GREEN SUBSIDIES AND LEARNING-BY-DOING IN THE WINDMILL INDUSTRY

by

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Abstract: This paper examines the remarkable learning-by-doing in the windmill industry since it emerged in the beginning of the 1980's. Green subsidies for producing electricity by wind power has been a precondition for the rapid growth in the production of windmills. Based on time series of prices of windmills a dynamic cost function for producing windmills is tested. The cost disadvantage of producing electricity by windmills relative to traditional power stations has narrowed considerably because of a strong learning-by-doing effect. The deliberate policy to subsidize production of electricity by windpower has placed Denmark in a first-mover position in this market and the future has to show whether this is a successful story of an infant industrial policy.

Key words: Learning-by-doing, infant industry, green subsidies
JEL Classification: D2, L5, L6

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1. Introduction

The windmill industry has grown rapidly during the 1990s. Calculated on the basis of the productive capacity of the installed windmills, the production has increased more than ten-fold. Since the 1980s, the Danish windmill producers got a leader position in this new industry which is illustrated by the impressive fact that the Danish producers at present satisfy around half the world demand for windmills. This rapid growth in production has triggered a considerable improvements in productivity and hence a substantial fall in the costs of producing electricity by windmills.

The reason for this spectacular development of the windmill industry is the endeavours at the political level of increasing the production of electricity from renewable energy sources. Since the early 1980s, production of electricity from windmills has been stimulated by various environmental policy motivated state aid schemes among which the most important has been a price guarantee per produced kWh (kilowatt-hour) to the producers of wind energy, i.e. the windmill owners (Morthorst, 1999). Without these subsidies, windmills as suppliers of electricity would not have been competitive compared to traditional power plants and hence the producers of windmills would not have got foothold in the Danish industry. This is also illustrated by the development in demand where nearly all windmills produced in the pioneering years in the 80's were sold domestically whereas exports made up a substantial part of sales in the 90's.

Though public subsidies to production of windpower have been legitimated by environmental objectives, the subsidies have resulted in the development of an industry with an increasing export performance. The development of the windmill industry thus illustrates an infant industry strategy where state aid in the upstart phase builds up an internationally competitive industry in the longer run. A precondition for a successful outcome of such strategy is the existence of learning-by-doing within the industry in order to overcome the infant cost. The paper therefore looks for evidence of experience cumulation in the period studied. The purpose of the paper is to test the dynamic cost function in the windmill industry and discuss the welfare implications of the strategy chosen by the Danish government to subsidize production of electricity through windmills.

The paper is organised as follows. Section 2 looks at the earlier industrial studies of learning-by-doing, Section 3 introduces the available data used and Section 4 presents the evidence of learning-by-doing in the Danish windmill industry. Section 5 gives an evaluation of cost and benefit from an infant industry perspective and section 6 concludes the paper.

2. Previous results on learning-by-doing

Learning-by-doing is demonstrated in the pioneer work of Wright (1936) who studied the development in labour productivity in the US airframe industry. Wright shows that the number of man hours required to produce an aeroplane body declines with the cumulative number of aeroplanes produced. An early theoretical contribution to the learning-by-doing hypothesis is given in Arrow (1962) who incorporates learning effects associated with cumulative investments into a macroeconomic growth model. Later on, dynamic scale economies have been analysed in large number of empirical and theoretical analyses. Recent empirical contributions are given by a.o. Zimmerman (1982), Irwin and Klenow (1994) and Benkard (1999). Of the theoretical contributions may be mentioned Dasgupta and Stiglitz (1988), who investigate for the implications of learning-by-doing on the market structure, Lucas (1988, 1993), Stokey (1988) and Young (1991, 1993) who continue the Arrow tradition of including learning-by-doing in macroeconomic growth models.

It is the firm or the plant that generates experience through its day-to-day operations. This learning effect may be internal and external. If the firm for example is capable of keeping all knowledge about production for itself then the learning effect is a pure internal process (internal dynamic scale economies). In this case the dynamic marginal cost including the value of the future cost reduction will be less than the static marginal cost and hence, the profit maximizing firm will expand production above the point where marginal revenue equals marginal static cost. As the dynamic externality in this case is appropriated by the firm itself, internal dynamic scale economies influence the strategic behaviour at the firm level and the long-term market structure at the industry level (see e.g. Dasgupta and Stiglitz, 1988).

In case of knowledge spillovers between firms, e.g. through labour turnover, the learning process reflect external dynamic scale economies. In the special case where there is a large number of firms and diffusion of knowledge between firms in the same industry is perfect, the level of production in the individual firm has only a negligible impact on total learning. What matters in this case is total production in the industry i.e. the dynamic scale economies are external and hence at the firm level static and dynamic marginal costs coincides.

However, the industry-specific learning creates an external benefit among the firms and the invisible hand of the market thus leads to an under provision of output from a social point of view. To eliminate this inefficiency, a subsidy to the production in the industry may be justified. In an open economy a subsidy may be even more attractive as a country can reap first-mover advantages when the comparative advantage depends on production in the past through a learning process. Infant industry strategies are thus often based on the precondition of industry-specific learning (see e.g. Krugman, 1987). In the macroeconomic growth literature, it is often assumed that productivity growth is a function of total activity in the economy, i.e. learning effects are country-specific (see e.g. Lucas 1988 and 1993).

The relation between the production costs and the cumulative production is usually specified by the following dynamic cost function:

$$c_t = \alpha Q_{t-1}^{\beta} \quad ; \ \alpha > 0, \ \ \beta > 0 \qquad (1)$$

where c_t is the production costs per unit of output in period t, Q_{t-1} is the lagged cumulative output, α a scale parameter illustrating the unit costs of producing the first unit and β a parameter for the learning elasticity i.e. the percentage decrease in unit cost by one percentage increase in lagged cumulative output. Empirical analysis often includes several other explanatory variables in the cost function such as capacity utilization (internal static scale economies), number of product generations and time (exogenously given technological progress). The studies usually report a high R^2. Table 1 lists the main results of the estimated learning parameter in earlier industry studies. Beside the estimated learning parameter β, the learning rate is often reported i.e. the percentage decline in unit production costs in case of a doubling of production, see the last column of the table.

The estimated learning parameter (measured by elasticity or rate) varies quite a lot between the different studies. The reported learning elasticities for all studies fall in the range from -0.06 to -0.44. One reason for this variation is the different estimation methods used in the studies. Over time new technologies reduce the unit costs and controlling for this effect by introducing a time trend in the regression, reduce the learning parameter. Also the advantages of scale economies reduce unit costs and this effect is normally controlled for by introducing the size of the yearly production in the regression. The studies controlling for this effects has a lower estimate of the learning elasticity.

Table 1. Industry studies of learning-by-doing

Industry	Author	Dep. variable	Control for		Learning	
			scale	time	elasticity	rate, %[1)]
US Aircraft	Wright, 1936	# labour hours	NO	NO	-0.32	20
	Mishina, 1999	# labour hours	YES	YES	-0.29	18
	Benkard, 1999	# labour hours	YES	NO	-0.29	18
Global Semi-conductor	Webbink, 1977[2)]	Selling price	NO	NO	-0.4	24
	Gruber,1992	Selling price	YES	YES	-0.15	10
	Irwin and Klenow, 1994	Selling price	NO	YES	-0.32	20
US Chemicals	Liberman, 1984	Selling price	YES	YES	-0.18[3)] -0.44[4)]	12 26
EU Electricity Technology	Williams and Terzian, 1993[5)]	Selling price	NO	NO	-0.29	18
	Neij, 1999[5)]	Selling price	NO	NO	-0.06	4

Notes: 1) The learning rate expresses the relative decline in production costs with a doubling of the cumulative production calculated as $1\text{-}2^{\beta}$. 2) The study is quoted in Irwin and Klenow, 1994. 3) Inorganic products. 4) Synthetic fibers. 5) The study is quoted in OECD/IEA,2000.

The studies from the aircraft industry are all based on plant-level data and measure the development in costs with the development in unit direct labour cost of output. The studies within the other industries (semiconductor, chemicals and electricity) are based on firms within the industry and use the average selling price within the industry as a proxy for unit costs of production. Available studies on electricity production (including windmills) as shown in the last two rows of table 1 are based on very aggregate data with a short time series. Accordingly the aviable estimates on learning-by-doing in this industry are quite suggestive.

Besides these industrial studies, Bahk and Gort (1993) examine new firm startup for a sample of 2150 new firms or plants in 41 industries. They decompose the internal learning in the plants into organization learning, capital learning and manual task learning, and they find that organizational learning appears to continue over a period of at least 10 years following the birth of a plant while capital learning disappears after 5 to 6 years. They also incorporate the industry wide learning in their study, but it seems to be connected to the technological development as the effect disappears when they control for embodied technical changes in the capital stock.

3. The data

The primary political objective of producing windmills is to increase the supply of electricity from renewable sources. This goal arose as a response to the first energy crisis in the beginning of the 1970s. But first from the late 1970s an actual market for windmills emerged making a larger scale of production possible. The data used in this study has been obtained from the Danish Wind Turbine Manufacturers' Association in Copenhagen and from EM Data in Aalborg. The Danish Wind Turbine Manufacturers' Association yearly publishes data for production and sales of Danish windmills in "Windpower Note" whereas EM Data conducts a survey among Danish windmill investors collecting information on investment expenditure and first year production.

Table 2 illustrates the yearly production of windmills since 1983 in Denmark measured either by the number of produced windmills or by total effect measured in MW (megawatt). The effect in MW measures the capacity defined as the produced quantity of electricity per hour under circumstances of optimal wind. At very low wind speeds, the windmill goes out of production and also at high wind speeds, production is discontinued to protect the mill from breakdown. Hence optimal wind conditions exist for an interval of wind speed where the windmill produces at its maximum effect[1]. Measured by effect, the annual production of windmills has increased from 117 MW in 1984 to 1900 MW in 1999. The average effect of a windmill has increased from 31 kW in 1983 to 698 kW for windmills sold in 1998. This fact point at a trend in the underlying technologies with production of windmills with larger effect (production capacity).

Beside these annual data, this study also has access to a micro data set with investment and production information for a sample of 833 new windmill installments. The sample is conducted by EM Data in Aalborg in the period from 1980 to 1999, and it is a representative sample of prices of new windmills in Denmark. The last column in Table 2 lists the average real price, i.e. investment expenditure on the purchase of a windmill, quoted in kW. It appears from the table that price per unit capacity has fallen to below half the price per unit capacity of a mill purchased back in 1981.

[1] The technology has improved during the investigation period so that the interval of the optimal wind has increased. Hence, for given effect new vintages of windmills produce more electricity during a year compared with older vintages for given conditions of wind

Table 2. Production, effect and prices for Danish windmills, 1983 - 1998

Year	No. of mills	Effect in MW	Effect per mill in kW	Price per mill in DKK/kW, 1980 prices
1983	1279	40	31	6846
1984	1694	117	69	6287
1985	3812	243	64	5598
1986	2246	212	94	5176
1987	767	88	115	4845
1988	597	102	171	3978
1989	754	136	180	4082
1990	723	162	224	4323
1991	778	166	213	4482
1992	712	165	232	4343
1993	689	210	305	4142
1994	1144	368	322	3882
1995	1530	574	375	3369
1996	1360	726	534	3433
1997	1644	968	585	3328
1998	1742	1216	698	3191

Source: Danish Wind Turbine Manufacturers' Association (1999): "Danish wind energy 4th quarter 1998", *Windpower Note*, no. 22, April 1999. EM Data, Aalborg.

Note: Calculations in fixed prices are based on the deflator for gross factor income for the period 1983-93 and gross domestic product for 1993-98.

This substantial fall in the price has brought the Danish producers of windmills at the forefront of the competitive edge with first-mover advantages. The export share of the industry is well above 75% for most of the years and this gives the Danish producers a dominant position at the world market. For 1998, the total worldwide installing capacity was 2,597 MW which gives the Danish windmill industry a world market share of around 50% according to BTM (2000) report.

The owner of a windmill also incurs operating costs during the years when the windmill produces electricity. For the evaluation of the recurrent costs over the life cycle of a windmill, another sample of 194 mills has been made available from EM Data. The sample is collected in

1999 and gives information of capacity and age of mills as well as average recurrent costs relative to expected yearly production of electricity. These data allow for estimation of the parameters of cost function showing recurrent costs as a function of capacity and age.

4. Estimation of the learning effects

The following empirical analysis estimates the total learning effect at the industry-level no matter whether it is a result of firm-specific learning or a result of knowledge spillovers between the firms. We therefore explain the experience accumulation in the industry by the total cumulative production in the industry. However, the average effect per mill increases during the investigated period and it is an open question whether learning-by-doing is triggered by production of windmill capacity (Q) or by the number of windmills (N) . We leave it to the estimation to judge between the two alternative explanatory variables for learning. Since no data is available on the unit costs of producing windmills, the price of the mill is used as a proxy for the unit costs.[2] Implicitly it is therefore assumed that the price-cost margin is either constant or at least does not change according to a specific trend during the period of investigation. More exactly, the price is specified as the real investment expenditure on the purchase of the mill.

An aggregate time-series model

We estimate the learning model on the aggregate time-series data in Table 1 and use the following logarithmic transformation of the learning model in equation (1):

$$\ln P_t = \ln \alpha + \beta \ln Q_{t-1} + \lambda_t + \varepsilon_t \qquad (2)$$

where t is the time period, P_t is the average windmill price per kW in fixed prices, Q_{t-1} is the accumulated experience measured by cumulative production in effects up to the last period (t-1), λ_t is a time trend to capture the exogenously given productivity growth rate and ε_t is a random, normally distributed error term. The estimation also uses the alternative proxy for experience accumulation: the number of windmills produced (N).

Table 3 shows the estimation results. The estimated parameter for the learning elasticity has the expected sign and is significant no matter the specification of the model. The technology has

[2] It is quite common to use the price as a proxy for unit costs, e.g. when estimating learning curves in other industries. See for example Gruber (1992) and Irwin and Klenow (1994) for estimations of learning curves in the semiconductor industry.

changed considerably over the period mostly because of a more than tenfold increase in the average size of the installed windmills. The learning elasticity therefore increases from -0.15 to -0.23 when we measure cumulative production at the industry level with number of wind mills instead of their capacity, compare model 1 and 3.

Table 3. Aggregate time-series estimates of the learning effect, 1983 - 1998

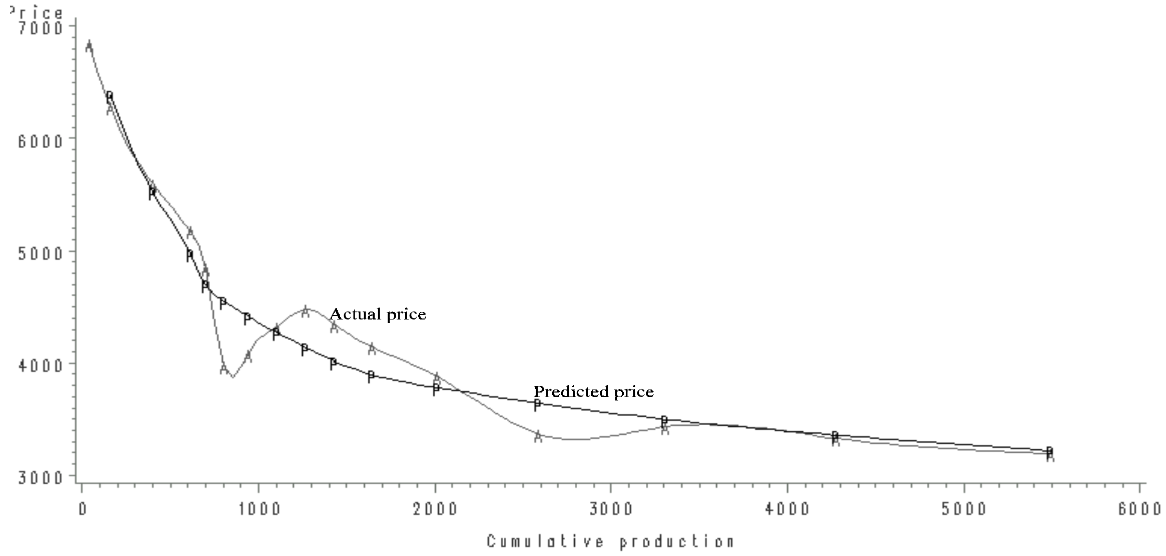
	Dependent variable: ln P_t			
	Model (1)	Model (2)	Model (3)	Model (4)
Intercept	9.39 (86.50)	10.60 (15.71)	10.58 (34.62)	11.69 (30.11)
ln $Q_{t-1,}$ Cumm. production	-0.15 (9.77)	-0.09 (2.55)		
ln N_{t-1} Cumm. production			-0.24 (7.33)	-0.11 (2.47)
λ_t, time trend		-0.02 (1.80)		-0.02 (3.50)
R^2	0.87	0.89	0.79	0.89
Observations	15	15	15	15

Notes: Numbers in brackets are t-values

The estimated models 2 and 4 in Table 3 further control for the exogenously time-dependent increase in productivity by introducing a time trend. The time-dependent growth in productivity is significant and 2% per year. However, the learning elasticity is reduced considerably to a level of -0.1, although it is still significant.

Figure 1 illustrates the development in actual and estimated average windmill price per kW along the cumulative production measured in installed capacity. The estimated price model (2) fits the actual decline in the average price of a windmill in this period very well and a learning-by-doing hypothesis is therefore consistent with the illustrated evidence. The figure therefore reveal the importance of the learning-by-doing effect in explaining the price decline.

Figure 1. Actual and estimated price levels against cumulative production of mills



A panel data model

The development of still larger windmills is an integrated part of the observed productivity improvements, and the fall in price per kW might thus be caused both by process innovation (productivity improvements in the production of a given type of windmill) and product innovation (production of new, larger and more efficient mills). To separate these two determinants of the price development, the learning effect is estimated on the representative sample of individual windmill projects where it is possible to take into consideration how either type of technological innovation has affected the historical development of the price of a windmill.

The panel model is estimated with the following logarithmic transformation of an expanded version of equation 1:

$$\begin{aligned} \ln I_{i,t} = \ln \alpha + \beta \ln N_{t-1} + \delta \ln E_{i,t} + \gamma \ln A_{i,t} \\ + \phi_j F_j + \lambda_t + \varepsilon_{i,t} \end{aligned} \qquad (3)$$

where $I_{i,t}$ is the total price or investment expenditure for windmills in project *i* delivered in period *t*, N_{t-1} is the accumulated experience, $E_{i,t}$ denotes the installed effects of windmills in project *i*, $A_{i,t}$ is the number of windmills in project *i* (note that for most observations A=1). The investment expenditure on a windmill is expected to rise less than proportional with the size of the mill since windmills with larger effect reflect better technology, i.e. $0<\delta<1$. Also, the investment expenditure is expected to rise less than proportional with the number of mills in the park since it is reasonable to expect that a discount is given when several mills are purchased at the same time, i.e. $0<\gamma<1$. F_j are dummies for the largest manufacturers of windmills correcting for heterogeneity among the producers, λ_t is a time trend to capture the exogenously given productivity growth rate and $\varepsilon_{i,t}$ is a random, normally distributed error term.

Results for this extended model are reported in Table 4. The dependent variable now expresses the total price of the windmill no matter its size and we therefore correct for differences in technology (mill capacity) in the models. The capacity variable (E) is very significant in all three models with a coefficient around 0.8, implying as expected that the price of a mill increases less than proportional to the size of the mill. Also the coefficient to the number of mills purchased per project (A) is very significant and stable across the different models. The coefficient of 0.95 suggests a 5% price discount when the purchases of windmills are doubled.

In these models, the size of the industrial learning-by-doing effect is estimated on the cumulative number of windmills produced and the effect is significant in models (1) and (2) with an estimated coefficient of exactly the same magnitude as in the time-series model above, where a 1% increase in the cumulative production of windmills reduces the price with 0.1%. Model (2) is a fixed-effect model that tests for heterogeneity among the largest manufacturers in their price-setting behaviour. The results suggest that in general the 4 largest manufacturers are marketing their windmills at lower prices than the small producers. Especially, the prices of windmills from Bonus and Micon are significantly under average prices at the market with a discount of 8% and 11% accordingly.

The last mentioned results may reflect that learning varies over manufacturers and that large manufacturers are able to reap more benefits from internal and external dynamic scale economies than small producers on the Danish market. Almost 3/4 of the windmills sold in Denmark come from the 4 largest Danish manufacturers, and this high level of concentration may reflect that the learning effect is internalized more strongly among these 4 producers. In model (3) of Table 4 we therefore proceed the estimation but with individual slopes for each of the 4 largest manufacturers concerning the learning effect.

Table 4. Panel estimation of the learning effect, 1983 - 1998

	Dependent variable: ln I_t		
	Model (1)	Model (2)	Model (3)
Intercept	9.08 (47.36)	9.06 (48.03)	8.86 (32.10)
ln N_{t-1}, cumm. production	-0.10 (4.36)	-0.11 (4.80)	-0.06 (1.87)
ln E, mill capacity	0.77 (56.81)	0.79 (56.25)	0.80 (57.26)
ln A, # of mills purchased	0.96 (35.06)	0.95 (35.43)	0.95 (36.05)
$\lambda_{t,}$ time trend	0.01 (3.66)	0.01 (3.85)	0.01 (2.63)
BONUS		-0.08 (4.76)	1.45 (3.44)
MICON		-0.11 4.94)	-2.17 (3.24)
NORDTANK		-0.03 (1.43)	0.67 (1.77)
VESTAS		-0.05 (2.68)	0.31 (1.11)
ln N_{t-1} * BONUS			-0.16 (3.62)
ln N_{t-1} * MICON			0.21 (3.02)
ln N_{t-1} * NORDTANK			-0.08 (1.84)
ln N_{t-1} * VESTAS			-0.04 (1.28)
R^2	0.94	0.87	0.78
Observations	720	720	720

Notes: Numbers in brackets are t-values

The results show significantly different learning capabilities among the main manufactures of windmills with a significantly higher learning effect in BONUS and NORDTANK whereas

MICON has a significantly positive coefficient to the cross product. However, the estimate for MICON may be unreliably due to a lack of time observations as the company has only existed in the last part of the period. According to these estimates, three of the companies experience a larger learning effect (reducing their prices relative to other producers) compared to other producers. But now the average price of a windmill offered from these manufacturers deviates positively from the average price as estimated with the separate intercepts.

5. An infant industry perspective

The Danish windmill industry has been heavily subsidised since its start in the end of the 1970s. The most important instrument has been implementation of the obligation of distributional electricity companies to buy 'green' electricity from the windmills to a guaranteed price which is considerably higher than the price of electricity bought from traditional power stations. The guaranteed price exceeds that of the expected unit costs of producing electricity by wind power. The incentive to invest in windmills has furthermore been strengthened by friendly tax rules allowing the revenue for sales of electricity from windmills for individual investors to be tax free up to a specific amount per year. This has stimulated the domestic demand for windmills considerably and because of the accumulated experiences, Denmark has obtained a remarkable strong position on the world market for windmills as mentioned above.

Has it been worthwhile or - as the project is still ongoing - is it likely that it will be worthwhile? This question is discussed in this section. In the traditional analyses of the infant industry, the welfare effects are assigned to two periods: an infant period where the experiences are accumulated and a mature period where further gains in efficiency are more or less exhausted. In the infant period, short-term social costs often exceed that of the social benefits. In the mature period, benefits hopefully exceed costs. The overall assessment therefore depends on the time preference which make it possible to discount all costs and benefits to a given time. Costs and benefits consist of effects on consumer surplus, producer surplus and expenses or revenue for the public sector compared with the situation of no intervention.

In the specific case analysed in this paper, domestic consumption of electricity in Denmark is imposed an excise duty which makes the consumer price more than four times higher than the price paid to the power stations . This excise duty has been implemented under the label, a CO_2 duty, referring to emission of CO_2 from the production of electricity by fossil fuels. In principle the size of the excise duty should be determined so the environmental damage was internalised in the consumer price. However, the excies duty has been raised from 100 to 600 DKK per tonnes of CO_2 emission during the 1990's and various exemptions and differential treatments have been introduced. The present level of this excies duty is therefore a dubious indicator of the environmental damage.

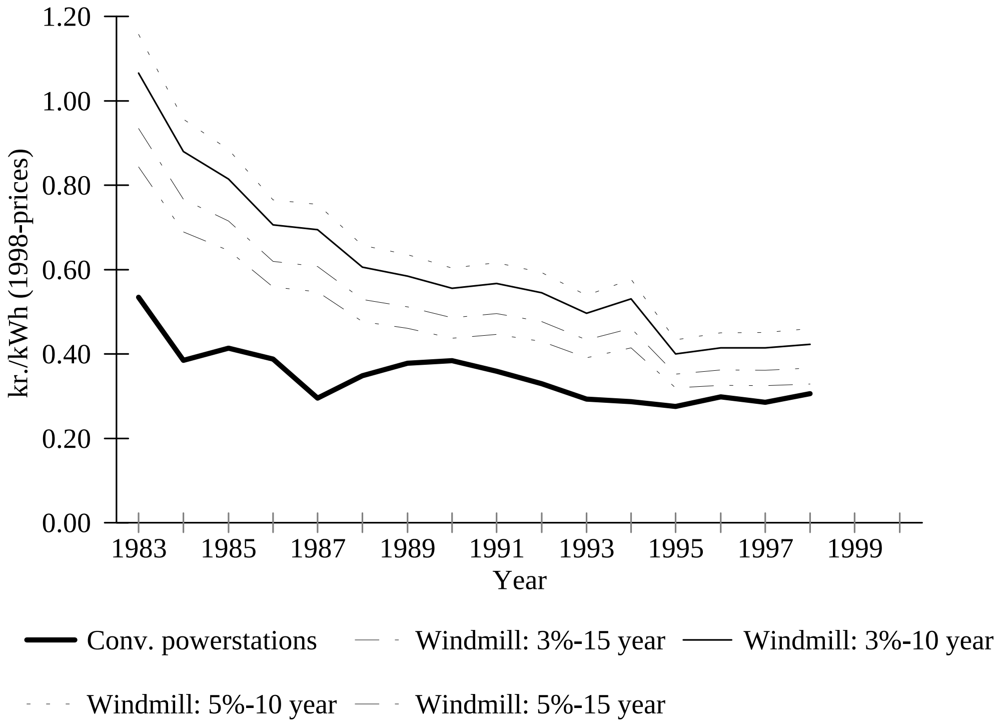
The obligation for distributional companies to buy electricity from windmills to a higher price than the price offered by the traditional power stations raises the average consumer price. This influences consumer surplus and causes a welfare loss or gain depending on the size of the consumer price relative to the welfare optimising price. However, the pass through of a higher price from electricity produced by windmills on the overall consumer price is modest and might have been taken into account when the government decided the size of the excise duty. The consumer price may therefore be treated as exogenously given i.e. the effect of a guaranteed price for green electricity at producer level for the consumer price is therefore disregarded in the following.

Opportunity costs

The problem therefore reduces to compare the costs of producing electricity by wind power with the costs of producing electricity by fossil fuels. The environmental benefits from using wind power is disregarded in this subsection i.e. we only look at the open costs of producing electricity from alternative energy sources. The unit costs of producing electricity from wind power or fossil fuels are illustrated in Figure 2. The unit costs in 1998 prices of producing electricity from the traditional power stations are calculated as an average of the price from the 15 traditional power stations to the distributional companies. In the investigation period, the traditional power stations were all publicly owned non-profit companies and hence, the price of each company is assumed to represent unit costs of the company. In calculating the average price the capacity (effect) of the 15 industrial power stations are used.[3]

[3] The 15 power stations cover more than 80% of the total domestic supply of electricity.

Figure 2. Unit cost of producing electricity by windmill and conventional power plant, DKK per kWh in 1998 prices.



Source: Own calculations reported in Table A and B for producing electricity by windpower and statistics from Danske Energiselskabers Forening for producing electricity by fossil fuels.

The unit costs for producing electricity by windmills is a little more complicated to calculate. First, the average price or installation costs of the individual vintage of windmills relative to the expected yearly production of electricity is calculated as reported in Table 2. These installation costs represent sunk costs. During the expected life of the windmill, the owner also incurs recurrent costs e.g. cost to repair and fixed recurrent costs e.g. insurance and land rent. From the data for recurrent costs in a sample of 194 mills the following recurrent cost function is estimated:

$$C = k\, E^{\mu} A^{\eta} \qquad (4)$$

where *C* denotes the recurrent costs relative to the expected yearly production, *E* is the installed effect measured in kW and *A* is the age. Estimating a logarithmic transformation of (4) gives the following result with t-values in parentheses:

$$\log C = 3.51 - 0.36 \log E + 0.42 \log A \qquad (5)$$
$$(2.53) \quad (2.16) \qquad (1.40)$$

$R^2 = 0.81 \qquad N = 10$

By using the parameters of equation (5) and the price deflator, it is possible to calculate the profiles of recurrent costs in fixed prices for windmills with effects equal to the average effect of each vintage of windmills. Table A in the appendix shows present value of recurrent costs in fixed 1980-prices for each vintage of windmills measured relative to the expected yearly production of electricity. Assuming that the duration of the windmill is 10 years or alternatively 15 years, present value of recurrent costs at the time when the mill is installed is calculated using a real rate of interest at 3% per year or alternatively at 5% per year.

These present values of recurrent costs are then added to the average price of the mill for each vintage and the total present values of all costs is subsequently transformed to unit costs of production of electricity for the assumed lifetime of the mills. Table B in the appendix shows the results of this calculation together with the unit costs of producing electricity by fossil fuels. Figure 2 illustrates the unit costs in 1998-prices and it appears that the cumulation of experience and development of technology within the windmill industry have narrowed the excess costs for producing electricity by wind mills compared to unit costs of production from a traditional power plant. Assuming the lifetime of a windmill is 15 years, the unit costs of producing electricity by wind power is seen only to be marginally above the unit costs of production from a traditional power plant at the turn of the century. Taking into account the recent rise in the oil and coal prices, the windmill may be competitive today under normal business conditions without state aid.

The perceived present value of the expected yearly loss at the time of installation for each generation of windmills might easily be calculated by the following procedure. First, the yearly loss for each generation of mills is calculated as the excess unit costs times the expected production which is reported in Table 5, column 1. Secondly, the perceived present value of the yearly loss is then calculated by discounting back to the time of installation the yearly loss for the whole span of years where the individual generation of windmills is expected to be in use. This gives the results reported in Table 5, columns 2-5.

Table 5. The perceived present value of the loss by producing electricity by wind power

Generation of windmills	Expected production	Present value of the yearly loss (DKK, million, 1998 prices)			
		10 years		15 years	
	million kWh/year	3%	5%	3%	5%
1983	38.1	172.98	183.40	158.46	158.46
1984	14.5	61.20	63.97	57.47	57.47
1985	45.8	156.37	166.07	142.78	142.78
1986	67.3	182.57	196.47	161.88	161.88
1987	65.8	223.76	232.94	212.87	212.87
1988	153.8	337.14	367.19	288.91	288.91
1989	131.5	231.84	259.85	182.63	182.63
1990	179.5	262.70	304.38	189.14	189.14
1991	163.9	289.53	324.14	230.61	230.61
1992	101.1	186.06	205.13	154.49	154.49
1993	69.4	120.02	131.60	101.05	101.05
1994	106.7	221.29	238.69	192.78	192.78
1995	243.2	258.92	297.15	195.98	195.98
1996	519.1	517.93	612.99	346.66	346.66
1997	649.0	715.21	829.04	510.93	510.93
1998	654.8	663.86	793.31	421.32	421.32
Total	3.213.5	4,601.37	5,207.31	2,462.85	3,547.96

Source: Own calculations.

The total loss for all generations of windmills is estimated to be in the interval DKK 2.4 - 5.2 billion, 1998 prices. Obviously, the loss is less if it is assumed that the lifetime of the mills is 15 years instead of 10 years. It also appears from the table that the loss varies inversely with the real rate of interest. Furthermore, the perceived loss for the recent vintages of mills is substantial although the excess unit costs of producing electricity by wind power is modest. This is due to the large capacity and hence large expected production of electricity for the most recent generations of windmills.

Environmental benefits

As previously mentioned, the subsidisation of producing electricity by wind power has been motivated by environmental considerations. Especially, that this production mode does not cause emission of CO_2. However, this has been at the expense of a considerable pecuniary loss as shown above. The CO_2 emission from traditional power stations based on coal is in the range 700

- 800 kg CO_2 per Mwh depending on age and technology of the power station.[4] The yearly production of electricity of all generations of windmills for the period 1983 to 1998 is about 3.200 Gwh (Gigawatt hours) as reported in Table 6, column 1. This is equivalent to a yearly reduction of approximately 24 million tons CO_2 if we assume that traditional power stations burden the environment with 750 kg CO_2 per Mwh. Table 6 shows the results of a simple calculation of the implicit price of CO_2 by relating the present value of the yearly loss for all generations of windmills to the total saving of CO_2 emission for a period of production of 10 or 15 years respectively.

Table 6. Implicit price of CO_2

		DKK per ton (1998 prices)
10 years	3%	190
	5%	217
15 years	3%	69
	5%	97

Note: The total production of electricity per year is assessed to 3.213,5 Gwh corresponding to a reduction of CO_2 of 24.101.250 tons for a 10-year-period or 36.151.875 for a 15-year-period. The implicit price is the present value of the yearly loss relative to the CO_2 saving.
Source: Table 5 and Finansministeriet (1996).

As the present value of the yearly loss decreases significantly with the lifetime of the windmills and the saved CO_2 increases, the implicit price of CO_2 is more than halved when the lifetime of the windmills increases from 10 to 15 years. Still, the implicit loss by producing electricity by the more expensive windmills instead of using the traditional power plant is still low compared to the CO_2 tax which the consumers and the industry have to pay.

However, this calculation may be too optimistic, as the size of the green subsidy may be bigger than calculated above. First, the traditional power plant has the obligation to pay the cost of connecting the windmills to the transmission network which can be quite expensive for mills offshore or fare away from the transmission wires. Second, the traditional power plants have the obligation to supply electricity also on a day without wind. Therefore investment in windmills do not reduce the capacity costs on the traditional power plants, and the price of electricity on the free market is often lower than the average price per kWh including capacity cost calculated above.

[4] Source: Finansministeriet, 1996

National benefits of capture of comparative advantages

The windmill industry now belongs to one of the spearheads of Danish manufacturing with very strong comparative advantage. In this section the benefits of the windmill industry for Denmark will be discussed. If a country increases the number of industries where it has comparative advantages two effects on welfare might be discerned. First, more export industries tend to improve terms of trade and hence welfare. This relationship holds also in the case where the industries operate under no entry barriers and hence zero profit (Krugman, 1987). However, a quantitative assessment of this effect on the Danish welfare of the appearance of windmill industry will be pure guesswork. Secondly, if entry barriers exist an oligopoly profit will exist in the industry, and the welfare may be improved through an increased producer surplus from exports of windmills.

An assessment of the size of this oligopoly profit generated by export of windmills is also difficult to make as we need also to introduce assumptions about the performance of the industry in the future. Still, the value on the stock exchange of the companies producing windmills may give a hint of the size of this welfare effect as the share price of a company incorporates the expected future profit of the production. The two main companies producing windmills in Denmark are listed on the Danish stock exchange, and their combined market value in 2001 is about 50 bill DDK. Compared with the paid in capital of less than one bill DKR the producer surplus from the Danish production of windmills are several time bigger than the expected green subsidy calculated above, and a large part of this surplus is expected profit from exports.

6. Conclusions

The paper analyses the rapid growth of the Danish windmill industry in the period from 1983 to 1998. The growth has been followed by a fast increase in productivity and the study finds that learning-by-doing has a significant influence on the growth in productivity in this period. While past studies on learning-by-doing in this industry have been rather suggestive our study shows consistent estimates of a learning rate between 6 and 7 percent across models based on aggregate time series data and panel data respectively. The learning rate for the windmill industry found in this study is on average lower compared to historical data on other industries such as aircraft and semiconductor. This lower learning rate could in part be explained by the constant launching of new prototype windmills of larger size during the period of study. At the same time the exact size of the learning rate is an empirical question and may vary across different industries and over time depending on general factors such as e.g. technological opportunity, demand conditions, the nature of markets, national and international rivalry.

The unit costs of producing electricity with wind power are calculated for each generation of windmills and compared with the unit costs in traditional power plants. The results show, that the windmills are not competitive on normal commercial conditions in this period. However, their competitiveness has increased over the period and today, windmills produce electricity at unit costs near the power plants depending on the expected lifetime for a mill.

The total perceived present value of the loss by producing electricity by wind power in Denmark is estimated to around DKK 4 billion. The investment in windmills has been subsided by higher electricity prices during this period. As the mills are about to be commercially competitive today and as Denmark has a high market share on the world market for windmills, the future may verify whether the green subsidies have been a successful industrial policy for an infant industry.

Appendix

Table A. Present value of recurrent costs for each vintage of windmills and the average mill price, øre per kWh in 1980 prices.

	Recurrent costs				Mill price
	10 years		15 years		
	3%	5%	3%	5%	
1983	79	127	71	109	370
1984	59	96	54	82	311
1985	61	98	55	84	282
1986	53	86	48	74	244
1987	50	80	45	68	243
1988	43	69	39	59	212
1989	42	68	38	58	204
1990	39	63	35	54	195
1991	40	64	36	55	199
1992	39	62	35	53	191
1993	35	56	32	48	174
1994	34	55	31	47	189
1995	33	52	29	45	136
1996	29	46	26	40	146
1997	28	45	25	38	147
1998	26	42	24	36	152

Source: Own calculations.

Table B. Unit costs of producing electricity, DKK per kWh in 1980 prices

	Wind power				Fossil fuels
	10 years		15 years		
	3%	5%	3%	5%	
1983	0.53	0.57	0.42	0.46	0.26
1984	0.43	0.47	0.34	0.38	0.19
1985	0.40	0.44	0.32	0.35	0.20
1986	0.35	0.38	0.28	0.31	0.19
1987	0.34	0.37	0.27	0.30	0.15
1988	0.30	0.32	0.24	0.26	0.17
1989	0.29	0.31	0.23	0.25	0.19
1990	0.27	0.30	0.22	0.24	0.19
1991	0.28	0.30	0.22	0.24	0.18
1992	0.27	0.29	0.21	0.24	0.16
1993	0.25	0.27	0.19	0.21	0.14
1994	0.26	0.28	0.20	0.23	0.14
1995	0.20	0.21	0.16	0.17	0.14
1996	0.20	0.22	0.16	0.18	0.15
1997	0.20	0.22	0.16	0.18	0.14
1998	0.21	0.23	0.16	0.18	0.15

Source: Own calculations reported in Tables A and statistics from Danske Energiselskabers Forening for producing electricity by fossil fuels.

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