2 Brief history

The WTG industry developed during the 1970s. Vestas, based in Denmark and today one of the world's leading suppliers of wind turbines with a market share of 20%[4], installed their first wind turbine in 1979, though orders procured by a delegation from the EU agricultural machinery industry visiting California in 1982 that secured the emergence of the wind energy industry. Global installed capacity has grown from 100MW to 100,000MW in 2009[5]. European manufacturers took an early lead, developing extensive technical experience, and remain dominant, though the industry is now considered to be global, with Chinese manufacturers Goldwind and Sinovel respectively taking 4% and 5% shares of the global market and Suzlon (India) approximately 9% .

[4]Market shares are for 2008 taken from the Enercon website and based on BTM Consult data

[5] Data from the European Wind Energy Association website

2.3 The sample firms

The sample firms are all generators that are leading firms in their country of origin. By leading firms we mean that they are among the largest five generators in their country of origin (but note that capacities are global capacities of the firm, not in EU member states either individually or in aggregate). This choice of sample is informed by two factors. First, collectively these firms dominate the European power generation sector and second, our interest in Schumpeterian competition, and the ability of firms to shape their long run market environment.

By defining leading firms in this way, we can be fairly confident that no large firms have been omitted. The unit size of WTG is small relative to more traditional generating technologies, which means that total wind farm size may be small[6]. The sample does not include such installations.

Theoretically the sample may consist of five firms for each of the 27 member states, $27 \times 5 = 135$, however both a significant degree of firm multinationality and the small number of generators in many member states leaves a sample of 40 firms.

2.4 Definitions of diffusion

For the sake of clarity we define the measures of diffusion that are used in this study.

Definition 1 ***Overall diffusion*** *is the product of inter firm and intra firm diffusion.*

Definition 2. ***Inter firm diffusion*** *is the cumulative number of adopters, as a proportion of the number of firms in the sample.*

Definition 3. ***Intra firm diffusion*** *is the proportion of an adoper's total global installed capacity accounted for by wind turbines*

Definition 4. *A firm becomes an* ***adopter*** *in the year in which it first reports generating power from wind turbines.*

[6]And indeed there is a multitude of small organisations such as farms and communities that own their own small wind farm consisting of a few turbines

2.5 Inter firm adoption

As the “California wind rush” took off in the 1970s, the first European power generators began to take an interest in the new technology. Vattenfall for example committed R&D funding and installed a 70kW prototype in 1976, followed by a larger 2MW unit in 1984[7]. But it was only in 1995 that the first 20 turbines formed part of the Vattenfall capacity mix. So we classify Vattenfall as an adopter from 1995.

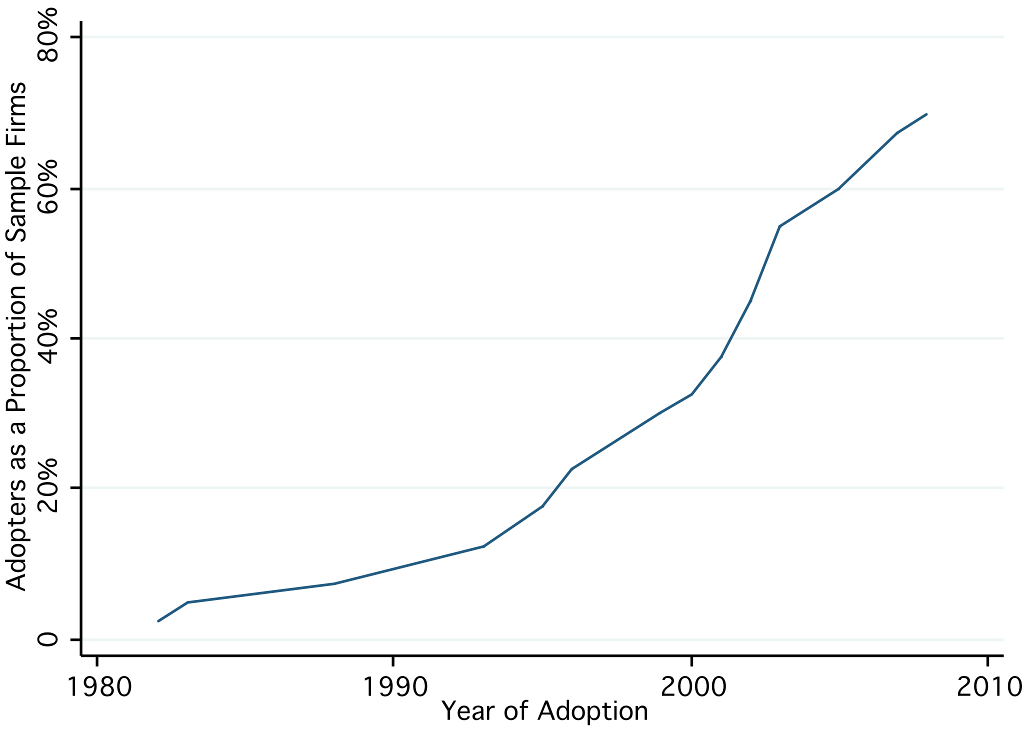

Figure 1: Inter firm adoption of wind turbines

Figure 1 traces out the time path of WTG adoption between the first commercial adoption of the technology (1982) and 2008. By the end of 2008, 26 years after the pioneering firm Nuon (then called PEN) of the Netherlands had adopted WTG, 70% of firms (28) in the sample had reported producing power with the new technology. Twenty years after Nuon adopted, around 50% of the firms in the sample had also done so. By comparison, Battisti and Stoneman (2003) find that 82.4% of firms in the sample had adopted

[7]Source: correspondence with Anders Sjogren at Vattenfall

Table 1: Inter firm diffusion in the United States

Innovation	Years for half potential adopters to acquire
Industrial robots	12
Numerically controlled machine tools	5
Diesel locomotives	9
Centralised traffic control	14
Car retarders	13
Continuous wide strip mill	8
By-product coke oven	15
Continuous annealing	13
Shuttle car	5
Trackeles mobile loader	6
Continuous mining machine	3
Tin container	1
High speed bottle filler	6
Pallet loading machine	5

Source: Mansfield (1989)

computer numerically controlled machine tools (CNC) 22 years after the first firm adopted. And based on data for the USA, Table 1 provides similar information for a variety of process technologies. The time taken for inter firm diffusion of WTG to reach 50% is considerably longer than any of the comparators.

Another way to look at the delay in introducing a new technology is with reference to the number of years firms wait before adoption. The mean number of years waited before adoption is 17 ,and the median 19 years, so the data is approximately symmetrical. 33% of adopting firms waited between 19 and 22 years to do so, as shown in Table 2. Overall, the data suggest that the inter firm adoption of WTG has taken place at an unusually slow pace.

Several factors may contribute to this lengthy delay. Technical factors include the complexity of the technology and hence the scope for post introduction refinements and declining prices, which may induce firms to wait in order to take advantage of expected lower prices in the future and to gain from higher quality information generated by the actual use of the technology. Institutional factors, in particular the increasingly widespread availability of a variety of support mechanisms such as feed in tariffs and green certificate schemes and more generally, the growing public and political commitment to

Table 2: Time firms waited before adopting, from the year the pioneering firm adopted

Years Wait	Number of Firms	Percentage of Adopting Firms
up to 10 Years	5	18
11-14 Years	5	18
15-18 Years	5	18
19-22 Years	9	32
22-26 Years	4	14
Total	28	100

renewable energy sources could be expected to impact all firms equally. For example, all firms wishing to invest in wind capacity in Germany at any given time face the same incentive structure. Therefore while such institutional arrangements cannot explain differences in the speed of adoption among firms, given that schemes vary considerably across member states, firms that do not (or cannot) pursue a multinational strategy, may be constrained by the arrangements in their domestic market.

Additionally, there may be an option value from waiting if the firm expects prices to fall considerably or for example, the introduction of a policy instrument that will alter the relative costs and benefits of adoption(Dixit et al., 1994). Similarly, resource availability may be important if for example the wind resource in a given member state is low and domestic generating firms do not follow a multinational strategy.

The pattern observed in Figure 1 is consistent with the predictions from the literature which suggests that inter firm diffusion follows a logistic curve (Hall, 2004, p.16), and further that typically, complex, expensive process technologies exhibit a cumulative normal curve (Davies, 1979, p.50). Learning affects the expected cost of adoption, which varies between firms, so the post invention period for a complex, expensive technology is characterised by a fairly slow rate of learning during which suppliers improve and refine the technology over time which leads to cost reductions. This is represented by the fairly flat portion of the curve up to about 11 years, after which the curve starts to increase more rapidly and interestingly, the rate of growth continues to rise, though there are possibly the first signs of a decline in the rate of growth at 25 years.

2.6 Intra firm adoption

The degree of intra firm adoption indicates the extent to which firms have substituted WTGs for old technologies. Because capital equipment earns rents in the same way as land, an old technology will remain in use while it earns a positive rent (variable costs are at least covered) but a new technology will be introduced only when the its total costs (fixed and variable) are covered (Salter, 1960, p.65). Assuming a durable technology that is not indivisible, it is therefore to be expected that at any one time firms will use a mixture of old and new technology (the technology mix).

This discussion naturally leads us to consider the saturation level of intra firm diffusion of WTG. Detailed analysis of this question is outside the scope of this study, but in theory there does not seem to be any reason that the capacity mix of any individual firm should not be dominated by WTG, indeed the capacity mix of one firm in our sample, Acciona, is over 95% wind. However given the technical features of existing electricity systems, notably the absolute necessity to remain in balance (supply $\equiv$ demand) at all times and the lack of economically efficient means to store electricity, combined with the intermittency of wind generation, it seems likely that without very significant investment in transmission infrastructure, for example in a "supergrid", system stability would be severely compromised in the unlikely case of 100% intra firm diffusion for all firms. However, Neuhoff (2005) argues that large scale deployment of renewables is feasible, and Sorensen and Meibom (1999) model a scenario where 100% wind power does not threaten system stability.

Of the sample of 40 firms, 28 had adopted WTG by 2008. Following earlier studies, (for example, Battisti et al., 2005), adopters have been categorised into one of three categories; basic users, low users and intensive users as illustrated in Table 2.6. The cut points dividing the categories are $\leq 10\%$ and $\geq 20\%$, and were derived by visual inspection of the data. There is a possibility that a bias is introduced by this *ad hoc* categorisation [8], however the results of the econometric estimation show the cut points to be statistically insignificant (see section 4.2) suggesting that is not the case.

Table 2.6 shows that among adopting firms, 61% were basic users in 2008, and only 11% were intensive users. The average level of intra firm

[8] For a discussion of modeling continuous data as fractional polynomials Royston et al. (see 1999)

Table 3: Intensity of intra firm adoption of WTG by category

	Use	Number of Firms	Percentage of Firms
Intensive	Over 20%	3	0.11
Low	10 - 20%	17	0.61
Basic	0.1 - 1%	8	.28
Total	28	100	

diffusion is only 7%, compared with, for example, 27% for CNC 22 years after its introduction (Battisti and Stoneman, 2003). Given that the WTG was first adopted in 1982, the low proportion of firms using the technology intensively some 25 years later may have important policy implications, which are addressed in Section **??**.

Two of the three adopting firms use that the technology intensively, Acciona and Ibedrola, are based in Spain, and the third, EDP, in Portugal, but are all multinational and have capacity outside their home country. None of the firms was an early adopter, waiting 12, 18 and 16 years respectively as compared to a mean of 17 years, which suggests that the prediction of Mansfield's (1963) model that the intensity of use of a new technology increases with experience, does not hold in this case.

Figures 2 and 3 show two alternative measures of the extent to which firms have adopted WTG in 2008. In Figure 2, intra firm diffusion is measured according to the definition provided in Section 2.4, that is, as the proportion of WTG in a firm's total capacity. We can see that the for the majority of firms, WTG remains a very small proportion of their capacity mix, though interestingly, there appears to be an upper bound (bottom left to top centre) which exhibits the expected logistic shape.

An alternative measure of technology transfer within the firm, the absolute installed capacity (in MW) is the basis for Figure 3 which again exhibits an upper bound of approximately the expected shape. Comparing the two Figures allows us to abstract from the effect of growth in firm size (total capacity in MW). We can see that the outlier at the top of the graphs has achieved a very high intensity of use in around 7 years, which is faster than that implied by Figure 2. This firm has pursued a strategy of early and significant investment in WTG for around 7 years, but subsequently diversified their capacity mix somewhat.

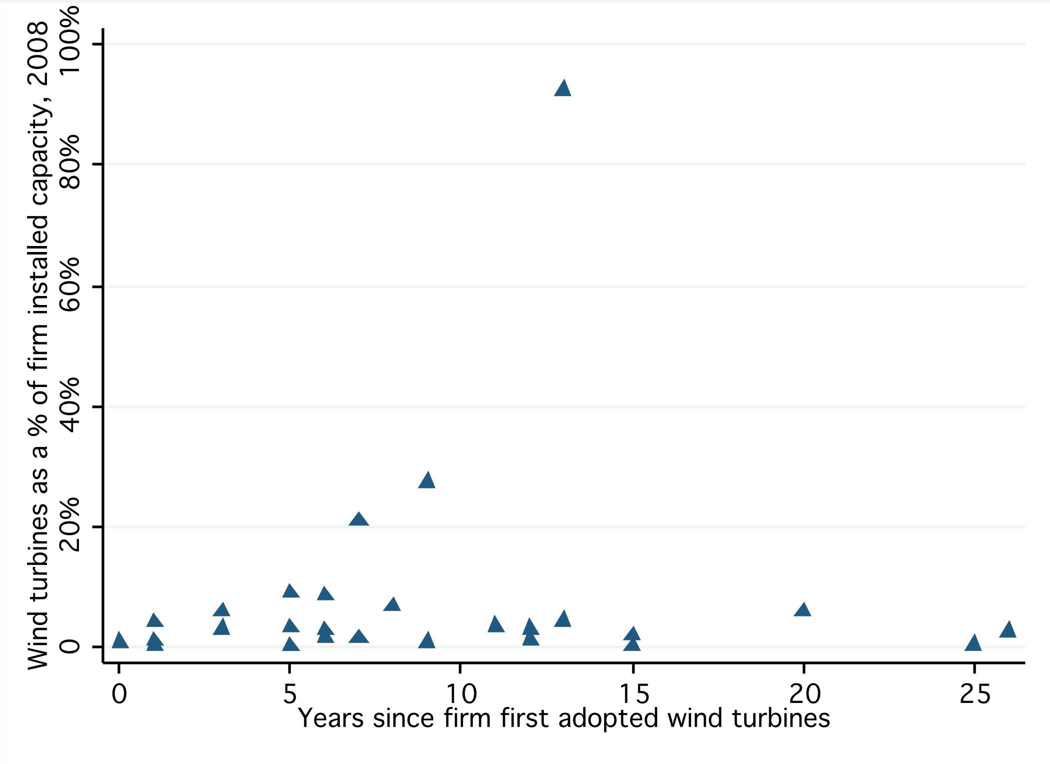

Figure 2: Proportion of wind generation in total installed capacity by years experience, N=28

Comparing the two Figures is instructive. It would appear that there have been two strategies in operation. One group of firms, lying on or around the upper bound, have not adopted the new technology early but rather have waited and then invested heavily in the new technology, that is proportionately more than the firm's average investment for all technologies. The alternative strategy seems to have been to invest in wind approximately in line with the general level of investment in capacity.

2.7 Diffusion across the industry

One objective of this study is to generate a sense of total diffusion of WTG across leading firms in the industry. A useful measure of total diffusion D_t is the proportion of the new technology accounted for in the total industry

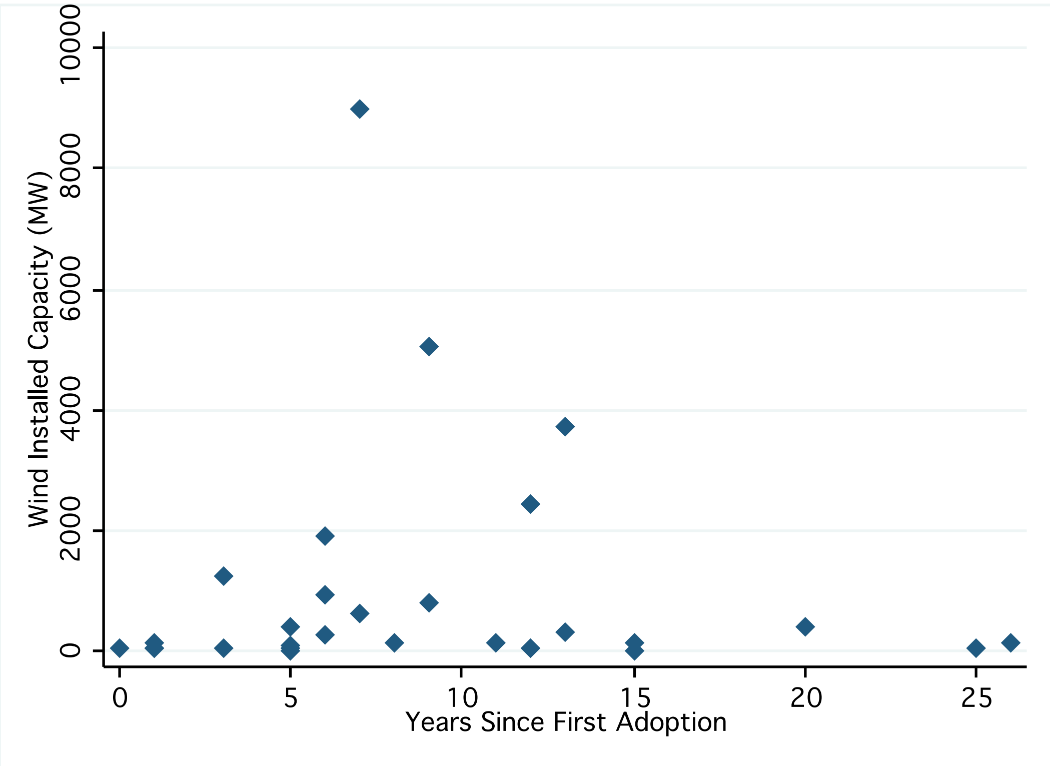

Figure 3: Wind installed capacity (MW) by years experience, N=28

installed capacity

$$D_t = \frac{K_t}{Y_t} \tag{1}$$

if $K_t = \sum_{i=1}^{M} k_{new}$ is the sum of firms' installed capacity of the new technology, and $Y_t = \sum_{i=1}^{N} k_{new} + k_{old}$ is the sum of firms' total installed capacity and where M is the number of adopters and N is the number of potential adopters.

Define average intra firm diffusion as $(K_t/M_t)/(Y_t/N_t)$, the average proportion of the new technology in the installed capacity of adopters, as a proportion of the average industry installed capacity per firm. Then Equation 1 is equivalent to Equation 2

$$D_t = \left(\frac{M_t}{N_t}\right)\left(\frac{K_t/M_t}{Y_t/N_t}\right) \tag{2}$$

From Section 2 we know that inter firm diffusion in 2008 is 70%, and calculate average intra firm diffusion to be 7%. Thus using Eq. 2, D_t for 2008 is $0.70 \times 0.07 = 0.049$. So 26 years after the technology first appeared, it is diffused through leading electricity generators only approximately 5%. It is immediately apparent that reliance only on measures of inter firm diffusion may yield a misleading picture of overall diffusion and supports the proposition that policy interventions based only on inter firm diffusion as likely to fail to achieve their objectives.

3 The Model

The modeling of intra firm diffusion is substantially based on the more developed inter firm models. Epidemic models of inter firm diffusion predict that the extent of use of the new technology will rise with the number of years since its introduction (Mansfield, 1963), primarily due to the spread of information which has the effect of reducing the risk associated with adoption. However, such models have been subject to considerable criticism (see Davies, 1979) More sophisticated treatments of inter firm diffusion have identified firm heterogeneity (Davies, 1979) and the consequential variation in the expected profitability of adoption as important. Other models have identified effects resulting from the accumulated stock of the new technology and first mover advantages (Fudenberg and Tirole, 1985, Reinganum, 1981) as important. These " second generation" models explore firm factors that alter the benefits and costs, or the profitability, of adoption to explain differential rates of diffusion within firms.

Mansfield (1963) first suggested that the same factors that affect the rate at which firms adopt new technologies, and the rate at which they intensify their use of the new technology. In particular, the spread of knowledge over time was thought to drive the diffusion process. Subsequently, Stoneman and Battisti (1997) among others have shown that epidemic models offer at best limited insight into the intra firm diffusion process and recently a limited number of studies have begun to explore the idea in the light of progress made on inter firm diffusion. The empirical analaysis of intra firm diffusion presented here is based on the models proposed by Battisti and Stoneman (2005) and Hollenstein and Woerter (2008) which incorporate insights from the inter firm literature on firm specific effects.

3.1 Econometric model specification

In this section the estimating equation is derived, based on the theoretical and empirical literature.

Dependent variable

The dependent variable is intra firm diffusion as defined in Section 2.4; the proportion of WTG in the firm's total installed capacity, which is obviously a continuous variable. However during the estimating process we experimented with alternative measures, and found superior results by categorising users into one of three groups, basic, low and intensive (see Section 2.6). The intensity of intra firm diffusion is given by

$$INTENSITY_i = k_{inew}/(k_{inew} + k_{iold}) \tag{3}$$

where k_{inew} is the absolute size of the firm i's installed capacity of the new technology and k_{iold} is the their installed capacity of all existing traditional technologies and supressing time subscripts.

Independent variables

The focus is on firm specific explanatory variables.

1. *Firm size*, measured by the firm's total global installed capacity in gigawatts (GW), $SIZE$. Results concerning the influence of size on the intensity of use of a new technology are mixed. Mansfield (1963) and Battisti et al. (2004) find the intensification of use of a new technology to be faster in small firms, but by contrast, Battisti (2009) show that large firms are more likely to use a set of complementary management practices more intensively than small firms. Accordingly, it is not possible to predict the sign of the coefficient *ex ante*.

2. *Capacity mix* represented by $THERMALSHARE$. Salter (1960) argues that when assessing an investment in new capacity the firm will invest in new capacity if $\Pi_i \geq C_{new}$ where C_{new} includes both capital, and operating and maintenance (O&M) costs and $C_{old} < C_{new}$ since C_{old} is O&M costs only; the capital stock has been amortized. This carries at least two implications with respect to diffusion. First, that a

high capital cost of the new technology is a barrier to both inter and intra firm diffusion, and to the extent that we would expect C_{new} to be lower for larger firms due to superior internal resources and for example, potential buyer power (Mansfield, 1963), and we expect this effect to be picked up in $SIZE$. Second, relative factor prices will affect the extent of intra firm adoption. In the specific case considered here, the capital costs of wind are moderate but O&M costs are both low and relatively stable. By contrast, for example gas plant has high and volatile O&M costs but nuclear carries very high capital costs but again low O&M. If we assume that firms are risk averse, then other things being equal, this suggests that those with a capacity mix dominated by a fuel with high and/or volatile marginal costs (gas, coal) will adopt wind technology more intensively than those locked into a mix with low and stable marginal costs (nuclear, hydro). $THERMALSHARE$ is measured by the share of thermal generating technologies in a firm's total capacity mix, and we would expect it to carry a positive sign.

3. *Competitive pressure* in the firm's product markets. The relationship between competitive pressure and innovation has attracted a vast amount of attention, but consensus has not emerged. The Schumpeterian hypothesis holds that perfect competition may not provide the strongest incentives to innovate, which rather requires the stability of a large and perhaps monopolistic firm (Schumpeter, 1994). By contrast, Arrow (1962) showed that divergence from the social optimal level of innovation to be greater under monopoly than competition; leading to the conclusion that competition provides higher incentives to innovate. Competitive pressure is measured by $CR2$, the 2 firm concentration ratio (CR) in the firm's country of origin. Bresnahan and Reiss (1991) show that even without information on prices or costs, it is possible to infer the competitive impact of entry in oligopolistic markets, and that the greatest effect on competition is by the entry of the second and third firms. Several measures of competitive pressure are available and though the simpler measures, for example the CR and Herfindahl Hirschmann Index are imperfect, particularly in electricity markets (Borenstein et al., 1999), they do provide an approximate measure of the relationship between the number of competitors and the degree of competition. More precise methods of calculating the ability of firms to exercise market

power, such as the Residual Supply Index (see) are computationally demanding and data intensive so are outside the scope of this study. The requirement is for an approximate measure of the relationship between the number of competitors and the degree of competition.

4. *Firm multinationality.* If the country of origin of a firm is, for example, relatively resource poor and opportunities for trade are limited[9] then multinationality may offer the firm exposure to better resources. In the present context, the UK has a high wind resource relative to for example, France, so we would expect a firm that owned capacity in both countries to use WTG more intensively than one that was restricted to France. In a sector that was until at least the mid 1990s characterised by vertically integrated monopolies that were either owned by the state or over which the state took a proprietorial interest, multinationality might also proxy institutional flexibility. Due to data restrictions, $MULTINATIONALITY$ is a binary variable, taking the value 1 if the firm is multinational and 0 otherwise. With more resources data for a continuous variable could be collected.

5. *Absorptive capacity* is represented by *R&D*, which captures the proposition that firms which devote resources to innovative activity have an enhanced ability to evaluate, assimilate and apply new information (Cohen and Levinthal, 1989, Zahra and George, 2002). Absorptive capacity is expected to have a positive relationship with diffusion. Numerous empirical studies support this expectation, including in the context of intra firm diffusion (Battisti et al., 2005). Since there are a number of missing values for the share of R%D in total revenue, and the sample size is already rather small (the population is limited), the *R&D* is included as a dummy variable that takes the value 1 if the firm conducts in house R&D in 2007, and 0 otherwise. Previous studies have followed the same strategy and not found it to be restrictive; it is arguably the fact that the firm conducts the innovative activity, not the absolute spend that seems to be important (see for example Battisti and Stoneman, 2005).

6. *Mergers and acquisitions* given by *M&A*. Hitt et al. (1996) argue that the time and resource commitment required to conduct an active acqui-

[9] A lack of infrastructure means that cross border trade in electricity is often severely constrained or impossible.

sition strategy leads to a lack of strategic control and in turn, a direct negative effect on internal innovation. This effect is found to be persistent even when the newly acquired firm is innovative. $M\&A$ takes a value of 1 if the firm made an acquisition in the sector between 2006 and 2007, the lag reflecting the lengthy nature of M&A activity, and is expected to have a negative effect on intra firm diffusion.

7. *Learning* given by $WAITYEARS$. One of the classical barriers to innovation is the inability of firms to fully internalise the benefits from their outlay which then becomes a positive externality for rival firms known as spillover effects (see Griliches, 1992). An alternative way of thinking about spillovers is as inter firm learning. On the other hand, if intra firm learning is important, then the length of time the firm waits before adopting the technology could be expected to reduce the intensity with which the technology is used. It is not possible to disentangle these two effects, however at least the sign on the coefficient will tell us if inter or intra firm learning effects dominate. $WAITYEARS$ is measured by the number of years that the firm waited to adopt the new technology from the time that the pioneering firm adopted it.

4 Econometric methodology and results

Given the very limited data we have on firms at the time they took the adoption decision, we were unable to conduct meaningful econometric analysis of inter firm diffusion. However in Section 2.5 we discussed characteristics of the inter firm diffusion curve, and from there developed a rough measure of the full extent of diffusion (between and within firms) Dt in 2008 in Section 2.7. We now turn to the econometric estimation of intra firm diffusion.

4.1 Modeling intra firm diffusion

Mansfield's (1963) early study of intra firm diffusion has only recently been augmented so the econometric modeling of intra firm diffusion is still under developed. Our empirical strategy involved experimentation with several approaches, including the Heckman two step procedure which has been used by, for example Battisti and Stoneman (2005) and Hollenstein and Woerter

(2008). We report estimates from fitting an ordered probit model, which accounts for the ordinal nature of the dependent variable Greene (2008, p.831), largely on the basis of results and test statistics. The estimating equation is given by Eq. 4

$$INTENSITY_{it} = f(SIZE_{it}CR2itMNAT_{it}M\&A_{it-1}R\&D_{it}WAITYEARS_{it}) \tag{4}$$

4.2 Results

The empirical results are presented in Table 4.2. Three models were estimated on the sample of 28 firms that had adopted the technology before the end of 2008. Variable selection was made on the basis of a general to specific approach, and variables were omitted on the basis of their significance. The goodness of fit indicated by Pseudo R2 values of between .321 and .318 suggest that the overall significance of the models is satisfactory. The AIC criteria suggest that the more parsimonious model (3) offers the best fit to the data. The hypothesis that firm specific characteristics are important in the analysis of diffusion is confirmed.

4.3 Assessment

As predicted, the coefficient on firm multinationality is both positive and significant at the 5% level in all three models, which suggests that firms with a higher proportion of their total capacity as wind are more likely to be multinational than those with low values for intra firm diffusion.

The CR2 in the firm's home member state carries a negative and significant coefficient in all three models, indicating an inverse relationship between the degree of intra firm diffusion and the share of total capacity held by the largest two firms. In other words, firms with high levels of intra firm diffusion originate from member states where the share of the largest two firms is low. This result provides some evidence for the hypothesis that competition, or at least the absence of monopoly, is conducive to innovation, specifically the intensification of adoption of a new technology. If increasing investment in new technologies is considered a strategic decision designed to confer long run competitive advantage as we argued in Section 1, then this also supports

Table 4: Results of fitting ordered probit model of intra firm diffusion: Dependent variable, intensity of intra firm adoption (basic, low, intense)

	(1)	(2)	(3)
SIZE (GW)	-0.516	-0.432	-0.346
	(0.445)	(0.489)	(0.496)
CR2	-3.186	-3.090	-3.069
	(0.015)*	(0.014)*	(0.015)*
MNAT	1.748	1.815	1.840
	(0.037)*	(0.025)*	(0.023)*
WAITYEARS	-0.0417	-0.0398	-0.0379
	(0.330)	(0.347)	(0.358)
R&D	0.107	0.155	
	(0.873)	(0.812)	
M&A	0.110		
	(0.739)		
N	28	28	28
pseudo R^2	0.321	0.319	0.318
AIC	50.22	48.33	46.39

p-values in parentheses

* $p < 0.05$

Bresnahan and Reiss' (1991) theory that the second (and third) entrant have the strongest influence on the competitive landscape.

The coefficient on size is negative but not statistically significant. The existing literature considering the relationship between firm size and intra firm diffusion is scant and ambiguous in its predictions. Battisti and Stoneman (2005) find size to have a positive and significant effect on intra firm diffusion of CNC, and Hollenstein and Woerter (2008) a positive but statistically insignificant effect on the intensity with which firms engage in e-selling. Considering the intra firm diffusion of ICT in the UK and Switzerland, Battisti et al. (2005) report a positive relationship for Switzerland, and a negative one for the UK, though neither is significant. This study provides no evidence that firm size has any influence on the expected intensity with which firms invest in the new technology.

Previous studies have found R&D to exhibit a positive and significant relationship with intra firm diffusion (see Battisti, 2008), a result that is not supported by the findings of the present study. We have data for the R&D share of 26 of the 28 firms, so tested the model substituting a continuous measure of R&D, but found almost no effect on the results, so in order to preserve the full number of observations, we report results where R&D enters as a binary variable. The usual explanation for a positive relation is that firms that conduct in house R&D are more easily able to endogenise the benefits of new knowledge. It may well be that for the technology under consideration, wind turbines, a more relevant measure of the ability of the firm to assimilate the new technology is, for example, the size of the in house engineering department.

Finally, the term $WAITYEARS$ was included to capture the effect of knowledge spreading over time on the transfer of technology over time. The variable is not statistically significant which confirms the earlier discussion (see Section 2.5) the kind of epidemic effects hypothesised by Mansfield (1963) to intensify intra firm use of a new technology, and found to be important in several studies including, for example Hollenstein and Woerter (2008), are not supported by this study. We interpret this result with reference to the technological characteristics of wind turbines, which are highly complex and significantly site-specific, suggesting that experience and knowledge built up within the firm is of little use in diminishing the barriers to transferring the technology within the firm, and that for the same reason firms are unable to capture the spillovers generated by other firms using the technology.

5 Interim conclusions and next steps

The overall diffusion of a new technology is a function of both inter and intra firm diffusion, both of which are considered in this study.

Intra firm diffusion was tested empirically by fitting an estimating equation derived largely from the theoretical and empirical literature on a specially collected cross section of firm specific data for 2008. The econometric results are largely, but not completely, consistent with the scant existing literature. There are two particularly important results. First, firm multinationality was found to be statistically significant and positively related to the degree of intra firm diffusion. We interpret this as reflecting the improved opportunities for technology transfer within the firm afforded by opportunities to develop sites with high wind resource. The technical barriers to transporting electricity across national borders is effectively overcome in the multinational enterprise. We are not aware of any other study in the intra firm literature that considers this firm characteristic. This is an interesting result that supports the EU drive for a single European market in electricity and may motivate the building of more cross border capacity. It may have implications for EU merger policy.

The second key econometric result is that the level of competition in the adopting firm's home member state is negatively related to intra firm diffusion, which provides support for the theory that competition, or more precisely, the absence of monopoly, is more conducive to innovation, specifically, the degree to which firms intensify their use of a new technology given that they adopt it in the first place. Again this result supports the policy of introducing competition at the generation level, and illustrates the dynamic benefits of the competitive process.

A further interesting finding that we intend to investigate further was that firms appear to have followed one of two strategies with respect to investing in wind capacity. The first, a minority, have waited until fairly late in the diffusion process to adopt, then have invested in wind proportionately more than other firms in the sector. The second larger group may have a low proportion of wind capacity even many years after first adopting the technology, and the rate of growth of wind in their overall capacity mix has remained approximately constant.

Empirical analysis of the rate of inter firm diffusion of wind turbine generators was based largely on descriptive statistics, since data to conduct econometric analysis was unavailable. However a fairly detailed picture was built up and compared with data for other technologies. It took 26 years for 70% of firms to adopt WTG, which is easily the slowest among the technologies considered. The rate of adoption during the first 11 years was particularly slow. We interpret this as reflecting the technical complexity of the WTG and the relatively high extent of site specificity in production, so that costs declined only slowly and potential adopting firms found it difficult to internalise the information generated as use of the technology spread. The more recent acceleration in the rate of adoption is likely to have been significantly affected by the proliferation of policy instruments aimed at mitigating greenhouse gas emissions, and the increasing multinationality of firms which has opened up new possibilities for investment in WTG in resource rich areas. It may also argue for measures to support learning in the early stages of the commercialisation of a complex technology such that the initial phase may be speeded up. The downside of that would be the problem of "picking winners".

A final result of interest is the decomposition of overall diffusion into its component parts. While some 70% of firms was generating power from wind turbines in 2008, and a small number of firms are using the technology extensively, intra firm diffusion remains stubbornly low for the majority of firms in the sample which drags the mean level down to only 7%. The separate analysis of inter and intra firm diffusion is supported, in particular if the analysis of diffusion is to be the basis of costly policy interventions.

There are two main shortcomings of the study, both of which relate to the empirical analysis. First, the data available was limited to a cross section, though it is obvious that a much fuller understanding of the inherently dynamic nature of the diffusion process would be permitted using panel data. This would also alleviate the problems associated with small sample sizes, which is inevitable in this case because the population itself is small. The second concerns the econometric methodology. As discussed, econometric studies of intra firm diffusion are rare, and have adopted several different econometric approaches and there remains a good deal of scope for experimenting with alternative strategies.

The next steps in the research follow from the previous points. Further data will be collected to create a panel on which to test intra firm diffusion, though this is not likely to be achieved in the short term. We will immediately explore the econometric specification, in particular with alternatives that permit the modeling of intra firm diffusion as a continuous variable and undertake detailed testing of the model and analysis of the results.

Bibliography

Predicting market power in wholesale electricity markets.

Arrow, K. (1962). Economic welfare and the allocation of resources for invention. In R.Nelson, editor, *The rate and direction of inventive activity.* Princeton University Press, Princeton,MJ.

Battisti, G. (2008). Innovations and the economics of new technology spreading within and across users: gaps and way forward. *Journal of Cleaner Production*, 16(1S1):22–31.

Battisti, G., Canepa, A., and Stoneman, P. (2004). Profitability, externalities and policy in the inter and intra firm adoption of new technology: The example of e-business activities in the uk. In *th Conference of the European Network on Industrial Policy (EUNIP), Birmingham*, pages 13–15.

Battisti, G., Hollenstein, H., Stoneman, P., and Wőrter, M. (2005). Inter and Intra Firm Diffusion of ICT in the United Kingdom and Switzerland. *Swiss Institute for Business Cycle Research Working Paper*.

Battisti, G., Hollenstein, H., Stoneman, P., and W
"orter, M. (2005). Inter and intra firm diffusion of ICT in the United Kingdom (UK) and Switzerland. Technical report, Working Paper nÂ 111, Swiss Institute for Business Cycle Research.

Battisti, G. and Stoneman, P. (2003). Inter-and intra-firm effects in the diffusion of new process technology. *Research Policy*, 32(9):1641–1655.

Battisti, G. and Stoneman, P. (2005). The intra-firm diffusion of new process technologies. *International Journal of Industrial Organization*, 23(1-2):1–22.

Battisti, G., I. A. (2009). The intra-firm diffusion of complementary innovations: Evidence from the adoption of management practices by british establishments. *Research Policy*, 38(8):1326–1339.

Borenstein, S., Bushnell, J., and Knittel, C. (1999). Market power in electricity markets: beyond concentration measures. *The Energy Journal*, 20:65–88.

Bresnahan, T. and Reiss, P. (1991). Entry and competition in concentrated markets. *Journal of Political Economy*, pages 977–1009.

Cohen, W. and Levinthal, D. (1989). Innovation and learning: the two faces of R & D. *The Economic Journal*, pages 569–596.

Davies, S. (1979). *The diffusion of process innovations.* Cambridge University Press, Cambridge.

Diaz-Rainey, I. (2009). Modelling international wind energy adoption: Are the patterns of induced diffusion s-shaped? Mimeo, University of East Anglia.

Dixit, A. K., Pindyck, R. S., and Davis, G. A. (1994,). *Investment under uncertainty*. Princeton University Press Princeton, NJ.

Fudenberg, D. and Tirole, J. (1985). Preemption and rent equalization in the adoption of new technology. *The Review of Economic Studies*, pages 383–401.

Geroski, P. A. (2000). Models of technology diffusion. *Research Policy*, 29(4-5):603–625.

Gilbert, R. (2006). Looking for Mr. Schumpeter: Where Are We in the Competition-Innovation Debate?

Greene, W. (2008). *Econometric analysis*. Prentice Hall Upper Saddle River, NJ, 6th edition.

Griliches, Z. (1957). Hybrid Corn: An Exploration in the Economics of Technological Change. *Econometrica*, 25(4):501–522.

Griliches, Z. (1992). The search for R&D spillovers. *The Scandinavian Journal of Economics*, 94:29–47.

Hall, B. (2004). Innovation and diffusion. *NBER Working Paper*.

Hitt, M., Hoskisson, R., Johnson, R., and Moesel, D. (1996). The market for corporate control and firm innovation. *Academy of Management Journal*, pages 1084–1119.

Hollenstein, H. and Woerter, M. (2008). Inter-and intra-firm diffusion of technology: The example of e-commerce an analysis based on swiss firm-level data. *Research Policy*, 37(3):545–564.

Mansfield, E. (1963). Intrafirm rates of diffusion of an innovation. *The Review of Economics and Statistics*, pages 348–359.

Mansfield, E. (1963). The speed of response of firms to new techniques. *The Quarterly Journal of Economics*, pages 290–311.

Mansfield, E. (1989). The diffusion of industrial robots in Japan and the United States. *Research Policy*, 18(4):183–92.

Neuhoff, K. (2005). Large-scale deployment of renewables for electricity generation. *Oxford Review of Economic Policy*, 21(1):88–110.

Porter, M. (1996). What is strategy? *Harvard Business Review*, 74:61–78.

PricewaterhouseCoopers (2009). A world beyond recession; utilities global survey 2009. Technical report, PricewaterhouseCoopers.

Reinganum, J. (1981). Market structure and the diffusion of new technology. *The Bell Journal of Economics*, pages 618–624.

Romer, P. M. (1990). Endogenous technological change. *Journal of political Economy*, 98(S5):71.

Royston, P., Ambler, G., and Sauerbrei, W. (1999). The use of fractional polynomials to model continuous risk variables in epidemiology. *Int. J. Epidemiol.*, 28(5):964–974.

Salter, W. (1960). *Productivity and technological change*. Cambridge University Press, Cambridge.

Schmookler, J. (1966). *Invention and economic growth*. Harvard University Press, Cambridge.

Schumpeter, J. (1994). *Capitalism, socialism and democracy*. Routledge.

Sidak, J. and Teece, D. Favouring dynamic competition over static competition: a neo-schumpeterian approach to advancing innovation through antitrust and merger law. Mimeo, Tilburg University.

Sorensen, B. and Meibom, P. (1999). Can wind power be sold in a deregulated electricity market? In *1999 European Wind Energy Conference: wind energy for the next millennium: proceedings of the European Wind Energy Conference, Nice, France, 1-5 March 1999*, page 375. Earthscan/James & James.

Stoneman, P. and Battisti, G. (1997). Intra-firm diffusion of new technologies: the neglected part of technology transfer. *International Journal of Industrial Engineering*, 4:270–283.

Zahra, S. and George, G. (2002). Absorptive capacity: A review, reconceptualization, and extension. *Academy of Management Review*, pages 185–203.