Energy Prices, Production and the Adoption of Cogeneration in the UK and the Netherlands

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Abstract

Whenever industrial plants consume power and heat there is a need to consider energy efficiency investment on a cogeneration (CHP) plant. We investigate economic incentives influencing the adoption of energy saving technology by industry, namely, CHP in UK and Dutch manufacturing sectors. Our analysis is based on an empirical model by the application of cross sectional time series econometric models and examine how industrial output and historical increases in the price of electricity relative to gas prices spark the diffusion of CHP. We estimate production and price elasticities across periods and consider heterogeneous industrial groups. Using data for 13 manufacturing sectors our model shows that fuel cost savings and industry output, over time, impact significantly on CHP uptake. For example, the model confirms that an increase of 10% in the spark spread leads to a 4.1 MW (1.3%) increase in CHP installed in the entire manufacturing sector, while a unit increase in industrial output is associated to a 37 MW (12%) increase in total CHP uptake. Model outcomes are found to differ depending on the period of estimation. The estimation period is key in determining the impact of gas price and purchased power prices on adoption of CHP. The model takes into account the historical experience of CHP uptake, for these reasons our model is an improvement over its rivals (Madlener and Schmid, 2003; Bonilla et al., 2003; Dismukes and Kleit, 1999; Fox-penner, 1990; Rose and McDonald, 1991 and Joskow, 1984).

Keywords: energy, manufacturing sector, econometric modeling, electricity prices, energy conservation, technology diffusion

JEL classification: C23, C50, Q40, L6;

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1. Introduction

Industrial plants consume energy to generate electricity and provide heat and raw material input for manufacturing industries. This research has implications for CHP uptake and industrial energy efficiency potentials and industrial demand for gas. The share of CHP in electricity generation grew to 6.2% and to 40% in the Netherlands in 2002. Manufacturing plants can be supplied with electrical and thermal energy by decentralised CHP and such plants have untapped the potential for energy savings during the 1990's given the decline in price of gas in the UK. The decline in prices encouraged firms to invest in CHP, gas turbines and combined cycle gas turbines (CCGT) and to cut electricity purchase costs by cogenerating power.[1]

We exploit panel data uniquely organized to achieve two objectives.[2] First to examine industry (investment) adoption in CHP technology installed in British and Dutch manufacturing industries within the 1991-2001 period. Second to determine if CHP prone industries follow economic theory. We focus in this paper on the historical effects of prices of gas and electricity on the decisions of energy managers considering CHP uptake.[3]

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[1] The decline in gas prices had two opposing effects. The first is to discourage investment in energy efficiency by lowering the electricity purchase costs; the second is to encourage new investment by lowering the operating costs of a CHP plant specially if the plant adopts a CCGT technology. Fuel costs represent the main cost for CCGT plants. Additionally an unexpected increase in energy prices could render obsolete a portion of a firms existing plant and equipment, yet at the same time create opportunity for profitable new investment in more energy efficient equipment (example given by Berndt 1991, pp. 259).

[2] Data from a (usually small) number of observations over time on a (usually large) number of cross-sectional units in this case, firms, or industries that have installed CHP.

[3] Cogeneration (CHP) is the simultaneous production of electrical energy and useful heat and it is usually installed in the manufacturing and commercial sectors.

Managers at manufacturing plants base investment decisions on CHP or other energy saving machinery according to expectations on the future direction of energy prices. Such direction will determine the expected profitability of a CHP project and investment in such technology and hence we ask whether or not current (historical) gas and electricity prices are a suitable proxy for expected payment streams, as examined by Fox-penner (1990b), thereby influencing adoption or CHP activity.

The paper consists of 6 Sections. The second section discusses the motivation of this paper along with a review of the relevant literature, on technology adoption, that relies on econometric methods. Sections 3 and 4 describe the status of CHP in the countries concerned and the evolution of gas and electricity prices along with industry output. Section 5 explains our (econometric) modeling strategy which is more complicated than previous studies on CHP activity have assumed. In Section 6 we present our model results. Section 7 contains conclusions and an Appendix presents material for the key points made in the paper.

2. Background

There are four reasons to examine CHP diffusion. First the decade of 1990s recorded a more than doubling of installed capacity of CHP in the UK; its share of total UK generation capacity rose to 6.2% in 2002 and to 40% in the Netherlands (DTI, 2002a; Eurostat, 2003). Second it is still not clear how rising gas prices, coupled with declining electricity prices, following the deregulation of the electricity market in England and Wales, will benefit CHP adoption and thereby energy conservation in industry. For example CHP entrepreneurs are reporting lower profitability (DTI, 2001). Third CHP development can strengthen energy security and reduce greenhouse gases, as pointed out in the European Commission Directive (2004).[4] Fourth, the energy economics literature focusing on time series-cross section data of observed CHP adoption at a disaggregated industry level is lacking.

The econometric research on the adoption of CHP shows a common thread: it is based on cross sectional data (Dismukes and Kleit, 1999; Joskow, 1984; Rose and McDonald, 1991; Fox-penner, 1990a, 1990b and Bonilla et al., 2003). See Table 1 for a survey of the literature in the field. The disadvantage of such studies is that they fail to 1) account for dynamic changes in CHP diffusion within manufacturing firms or sectors and 2) they ignore historical and structural change within the output of the manufacturing sector impacting on CHP potential market share. The result is limited price and production elasticities estimated on only one year's data of manufacturing firms that adopt CHP leading to inaccurate policy prescriptions.

Studies on CHP are based on a variety of econometric techniques: on simultaneous equations to explain the relationship between factor prices and CHP (Rose and McDonald, 1991); on maximum likelihood method using a binary dependent variable to model the decision whether to cogenerate or not to do so (Fox-penner, 1990a); on binary and multinomial methods to explain the adoption decision of CHP (Dismukes and Kleit, 1999); on the Tobit technique to observe the adoption of CHP using cross sectional data (Bonilla et al., 2003); and on linear cross sectional models used by Joskow (1983) where CHP changes are related to changes in fuel operating costs savings, industrial value added and plant scale.

[4] In the light of potential dependence on Russian gas of UK electricity plants, CHP can decrease that dependence by its efficient use of energy.

The effect of prices is crucial to understand the adoption of energy conservation technologies. Jaffe and Stavins (1995) report positive effects of energy price and technology costs on conservation technology adoption in buildings. But their econometric evidence points that the effect of technology cost is three times as large as the effect of energy price. Their model relates US building insulation to prices and capital costs, among other variables. Jacobson (2000) finds that replacement rates for heating equipment increase with fuel price increases but that economic growth has scant impact on technology adoption.

The literature focusing *on the direction* of the energy price effect on CHP adoption provides undetermined evidence. For example, Rose and McDonald (1991) assert that an expansion in selfgeneration (cogeneration) will be positively affected by the rise in the price of purchased electricity. Fox-penner (1990a) finds no conclusive evidence on the explanatory power of prices, save for gas prices, on the probability of adopting cogeneration. Fox-penner (1990b) reports positive coefficients for power and gas prices in his "participation" model and negative coefficients in his "magnitude" model for the same variables.

The cross sectional models developed by Dismukes and Kleit (1999) show that the probability of cogeneration, or on-site generation, increases with higher power prices and with lower gas prices. Farhangi et al. (1990, pp.185), through a cost share equation, finds that the amount of CHP increases as the price of electricity increases relative to other fuels. In a large scale study Boyd (2001) finds a positive but small power price effect and a large and positive gas price effect on the probability of adopting cogeneration. In the UK energy economy context an analysis of price impacts determining the future of CHP is essential given the changes in the power market created by NETA (New Electricity Trading Arrangements) policy instruments (DTI, 2001).

Table 1. Survey of the literature on econometric analysis of CHP

Study	Functional form	Variables used	Scope
Bonilla et al. (2003)	binary dependent variable cross sectional	Operating hours, on site power demand, steam capacity and pay-back period	medium sized industrial plants Japan
Boyd (2001)	binary dependent cross sectional	capital cost, gas price, Electricity price and others	medium sized industrial plants, US
Dismukes and Kleit (1999)	binary dependent logit probit	electricity price, gas price, on site power demand, operating hours, industrial power demand, and steam capacity	industrial plants Louisiana, U.S.
Fox-penner (1990a), (1990b)	maximum likelihood cross sectional	electricity price, gas price industrial output, regulation	US States,
Joskow (1984)	simulltaneous equation cross sectional data	electricity Price, gas price, and industrial production	industrial plants U.S.
Madlener and Schmid (2004)	hazard rate time series data	CHP capacity Time trend	German cogeneration sector
Soren and Newell (2004)	fixed effects logit	energy savings, implementation costs and energy prices	industrial plants U.S.
Ishii (2004)	fixed effects	capacity, heat rates,	gas turbines (world)
Rivers and Jaccard (2005)	discrete choice data sample: cross sectional	capital cost, operational cost, CHP-generation of electricity	Industrial plants Canada
Rose and Joskow (1990)	hazard rate bayesian methods cross sectional	fuel price, plant size and ownership pattern	electric utility industry U.S.
Rose and Macdonald (1991)	tobit simultaneous equation	electricity price, gas price, on site power demand, operating hours and industrial power demand	industrial plants U.S
Strachan and Dowlatabadi (2002)	net present value optimisation		UK, Netherlands

In the case of the Dutch energy economy a historical analysis of energy price effects on CHP uptake is called for. Examining the cost effects of gas and electricity (and on the demand for fuels) on the behaviour of plant managers is complex since the practice of suppliers of charging a price for gas and electricity depends on the volume of fuels used by the industrial plant. Plants do not face a single market price for fuels. Instead they face a complete price schedule that specifies what the price will be at each level of consumption (Woodland, 1993, pp.65). Correcting for this is beyond the scope of this paper. Using microeconomic data on plants, Pizer et al. (2002) report that energy prices, profits and working capital have a positive influence on the adoption of energy saving technology. Under a net present value analysis of CHP investments, Strachan and Dowlatabadi (2002) reason that adopting CHP is a response to reap economic savings that stem from (avoided) purchases of power and heat. The studies cited above show that fuel prices hold the largest effect on CHP adoption regardless of the direction of the energy price effect.

In the opinion of the authors limited time series econometric work has been done on the production and price signals that incentivise UK manufacturing industry to adopt CHP. The conventional wisdom holds that higher power prices stimulate investment in energy efficient equipment. Recent econometric research on technology adoption, however, shows that manufacturing firms are more responsive to the level of energy saved than to energy prices. Hence firms should receive tax breaks or subsidies for promoting energy efficiency technologies (Soren and Newell, 2004).

One commonality of the studies cited is that they focus on North America’s manufacturing sector, except for that of Bonilla et al. (2003), which extends to Japanese manufacturing plants, and Madlener and Schmid (2003) which investigates the diffusion of CHP in Germany. We have no equivalent econometric evidence for UK or Dutch manufacturing plants, which adopt CHP, hence adding to the newness of this research. Another feature is that the literature has ignored historical change in industry output, drawn empirical evidence from a limited set of manufacturing sectors and failed to examine the spark spread effect on CHP diffusion (the ratio of electricity price to fuel price overtime). [5]

3. Energy prices and CHP in the UK

The relative price of energy (gas and electricity) affects the economics of CHP (CE, 2002; DTI, 2002a; IEA, 2002). The ratio of electricity to gas price (or the spark spread) captures the operating cost pressures of industries or firms when consuming energy and the higher ratio the higher the expected profits and savings obtained leading to a higher rate of uptake of CHP by the manufacturing sector. [6] The electricity price determines the cost of buying power from the utility as opposed to buying gas and cogenerating heat and electricity. In figure 1 the ratio of electricity price is 6 times that of gas price in 1996; 4.5 times in 1991 and 3.8 times in 2001. In figure 1, on the X-Y- axis, UK prices of electricity are plotted against years. On the Z-axis the spark spread is shown. Figures 1 and 2 show that the electricity price to gas price (fuel cost savings or the spark spread) ratio rises until 1996.

[5] By the spark spread, we mean the difference between gas costs and the price for which cogenerators can sell their power or avoid electricity purchases. We represent the spark spread by the ratio of electricity price to gas price.

[6] Mansfield argues that firms that have (not) adopted the innovation, is a function of 1) proportion of firms that already introduced it, 2) the profitability of installing it, 3) the size of the investment required to install it, and 4) other unspecified variables. See Mansfield (1968), pp.137).

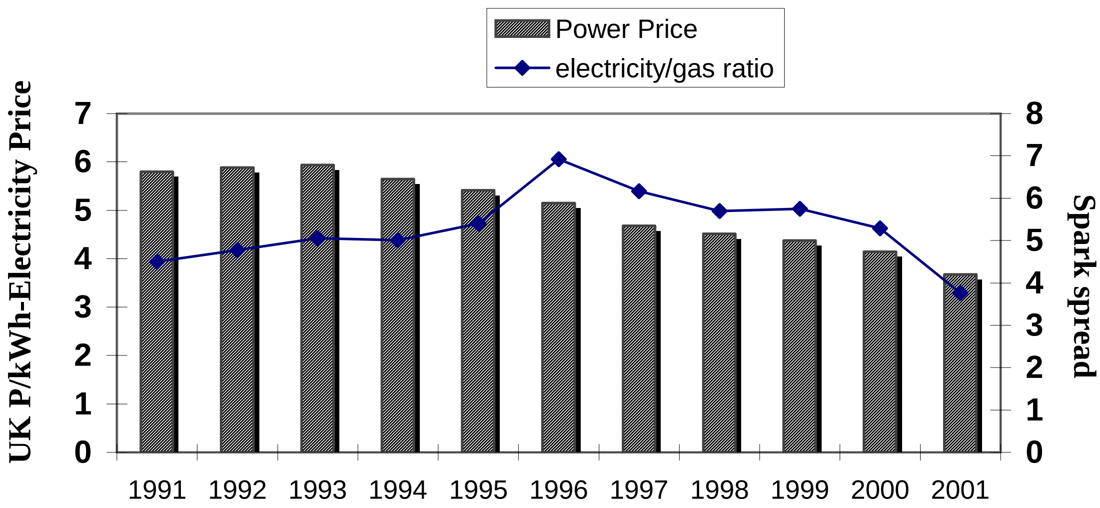

Figure 1. The change in the spark spread and electricity price. Source: DTI (2002 b)

Price data is taken from DTI's Quarterly Energy Price. [7] For the entire 1990s decade, however, the raw data does not show that CHP adoption is sparked by that ratio since the ratio declines after 1996. Economic theory points that increases in the spark spread should improve the commercial viability of plants that cogenerate electricity but plants that do not sell power will benefit less from increases in the ratio. Figures 2 and 3 show that the relationship between CHP adoption and the spark spread is non linear**.** Figure 3 also shows that gas prices follow a random walk. Gas prices fell by 42% between 1991 and 1996 spurring the adoption of CHP. These prices only rose after 2000.

[7] Prices are converted to real prices using data on the GDP deflator published by the DTI website

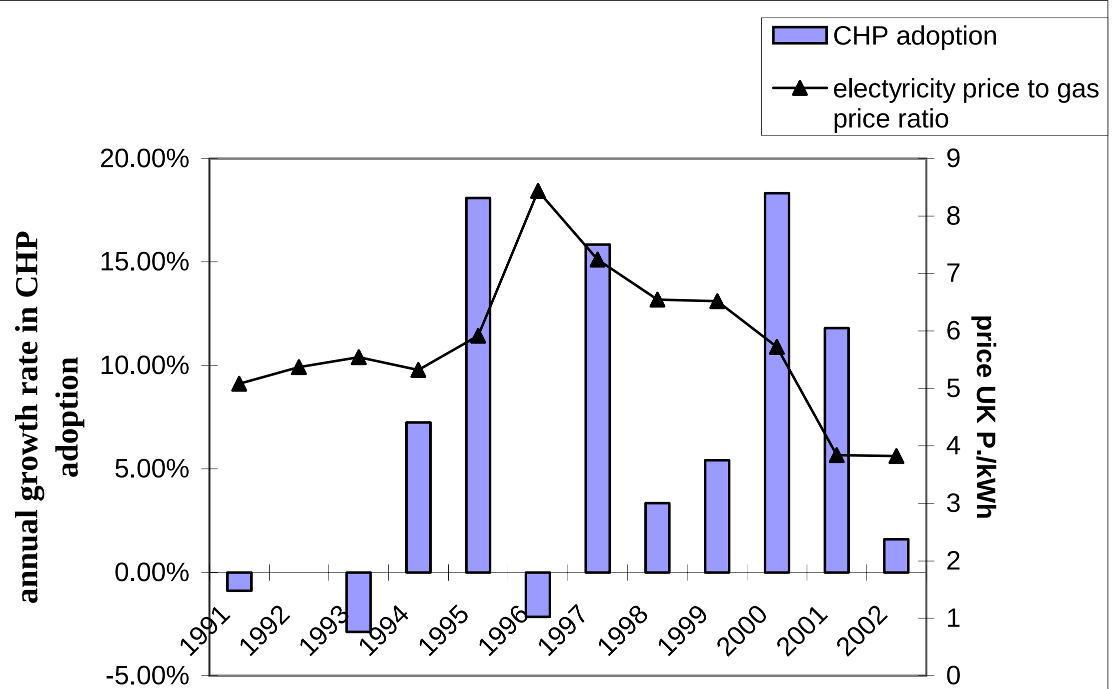

Figure 2. Energy price and CHP annual adoption (UK).
Source: DTI (2002b)

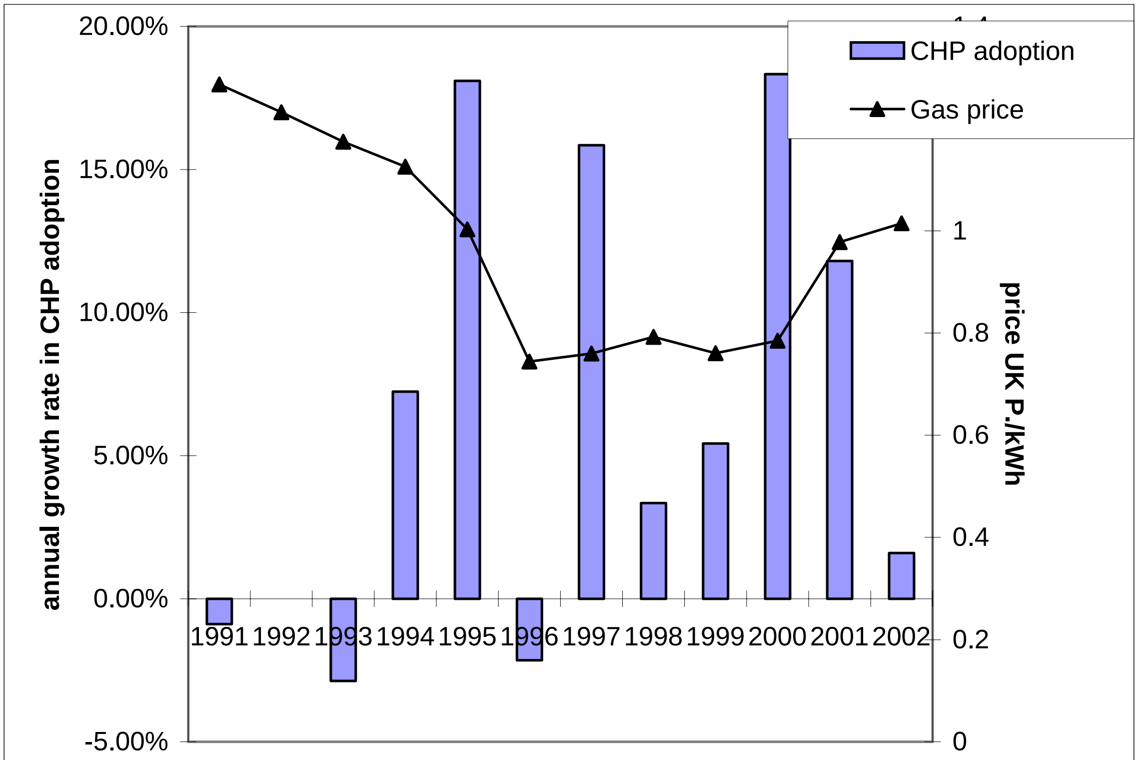

Figure 3. Energy price and CHP annual adoption (UK).
Source: DTI (2002b)

Gas prices leveled off from 1996 onwards and then increased considerably growing by 33% during 1999-2002. In recent years gas price increases have reduced current (and expected) profitability of CHP projects (DTI, 2001, pp. 148). An increase in CHP diffusion in 1995 and 1997 (with a time lag of 1 year) coincides with the peak in the electricity price to gas price ratio (figure 2). Figure 3, however, does not show that gas prices have been at their lowest point for 20 years turning CHP economically viable and hence encouraging its uptake. Figures 2 and 3 suggest that CHP adoption responds asymmetrically to changes in power prices and gas prices. Figure 4 depicts the development of CHP in the Netherlands.

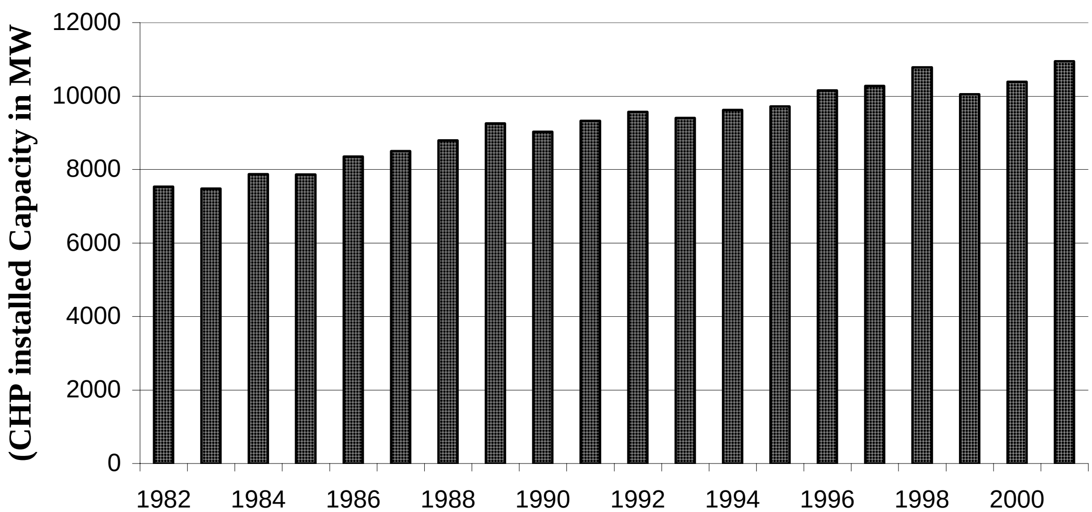

Figure 4. CHP Capacity installed in the Netherlands (1982-2001).
Source: CBS, Netherlands

On a per capita basis the Netherlands installed 20 times more CHP units than the UK (Strachan 2002). Figure 4 has been converted from Petajoules into Megawatts assuming 7500 annual operating hours (see Newbery et al., 2002, pp. 5). Figure 4 indicates that CHP adoption stands at 11000 MW in rough terms: the actual figure could lie between 7400 to 9092 MW (Newbery et al., 2002, pp. 3; Eurostat, 2003).[8] In Table 2 we find that CHP diffusion is not responding to higher industrial demand for electricity: Most sectors show annual declines in electricity consumption. In Section 3.1 we examine price effects on CHP in the Netherlands.

Table 2. Compound annual growth rates of CHP, of industrial output and of power consumption in Dutch Manufacturing sectors. (1985-2001; in % per year).

Manufacturing Sector	Industry Output	CHP Capacity	Power Consumption
Food-tobacco	1.8	8.7	-0.88
Chemicals	2.2	7.6	-0.92
Paper	1.6	6.6	-0.89
Metals	1.6	12.1	-0.90
Building materials	1.1	-2.4	-0.92
Oil refining	0.2	4.2	-0.87

Source: Central Bureau of Statistics (Netherlands).

[8] There are no official statistics on total installed CHP on an electrical capacity basis in the Netherlands; hence we only report estimates here.

3.1. Energy prices and CHP in the Netherlands

What is the relationship between CHP and energy price fluctuations? Figure 5 depicts that the spark spread rises until 1999 thus improving the profitability of CHP. The spread decreases thereafter. Figures 6 and 7 depict the changes in the uptake of CHP and industrial fuel and power prices (1983-2001). Price data is published by the IEA (*IEA Energy Prices and Taxes,* 2002*)*. There were three periods during which gas prices impacted on CHP diffusion: 1991, 1996 and 2000 (figure 7). Figures 6 and 7 show that CHP uptake as well as energy prices are volatile for most of the period. For the entire 1990s decade, unlike the UK case, the raw data confirms that CHP adoption is sparked by the increase in the spark spread (figure 4).

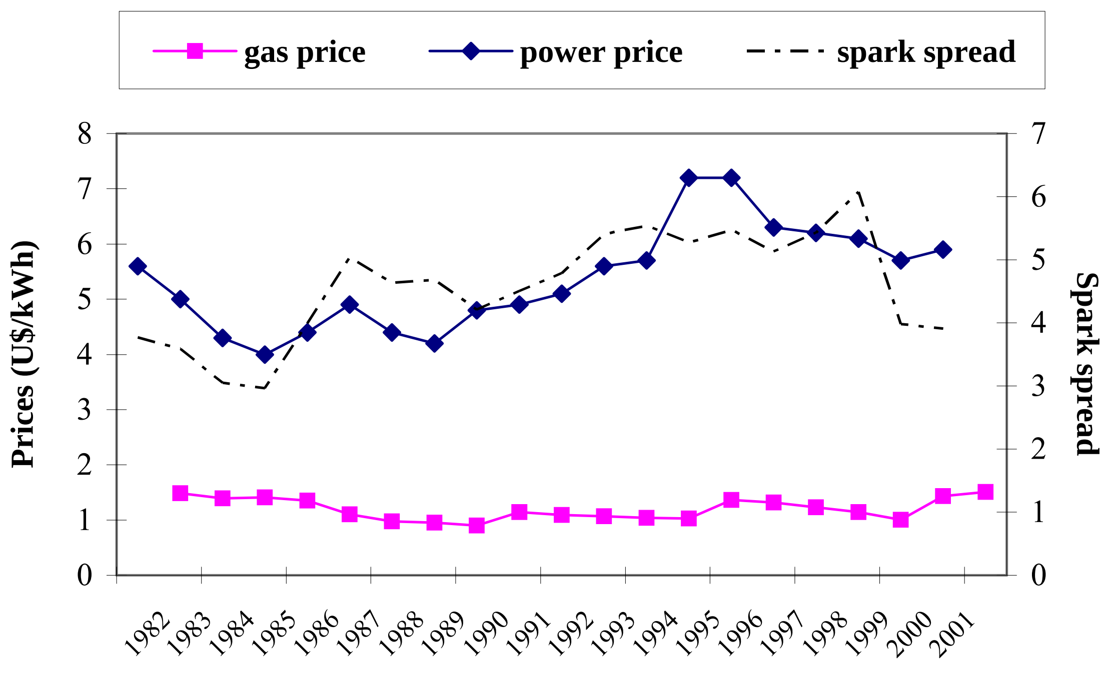

Figure 5. Fuel and Electricity prices: 1982-2001.
Source: IEA, Energy Prices and Taxes

In our view within the decade of the 1980s and half of the 1990s gas prices did stimulate the uptake of CHP since favourable gas prices were offered from a state owned gas supplier until 1995 (IEA, 2002, pp.61). Electricity prices also fell considerably in the decade of the eighties but electricity prices are not sufficient to explain adoption.[9] The uptake of CHP responds less to the needs by industry to sell power to other users or utilities than to lower (gas) input prices to selfgenerate power.[10]

Two policy changes undermined the adoption of CHP. First the liberalization of the Dutch electricity sector in 1998 resulting in rising gas prices and lower electricity prices, and second, overcapacity of Dutch electricity generation. In short our research has implications for CHP uptake and for industrial energy efficiency: lower (higher) gas

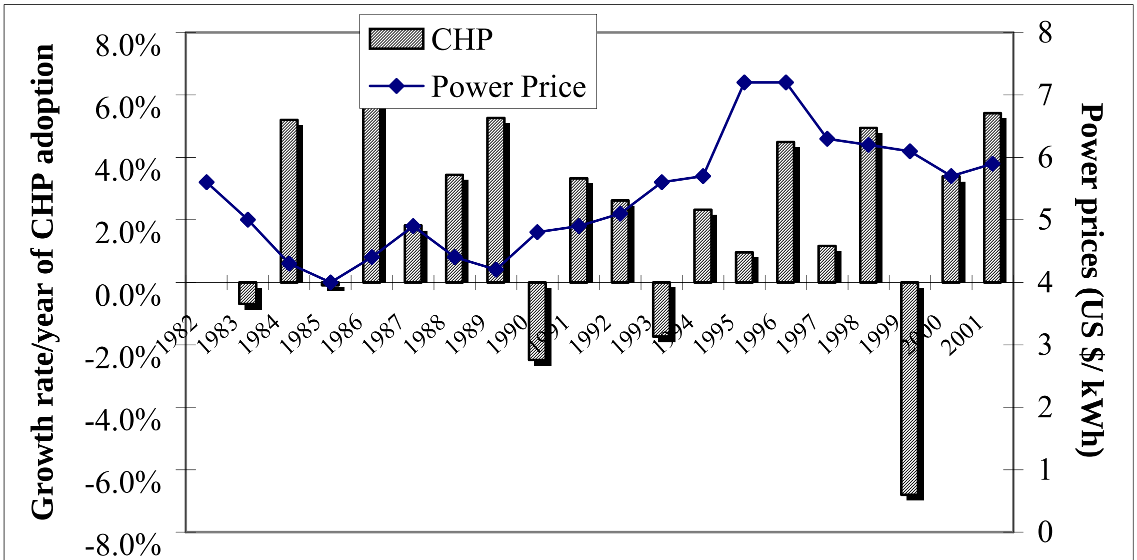

Figure 6. CHP in Netherlands. Source: CBS, Netherlands

prices accelerate (decrease) CHP uptake.

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[9] We abstract from the following factors impacting on CHP take up: 1. The effect of regulatory changes in the UK and the Netherlands, in electricity, natural gas and other markets. 2. The volume of electricity sales by CHP affected by the feed-in tariff. 3. The access to the national electricity grid and opportunities for other forms of self generation of heat and power. 4. The role of government subsidy and other programs. 4. The impact of energy efficiency information campaigns. 5. The degree of market saturation in the power generation sector, given the higher penetration of CHP in the Netherlands than in the UK. 6. The proportion of CHP units that are run on non fossil fuels; and the number of dual fuel units of a CHP plant. 7. The short term energy price expectations affecting "animal spirits" within the industry; and the importance of energy service companies that contract out CHP equipment. 8. The access to capital which differs among industries; among others.

[10] We ignore the proportion of plants that commercially cogenerate power; that is we do not know the proportion of plants that sell power to the grid; these plants would normally be extremely sensitive to power prices since their profitability depends on them.

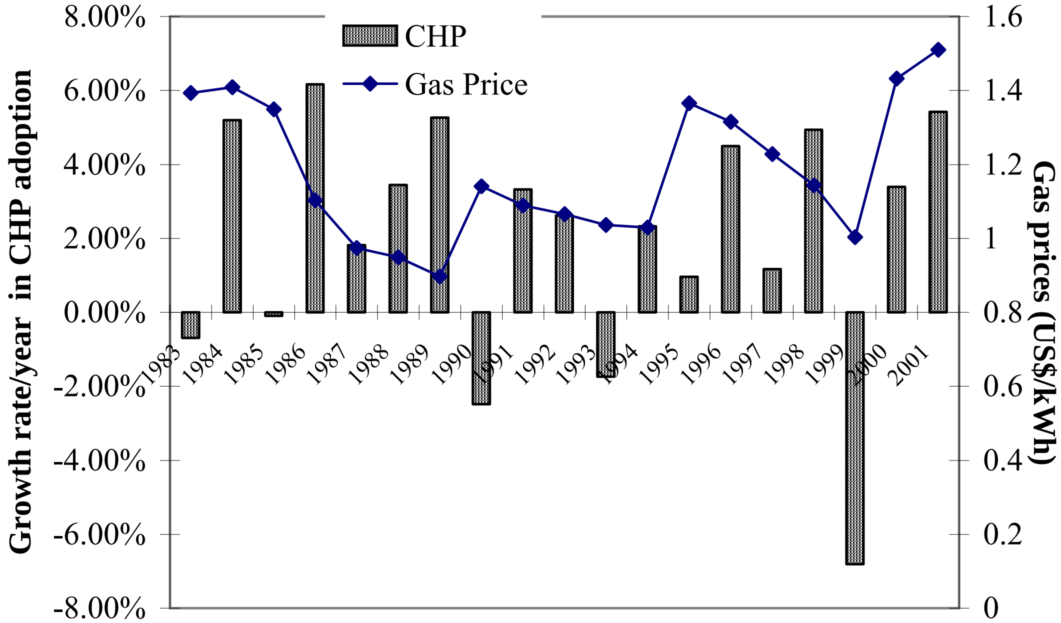

Figure 7. CHP and input prices in the Netherlands. Source: CBS, Netherlands

4. The Evolution of CHP in 1991-2001: the UK case

What growth pattern does the adoption of CHP show? Figure 8 depicts annual changes in UK CHP capacity in 1991-2003 for the 6 manufacturing sectors concerned. (pulp & paper, chemicals, iron and steel and non ferrous metals, oil an refinery, food beverages and tobacco, machinery and vehicles). Supported by UK Government measures (Table 9 in Appendix) CHP capacity has doubled in a decade and grown uninterruptedly on a cumulative basis. Growth of CHP capacity was supported by the opportunity of CHP to sell electricity to industrial consumers or utilities; in 2001 a third of electrical output of CHP plants was sold to third parties (DTI, 2002a).

In Table 3 UK CHP adoption growth rates (capacity additions) are tabulated. The highest growth rates of CHP take up are found in the machinery (associated industries) and oil refining sectors. The six manufacturing sectors recorded an average of 21% growth per annum in capacity terms. Cogenerated electricity rose by 6.2% annually and it superseded the growth of utility power demand in every sector (Table 3). In the iron & steel sector the industry scaled back CHP capacity as it reduced its total power needs. At the same time positive rates of growth in industrial output raised industry demand for electricity as shown in Table 3. Industrial output also has declined in oil refining and pulp (associated sectors) and in the iron and steel (associated sectors) sectors. In contrast positive rates of growth in industrial output in 1985-01 in the Netherlands contributed to investment and thus diffusion of CHP in that country (Table 2). The exception was the oil refining sector which experienced a decline in its output from 1998-03. In the Netherlands total manufacturing output rose by 1.4% per year, on average, during the 1980s and 1990s.

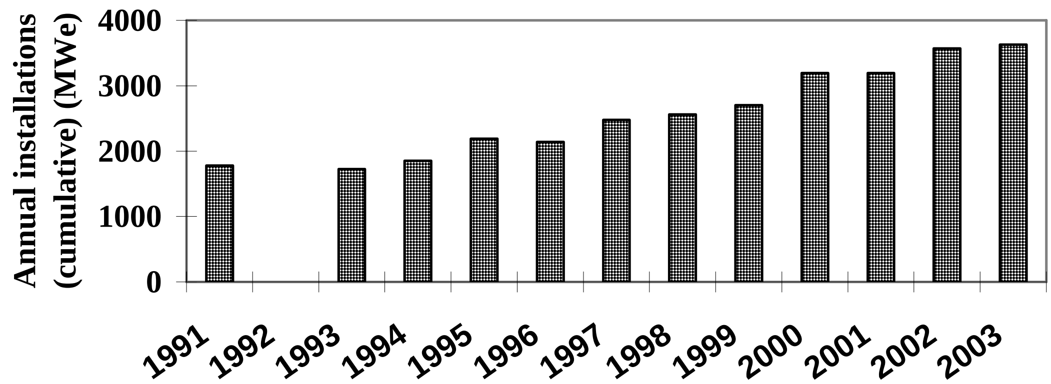

Figure 8. CHP installed in the UK 1991-2003.
Source: DTI (2002 b). 1992 data is unavailable

Table 3. Compound annual growth rates of CHP in UK Manufacturing sectors. (1991-2001; in % per year).

Manufacturing Sector	Industrial Output	CHP Capacity	Power Consumption
Pulp & Paper-Printing	-0.52	6.7	3.1
Chemicals	1.9	4.4	1.7
Iron. & Steel NFM	-0.4	-4.3	-0.6
Oil & Refinery.	-1.21	8.2	2.3
Food , beverages & Tobacco	0.3	5.5	0.2
Machinery & Vehicles	-0.2	11.9	-0.3

Source: DTI (2002a)

5. The Diffusion of CHP and the potential fuel cost savings

5.1. The Model

In Equation 1, we express the relationship between CHP adoption and operating cost savings. We test the relationship in Section 6. Such relationship has been econometrically tested by Dismukes and Kleit (1999) and Joskow (1984). Joskow uses US pulp and paper sector data on the fraction of cogenerated electricity in electricity consumption for 32 US States. In our study we posit that CHP diffusion is an increasing function of fuel cost savings (FS) and that the relationship between CHP and fuel cost savings is nonlinear as Joskow (1984) argued. CHP is to be installed as long as is profitable to do so as first argued by Mansfield (1968, pp. 137) in his analysis of the diffusion of innovations. We define fuel cost savings (operating cost savings) as:

$$ratio_t = \frac{electricity\ price_t}{gas\ price_t} \tag{1.1}$$

$$FS_t = \left[\frac{1}{ratio}\right]^2 \tag{1.2}$$

$$CHP_{it} = f\left(FS_t\right) \tag{1.3}$$

In this case: *FS (*operating) is fuel cost savings of the firm/industry; *CHP* reflects the adoption of CHP (capacity); *t* is years (1991- 2001) and i is manufacturing sectors.

5.2. Explaining the Econometric Model of CHP

In the Appendix we present details on the econometric method to examine annual trends of CHP adoption by industry.

Our aim is three-fold:

(1) to deal with the direction of the change in CHP aggregate adoption (investment);

(2) to deal with the magnitude of the change in CHP;

(3) to model the drivers of CHP adoption.

5.3. Explaining the adoption model of CHP

In this Section we describe the variables of the adoption model. We assume that each of the 13 manufacturing sectors behave like a single firm which sets its inputs and its level of investment to maximise its output (CHP power capacity) subject to its production function and a vector of prices.

CHP capacity is measured at the single sector level to capture the adoption phenomenon. The CHP_{kt} variable is obtained by stacking capacity of each industrial site within each of the manufacturing sectors for each year. Coefficients to be estimated:

$\delta = steam\ capacity\ coefficient$;
$\omega = industrial\ production\ coefficient$;
$\theta = fuel\ cost\ savings\ coefficient\ (electricity\ price\ and\ gas\ price)$;
$\varepsilon = residual\ error$;
$subscripts$:
$k = manufacturing\ sector$;
$t = years\ 1991-01$;

$FS = fuel\ cost\ savings$;
$CHP = cumulative\ CHP\ investment\ in\ a\ year$.

The dependent variable is built as:

$$\sum_{i=1}^{n} CHP_{ij} = plant_1 \ldots + plant_n \qquad \textbf{(2)}$$

where i is a plant that has adopted CHP, at the *jth* industry. Hence total CHP adoption at year t in the *kth* sector is captured in:

$$CHP_{ij} = CHP_{kt} \qquad \textbf{(3)}$$

we can generate different outcomes through CHP_{kt} in Equation 4.[11] Ignoring time subscripts on the r.h.s., *CHP* plant adoption (investment) is determined as:

$$\begin{aligned} CHP_{kt} = \alpha_k + \delta_k\, steam\,capacity_k + \omega_k\, industrial\,output_k \\ + \theta_k\, fuel\,\mathrm{cos}t\,savings_k + \varepsilon_k\, residual\,error_k \end{aligned} \qquad \textbf{(4)}$$

The k subscript stands for manufacturing sectors. Equation 4 expresses the determinants of CHP adoption.[12] Note that Equation 5 is based on the econometric estimates of Equation 4. Following Equations 1.1, 1.2 and 1.3, the elasticity E (% change in CHP for % change in (operating) fuel cost savings) of CHP w. r. t. fuel cost savings is obtained as follows:

$$E_{it} = -2\hat{\theta}_k \times F\overline{S}^{-3} \qquad \textbf{(5)}$$

Where:

θ_k is a linear coefficient with the variable entering the Equation 4 non linearly;

FS represents average of the spark spread (between electricity price and gas price);

[11] For the UK only, we initially regressed CHP against industrial power consumption, steam capacity of CHP, industrial output, a time trend and a squared term for electricity price and gas prices. The results failed to meet our expectations in that the fuel cost savings are not associated positively to CHP adoption. These initial econometric results are available from the author.

[12] As alluded in section 2, the variables of eq. 5 were previously examined by other economists [Dismukes and Kleit (1999); Fox-penner (1990b); Rose and McDonald (1991)]. Those authors used specific plant data on CHP plants to represent the CHP activity and investment. Joskow (1984) used industry level data for CHP instead of using plant specific data. This paper follows Joskow's approach.

t is time and i is manufacturing sectors;

E_{it} is the elasticity of CHP w. r. t. the operating cost savings.

In Equation 4 we assume an instantaneous reaction of price and production on CHP adoption, that is, the model is contemporaneous. Detailed description of the assumptions of Equation 4 is given in the Appendix.

We expect that all the right hand side variables of Equation 4 will lead industry to invest in and thus adopt CHP. As said before Equation 4 tests the relationship between CHP adoption and fuel cost savings. Following the work of Fox-penner (1990b) Equation 4 is used to test the several outcomes of industry investment in CHP. [13]

6. Interpretation of results

6.1. Descriptive statistics

Table 4 shows that UK industrial output data exhibits the lowest volatility. Its standard deviation as a percent of its mean is the lowest, in contrast to CHP data which shows the highest volatility. Tables 4 and 5 also provide data definitions for data on both countries. Combined data sets (UK-Netherlands) of CHP diffusion and of heat outputs show that the data is also highly volatile (Table 5). The least volatility is shown by electricity prices with gas prices exhibiting slightly more volatility than electricity prices. Hence CHP data is more dispersed than price data.

[13] Fox-penner (1990) examined two modes of CHP operation : the arbitrage mode (CHP sells power to the centralised power station) and the displacement mode (CHP displaces centralized power plants). In theory Equation 5 would have to include the two modes of operation even though our data does not explicitly show such operation modes. By means of a production function Fox-penner (1990) derived the Hessian matrix to determine theoretically the effect, or the expected coefficient sign, of the price impact (for electricity and gas) on the mode of CHP operation. See Fox-penner (1990b: pp. 526-528).

6.2. Discussion on estimated coefficients

What is our econometric evidence on how prices and production alter the adoption of CHP by UK manufacturing firms? Econometric results (Equation 4) are shown in Table 6. Panel regressions results were obtained by Time Series Processor (TSP) software. Coefficients of industrial output, fuel cost savings are statistically significant at the 95% probability value for the fixed effects model. Industrial output and fuel cost savings have the expected signs. Additionally the coefficient of heat output is not significant but shows the expected sign. The model of fixed effects explains 97% of the variation in the dependent variable (CHP capacity).

Table 4. Descriptive statistics, Dependent and Independent variables for CHP installed in UK manufacturing sectors.

Variables	Unit Definition	Sample mean	Sample Standard Deviation
CHP capacity	Installed, MW	434	413
Power consumption	GWh	12,230	5787
Heat Output	GWh	9,270	8152
Electricity Prices	UK Pence/kWh	4.32	0.66
Gas prices	UK Pence/kWh	0.75	0.17
Ind. Output	Index (100 =2000)	99	7.62

Source: DTI (2002a; 2002b)

Table 5. Descriptive statistics, Dependent and Independent variables for cogeneration in UK and Dutch manufacturing sectors.

Variables	units definition	Sample mean	Sample Standard deviation
CHP capacity	MW	313	298
Heat Output	Gwh	4806	7182
Electricity Prices	UK p./kWh; U$/kWh	5.79	0.73
Gas prices	UK p./kWh; U$/kWh	1.12	0.17
Ind. Output	Index	96	19

Source: for CHP capacity (DTI, 2002a) and Central Bureau of Statistics, Netherlands (various years); Industrial gas and electricity prices (IEA, *Energy Prices and Taxes)*; and DTI, (2002b). Industrial output index (100 =2000) from DTI website and (CBS) Netherlands.

Table 6. Coefficients of adoption model (Equation 5) for the UK and Dutch manufacturing sectors: CHP as a function of industrial output, fuel cost savings, heat capacity.

Dependent Variable	Industrial Output*	Fuel Cost. Savings	Heat Output	Adjusted R sq.
CHP; (1991-96); Industry effect observations=78; (linear model).[a]	0.12 (2.6)	-9.17 (3.19)	0.16 (e-4) (1.16)	0.97
CHP; (1991-96); No industry Effect; observations=78; (linear model).[b]	0.46 (0.67)	-12.2 (1.3)	0.87 (e-4) (6.2)	0.33

The Hausman test shows that the industry effects model is accepted. Industry (Fixed) effects is accepted; Ho: random effects vs. Fixed effects. Source: elaborated by the authors.

t-values in brackets. Dependent variable: Capacity of CHP for 13 sectors of UK and Dutch manufacturing sectors. CHP=MW, IP=index, Heat output of CHP system=MW, FS= see Equation 4; number of industries: 13. The log linear functional form used assumes both slope and elasticity change at each point (Carter Hill, et al., 2001, pp. 132). That is the slope of the CHP function and its elasticity can change at every data point or year.

Notes:

[a] Different adoption level; [b] Common adoption (starting) level; * The coefficients measure the $(100 \times \hat{\beta})$ % Change in CHP associated with a unit change in, say, industrial production.

6.3. Modeling strategy

Through Equation 4 we first generate several scenarios of adoption. We assume two cases 1) a common starting level of adoption (no industry effects) and 2) a differing starting level of adoption (fixed effects or industry effect). We also apply Equation 4 to the UK case alone and to both the UK and the Netherlands combined. In our modeling strategy we consider:

Model 1. Adoption of CHP using UK data (6 sectors), covering 1991-01 period; (results are omitted here)

Model 2. Adoption of CHP prone industries (13 sectors of the two countries), covering 1991-01 period (results are omitted);

Model 3. Adoption of CHP prone industries (13 sectors) covering the 1991-96 period using UK and Dutch Manufacturing industry data. (Table 6).

We reject Model 1 since Equation 4 generates wrongly signed coefficients and low statistical significance for the 6 UK industries. For Model 1 we assume that industry adopts CHP at the same starting level: common intercept across industries. For Model 3 we reject the common intercepts (no industry effect) model and accept a model with different intercepts (industry effect); the latter model is closer to reality since industries face different energy cost structures and scale economies. Further we assume that today's adoption is determined by today's level of prices and production (see Equation 4). [14]

We also ran fixed effects regression for the whole period (1991-01) for both countries combined using a data matrix of 13 by 10. The fixed effect model incorporated dummy

[14] Using a data set covering 1991-01 we lagged fuel prices and production but their effects did not change coefficient signs on CHP adoption. Therefore we abandoned a lagged expectations model.

variables which are used to capture time effects but the results (omitted here) did not confirm that fuel cost savings spur CHP diffusion and hence we abandoned that model.

Given the inconclusive results of Model 1 for the UK alone we examine only CHP prone industries (see Tables 7 and 8 in Appendix for a list of manufacturing industries examined) for both the UK and Netherlands. In Model 2 we find statistically significant results but the sign of the fuel effect coefficient is not what we expected since the period 1991-01 includes rising and falling spark spread levels (Figures 1 and 5). Hence the direction of the effect of energy prices on adoption of CHP changes.

We accepted Model 3 (industry effects) since the model behaves in the expected pattern, shows high t-values and most coefficients show the correct signs. Model 3 (fixed effects) indicates that, given the heterogeneous characteristics within industry, industry managers are theoretically more likely to enter the CHP market. Model 3 therefore captures the adoption process.

The period 1991-96 is important in the formulation of the model since in this period the spark spread was more favourable than that of 1996-2001 years (see Figures 1 and 5), to potential entrants (the industry's energy managers) that would consider CHP investment.

6.4. Sensitivity Analysis: Changes in Industrial Output

Should the production effect (expressed in industrial output), motivate firms or manufacturing sectors to adopt CHP? Through Equation 4 we say that output would reveal the ability of industry to invest in CHP technology. Under Model 3 (industry effects, assuming different starting adoption level of CHP by industries) the growth in industrial production enhances CHP adoption but its contribution is small, relative to the other effects, in explaining adoption (Table 6). For example, on average, for the combined 13 manufacturing sectors, CHP diffusion grows by 37.6 MW, or increases by 12% following a one unit change in industrial production per year; note that a one unit change is a large number for this explanatory variable (see Table 6). The positive performance of manufacturing activity and expectations of future growth in industrial activity explain the positive sign of the industrial output coefficient on CHP adoption. One caveat is that some sectors have recorded contractions in industrial output (Table 2).[15]

As outlined in Section 2 our results are in agreement with other cross sectional studies focusing on CHP (see Dismukes and Kleit (1999); Bonilla et al. (2003); Rose and McDonald (1991); Joskow (1984) and Pizer et al. (2002) and Fox-penner (1990a). The latter did not find large effects on additional CHP stemming from industrial output.[16] Our model goes one step further by considering the changes overtime of industry output on CHP. Therefore our model (Equation 4) shows the historical effect of production on CHP capacity additions and hence on adoption.

6.5. Sensitivity Analysis: Power and Gas prices

In the period 1991-96 the coefficient of fuel cost savings (Equation 4, Table 6) reflects the percentage change in the decision to start using CHP associated to an absolute change in fuel cost savings per year. The coefficient is the largest contributor in terms of explaining the adoption of CHP. This result is consistent throughout our regressions

[15] For the UK, under a seemingly unrelated regression system industrial activity sparks the adoption of CHP in all sectors. But we obtained statistical significant coefficients in only four sectors out of 7 sectors.

[16] Fox-penner (1990) examined data at the US State level of CHP installations; he regressed CHP against buy back rates, industrial gas prices, industrial electricity rates, wages, population and industry value added (production).

(Table 6). In Model 3 (industry effects) the fuel cost savings coefficient shows that: a 10% increase in fuel cost savings, on average, will lead to a 4.1 MW (1.3%) increase in CHP diffusion in the manufacturing sector.[17] During 1991-96 the spark spread rose by (compound annual growth rates) 1.9% per year in the UK and 4.3% in the Netherlands. The rate of growth, however, in the spark spread turns negative within 1996-01 period (-5.4/yr and –9.6/yr respectively). Hence assuming this level of increase in fuel cost savings is accurate to estimate the potential of CHP adoption.

The take up of CHP in this sense will grow less than proportionately following an increase in the spark spread.[18] The coefficient of fuel cost savings is statistically significant and economically important. One advantage of this result is that it is based on data set involving the dynamic effect of fuel costs on the diffusion of CHP, which the cited studies ignore (see Dismukes and Kleit 1999; Joskow, 1984). This result is based on the historical experience of adoption rather than on only one year's data as most studies reviewed in Table 1 have assumed.

[17] Following equation 4 and 5 in pp. 20 : the diffusion of CHP can be computed as follows using the estimated coefficient of FS in Table 6 of the industry effect model as: [(-2)(-9.17)] x [Fuel cost savings raised to the power of -3] = 0.13. The estimated coefficient of fuel cost savings is: -9.17.

[18] For the UK under separate regressions using the SUR estimator we obtained wrongly signed coefficients for the whole period 1991-2001. Contrary to our expectations higher fuel cost savings do not spur the adoption of CHP for the Iron & Steel, Food, Pulp & Paper and the Machinery sectors. Therefore we rejected this model. Only the regressions for Chemicals and Oil refining sectors showed correct signs (negative ones) for fuel prices. These two sectors are the main adopters of CHP in manufacturing industry. For example for a 1 % increase in fuel cost savings in the Chemicals sector, CHP diffusion improves by 0.11 % on average (or by 1.2 MW) and declines by a small percentage point in the Pulp and Paper sector. The latter coefficient is statistically insignificant. The results are available from the author.

6.6. Sensitivity Analysis: Steam Capacity

For Equation 5, the steam capacity (output) coefficients *are positive but too small to convey much* information. The result indicates that the higher steam demand at the site should improve the probability of installing a CHP system. Dismukes and Kleit (1999) report a similar result using cross sectional data.

7. Conclusions

Whenever industrial plants consume power and heat there is a need to consider energy efficiency investment on a cogeneration (CHP) plant. The share of CHP in total electricity generation has grown tremendously in the UK and even higher in the Netherlands. The literature however, has failed to examine the historical role of prices, industry output and heat demand on CHP. The econometric model presented in this paper captures the uptake of CHP by industry involving 13 manufacturing sectors changing across years as well as cross-country data. This study is the first one involving data of disaggregated sectors and of historical levels of CHP diffusion for both countries using econometric methods. This study also is unique in that we constructed a variable to capture fuel cost saving effects using data on CHP adoption by industry.

We find econometric evidence to support the view that industry actively adopts CHP following historical variances in energy prices, in electricity prices and in industrial output; but the industry does respond much more to changes in fuel cost savings than to changes in industrial output and in other technological factors.

The econometric results for the period 1991-96 meet our expectations. Additionally changes in sectoral economic growth and in industrial heat demand help to spark the installation decision by industry. How the evolution of fuel and electricity prices impact on CHP during the period of 1996 to the present should be the subject of future research. A different model is required, however, to capture adoption of CHP under falling spark-spread levels.

Our model could be further tested to explain the diffusion of diesel engines, gas turbines, combined cycle plants and fuel cells. We could also consider CHP diffusion under the effect of declining capital costs. Further our analysis of technology diffusion should be based on plant specific prices for fuels and power, and on data beyond 13 manufacturing industries from other OECD countries.

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APPENDIX on the econometric model and assumptions

The econometric model:

A system of equations is used to build the CHP adoption model. The model is solved by the OLS technique within a fixed effects regression using panel data. A fixed effect regression is a method for controlling omitted variables in panel data when the omitted variables vary across sectors but do not change overtime (Stock and Watson, pp. 278, 2003). Consider the following model:

$$y_{it} = \alpha_i + \sum_{k=1}^{k} \beta_k x_{kit} + \mu_{it} \qquad \text{(A1)}$$

where y_{it} is the dependent variable (CHP) for different industries. The fixed effect regression model requires α intercepts for each industry. α is assumed to differ across industries; that is we can assume different starting levels of adoption of CHP with this model. The intercepts function as dummy variables capturing the influence of unobserved variables and each intercept needs to be estimated. β_k's are assumed to differ across manufacturing sectors that cogenerate. μ is the disturbance term and is uncorrelated across the sectors and time; μ is allowed to correlate with the intercepts; the disturbance term has a conditional mean of zero. The i subscript indexes industries at time or year t. x is a vector of exogenous variables for each of the sectors.

Assumptions for modeling CHP adoption by firms in the manufacturing Sector

We make three economic assumptions and one technical to test Equation 4. Equation 4 enables us to test Fox-penner's (1990b) analytical and econometric finding on the expected direction of price (electricity and gas) coefficients on CHP.

Economic assumptions:

(1) Growth in industrial activity (production) leads to two effects: a) it increases the demand for electricity and heat ; and b) it improves a firm's financial position increasing its ability to acquire new plant and equipment or CHP. We use an index (weighted value added) of industrial production per sector. The index refers to 1991-2001 period for the manufacturing sector.

(2) As we stated at the start of Section 5, the model of CHP adoption can be explained by annual changes in energy prices (or the ratio between electricity price to gas price, (liquid natural gas).

(3) Higher power or heat consumption given higher industrial output as in (1) leads firms to acquire new CHP.

Technical assumptions:

i) As the steam capacity increases at an industrial site CHP adoption increases. Steam capacity of the CHP installed reflects heat demand at the plant and the heat to power ratio. Plant managers usually determine the size a CHP unit based on large steam and heat demand at the site or on existing boiler capacity (see Dismukes and Kleit (1999); Strachan 2002; IEA 2002; DTI, 2002a). Therefore steam capacity should reflect existing demand for steam and heat.

Table 7. Industry sectors examined (Netherlands).

- Building materials
- Chemicals
- Food
- Other Metals
- Paper
- Power plants
- Refineries
- Services
- Basic metals

Table 8. Industry sectors examined (UK).

- Chemicals
- Food, beverages
- Iron and Steel
- Machinery
- Oil refining
- Pulp and paper, publishing

Table 9. Government policy measures to support the diffusion of CHP (UK)

- Exemption of GQ CHP fuel input form the Climate change levy
- Exemption of direct sales of GQ CHP electricity from CCL
- Exemption of CHP exports of electricity via licensed suppliers
- The Climate change Levy, Climate Change Agreements (CCA) and the lower CCL rates (20% of the standard rates) for industrial sectors with a CCA (affecting fuel prices of alternatives to CHP).
- Enhance capital allowances for CHP
- Exemptions from Business rates for CHP power generating equipment and Machinery
- The effect of emissions trading scheme
- The effects of Community Energy Programme and
- The effects of the quality improvement via incentives to improve non qualfying CHP so that it becomes eligible as qualifying CHP
- Promotion of Carbon Trust and the Energy Saving Trust

Source: DTI Digest of UK Energy Statistics