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Energy Policy 30 (2002) 649–661

ENERGY POLICY

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Distributed generation and distribution utilities

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Abstract

Distributed (co)generation (DG) represents an alternative paradigm of energy supply and the opportunity for significant CO_2 emission reductions. This paper investigates the adoption of the DG technology of internal combustion (IC) engine cogeneration in the Netherlands and UK from 1985–1998. This detailed comparison was motivated to understand why the Netherlands installed 20 times as many units and 40 times as much DG capacity (per capita) compared to the UK. The primary finding of this study emphasizes the win–win partnerships between DG adopters and utilities. While both governments promoted DG as part of their CO_2 reduction goals, only distribution utilities in the Netherlands were primed to support greater DG penetration. Crucially, Netherlands utilities offered high electricity buy-back rates which enabled innovative utilization of DG. Flexible operation modes allowed investment in larger units, benefiting from economies of scale due to fixed components in maintenance costs, and extended DG use to the much larger set of sites with limited electricity base-loads. The win–win partnerships between distribution utilities and DG adopters for cost savings also facilitated improved management of the electricity network. A final consequence was a virtuous circle of maintenance cost reductions from geographic concentration of DG units, resulting in improved returns and hence more DG unit sales. © 2002 Published by Elsevier Science Ltd.

Keywords: Distributed generation; Adoption; Utilities

1. Introduction

Technical and economic developments in distributed generation (DG) represent an opportunity for a radically different energy market paradigm (Patterson, 2000). Small, localized electricity generation near the point of demand allows on-site use of heat in cogeneration or trigeneration[1] applications for high overall efficiency (for base-load use, up to 95% HHV[2]). Gas-fired DG technologies also avoid electricity transmission losses. Therefore DG offers significant cuts in CO_2 emissions compared to centralized electricity generation and on-site heat production, even when all these applications use natural gas. The rate and magnitude of the adoption of such CO_2 emission reducing technologies will be critical in determining the effectiveness of policies designed to abate the threat of global climate change (Dowlatabadi, 1998).

Despite its attractiveness for reducing CO_2 emissions, DG units (as an energy efficient technology) are primarily adopted for economic savings relative to purchases of electricity and heat.[3] The literature on investment in DG and other energy efficient technologies has focused on why levels of adoption are low despite the high projected rates of returns (Train, 1985). Any disparity between economically wise investment levels and actual rates of adoption has been labeled the “energy efficiency gap” (Jaffe and Stavins, 1994). Explanations of this poor uptake have centered mainly on the motivations and behavior of adopters. Section 3.3 discusses why many commonly proposed explanations do not apply to DG in this comparison. Section 3.4 discusses the role of subsidies in this comparative study.

There is debate as to whether electricity buy-back rates are an important factor in the economic return of DG and cogeneration. Studies of US State levels of self-generation following PURPA have supported the

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[1] Trigeneration: cooling requirements are met using heat via an absorption chiller.

[2] Higher heating value (HHV) of input fuel (Gross calorific value).

[3] Low capital cost DG units may be retained to meet emergency electricity demand. These units are not a focus of this paper.

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PII: S0301-4215(01)00134-3

importance of electricity buy-back (Devine et al., 1987). Rose and McDonald (1991) used an economic model that took the electricity buy-back tariff to be less than marginal plant costs and hence not a decision factor in installation sizing. Dismukes and Kleit (1999) carried out econometric analysis of self-generators that found that buy-back tariffs were not important in the decision to self-generate. However, we disagree with the more recent studies and discuss the critical importance of buy-back tariffs for economic returns from DG in Section 4.1.

In addition to economic savings to users, DG offers the potential for improved economic management of electricity distribution networks. These benefits include deferral of investments in network infrastructure. For benefits to occur at a minimum, utilities should know when, where and how much electricity will be exported to the grid. The use of DG for network management is much improved if utilities also have some measure of control over DG resources. Models investigating distribution networks (Hoff, 1996; Feinstein and Chapel, 2000) conclude that DG capital and operating costs are critical to cost-effective use in network management. In a continuing debate, it is argued that DG costs should reflect all impacts on electricity networks (Cogen Europe, 1999). This paper considers a case where DG has been made available for distribution network management.

This paper investigates the adoption experiences of internal combustion (IC) engine cogen in the Netherlands and UK from 1985 to 1998. The terms DG and IC engine cogen will be used interchangeably as other DG technologies were limited to demonstration projects during the study period.

Section 2 describes the economic underpinnings of IC engine cogen, with emphasis on economies of scale. Section 3 reviews energy market developments and IC engine cogen adoption in the Netherlands and UK. The stark difference in DG adoption levels is reviewed, together with the market similarities that preclude many potential explanations of this disparity. Then the importance of subsidies and institutional factors for DG uptake are discussed. Section 4 illustrates how distribution utilities are crucial in explaining the level of DG adoption. Section 5 presents conclusions.

2. Economic analysis of IC engine cogeneration

2.1. Returns to investment in IC engine cogen

The determinants of economic return from IC engine cogen are important in understanding the factors governing adoption of this DG technology.

Commercially available natural gas-fired IC engine cogen units in the period of study (1985–1998), range in electrical output from 50 to 1000 kWe, with typical heat-to-power ratios (HPR) ranging from 1.8 to 2.1. Units are typically sized for site base-load electricity and heat requirements resulting in overall efficiencies ranging from 85% to 95%. Excess heat can be stored to smoothen on-site demand fluctuations, or dumped resulting in a lower overall efficiency. Excess electricity cannot be easily stored or dumped. Electricity export to the distribution grid allows potential applications with variable requirements to be considered, with larger unit sizing if a sufficient heat base-load exists. Typical DG applications are commercial buildings or small industrial sites, and include hospitals, leisure facilities and greenhouses.

Individual IC engine investment decisions were modeled using the conventional net present value (NPV) calculations over a 15 yr life. Use of a simulation model allowed uncertain input parameters to be expressed as probability distributions. Summed and discounted costs are subtracted from summed and discounted income streams. Costs are capital investment, maintenance costs, and natural gas purchases for the DG unit. Income streams[4] are avoided costs of purchased electricity, avoided costs of purchased natural gas, electricity sales and avoided boiler costs in a retrofit application.

In constructing the model, site-specific factors are taken from actual case studies and supplier literature. In addition, a series of open-ended interviews were conducted with a range of experts from differing viewpoints on IC engine cogen (adopters, suppliers, consultants, government experts, trade-body professionals). Further details of the engineering economic analysis of IC engine cogen, including detailed sensitivity analysis on input parameters, can be found elsewhere (Strachan and Dowlatabadi, 1999; Strachan, 2000).

2.2. Economies of scale

This DG technology exhibits site economies of scale owing largely to scale invariant maintenance costs. A major maintenance cost component is man-hours for the regular monitoring and repair costs which differ little between a 50 kWe unit or a 500 kWe unit. Maintenance costs are thus proportionally larger (per kWe) for smaller sized units (see Fig. 3).

Fig. 1 gives median values for returns to investment (NPV) on base-load DG units in the Netherlands and the UK. For a positive NPV, units in the UK need to be larger than around 140 kWe. For the Netherlands, this size threshold drops to around 100 kWe. Investments in the Netherlands have a smaller size threshold due to

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[4] Owing to transfer losses, there is no off-site sale of heat in this model.

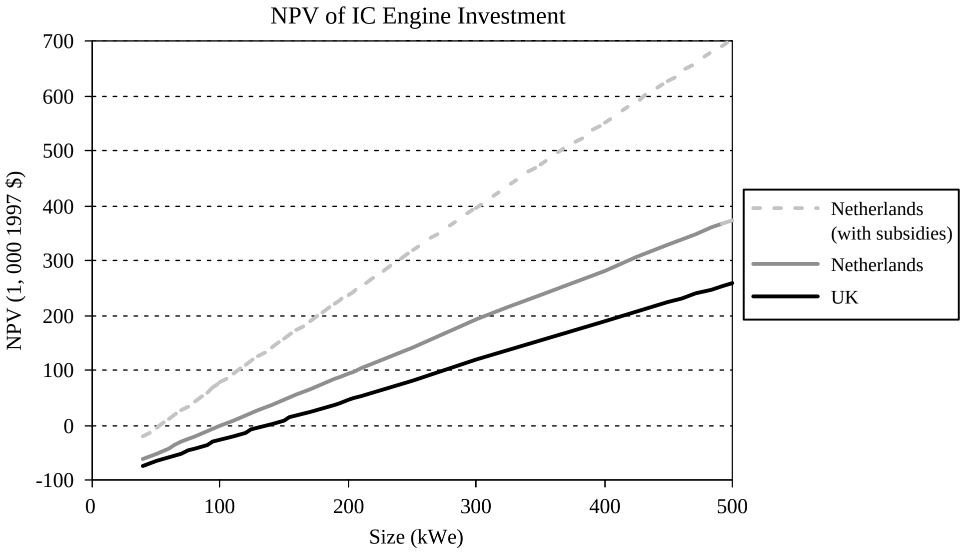

Fig. 1. DG economic size thresholds: Netherlands and UK.

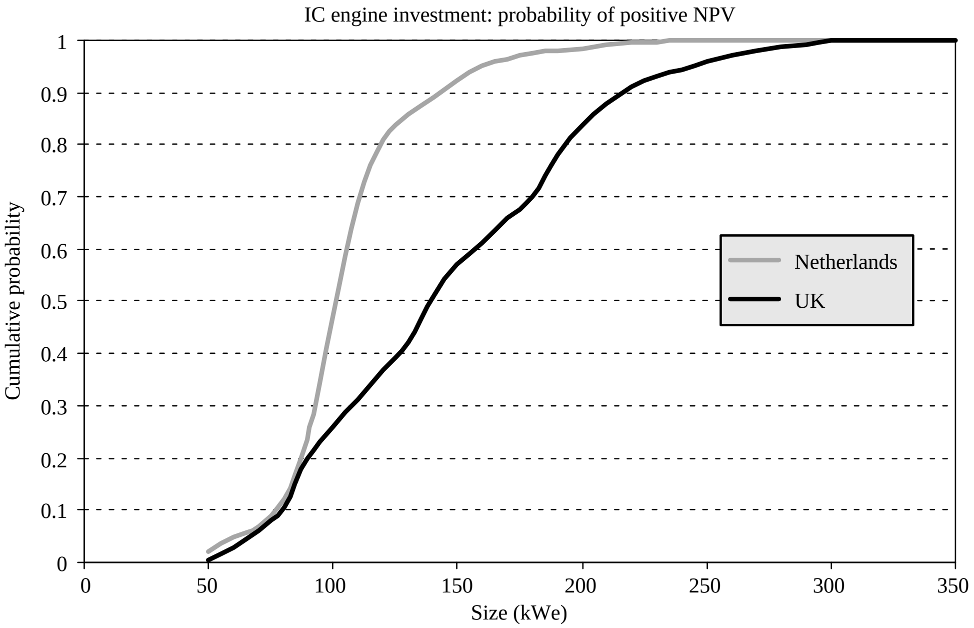

Fig. 2. Cumulative probability of a positive NPV for IC engines.

reduced capital and maintenance charges, and lower connection fees to the electricity network. Also shown is NPV when including the Netherlands subsidy programs (see Section 3.4). These measures have allowed units down to 70 kWe to be profitable and improved the returns on all units.

The full range of possible outcomes can be summarized as a cumulative probability distribution of the capacity at which NPV turns positive. Fig. 2 shows the range and associated probability of capacities at which NPV turns positive while accounting for site-specific factors including operating hours, reliability (and hence back-up electricity tariffs), and capital and maintenance costs.

Median values of size threshold for positive NPV are the same as in Fig. 1, at about 100 kWe for the Netherlands and 140 kWe for the UK. However, while units of 200 kWe have an extremely small probability of having a negative NPV in the Netherlands, in the UK there is a 15% chance that units of even this size will have a poor return on investment. Consequently, profit seeking investors would be well advised to invest in larger units still, or ensure long hours of operation, high reliability and the lowest possible maintenance charges.

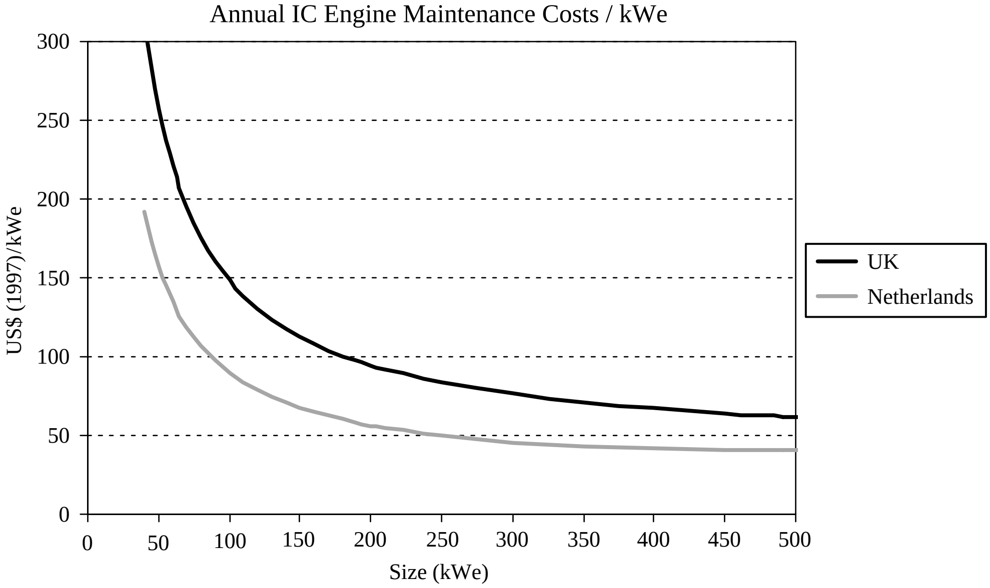

Fig. 3. IC engine maintenance costs by country.

2.3. *Economies of geographic concentration*

As with the introduction and adoption of other technologies needing support infrastructure, DG uptake is enhanced with each preceding installation. A higher density of units allows economies of geographic concentration in maintenance costs. As more units are installed, the maintenance costs per unit declines as labor time, parts inventory and other support functions can be organized more efficiently. This leads to a virtuous circle of cheaper maintenance, improved economic savings and hence more sales.

Fig. 3 illustrates the difference in annual maintenance costs for the Netherlands with its much higher density of units (and much greater absolute number of units) compared to the UK. The technology was identical in both countries and a number of Netherlands supply firms operate in the UK. We suggest that economies of geographic concentration are the underlying cause of the Netherlands maintenance cost reduction.

3. Netherlands and UK adoption of IC engine cogen

This section details the dramatic difference in IC engine cogen adoption levels in the two countries, provides an overview of installed DG units, discusses market similarities which preclude many potential explanations for variation in DG investment, and finally discusses the role of DG subsidies and of institutional factors.

3.1. *DG adoption: disparity in country adoption levels*

IC engine cogen has been a remarkable success in the Netherlands with over 5000 installations and 1500 MWe of installed capacity by 1997. However, the technology has struggled in the UK with an installed capacity of only 160 MWe from around 1000 sites. Fig. 4 illustrates the dramatic difference in uptake of IC engine cogen in both countries.

The Netherlands market is only 25% of the UK, but it had 5 times as many installations than the UK. What is even more striking is that the Netherlands realized 10 times as much installed capacity as the UK (40 times on a per capita basis), implying a much larger average size of DG plant. IC engine cogen investments have economies of scale (Section 2.2), and unit sizing is found to be a key issue for the level of adoption.

In both countries, promoting DG adoption was a public policy priority for its potential to lower national CO_2 emissions (discussed in Strachan, 2000). Calculating CO_2 reductions due to IC engine cogen adoption depends on which electricity and heat supply technologies are replaced. Emissions savings are additionally a function of carbon intensity of primary fuels, efficiency of generation, efficiency of energy transfer, DG heat utilization and DG operating hours.

Table 1 gives representative CO_2 emission reductions from DG, using published data and assuming that DG operational hours are 6000h/yr with heat fully utilized (i.e. base-load was the convention for DG operation). Centralized electricity distribution efficiency is 91.7%, and gas distribution efficiency is 98.7% (source: EIA, 1999). Technology specific and national CO_2 emissions are taken from UK DTI (1998), EnergieNed (1999), and Strachan (2000). Plant emissions in kg/MWh[5] are: IC

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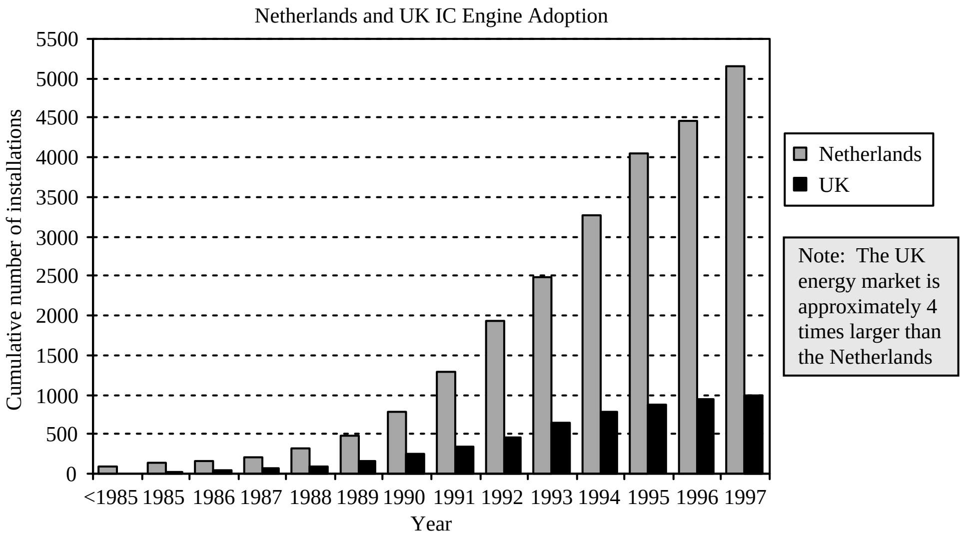
[5] kg/MWh is an output measure. To convert from kg/MWh to the input measure of lbs/MMBtu, multiply by the efficiency, multiply by 0.293 for MWh to MMBtu and multiply by 2.2 for kg to lbs.


Netherlands and UK IC Engine Adoption

Note: The UK energy market is approximately 4 times larger than the Netherlands

Fig. 4. IC engine cogen installations in the Netherlands and UK (data sources: CHPA, 1998; OFFER, 1998; CBS, 1998; Cogen Nederland, 1999).

Table 1
Representative CO_2 emission reductions from DG

CO_2 emission reduction case	Annual (1997) CO_2 reductions (million tonne)		CO_2 reduction as % of 1997 national emissions	
	UK (160 MWe)	Netherlands (1500 MWe)	UK (%)	Netherlands (%)
Low: replacing electricity portfolio, gas-fired heat boilers	0.44	4.2	0.07	2.4
High: replacing coal-fired steam turbines and oil-fired heat boilers	0.73	6.7	0.11	3.8

engine cogen = 620 kg/MW h, coal-fired steam turbine = 885 kg/MW h, UK electricity portfolio[6] = 685 kg/MW h, gas-fired boiler = 200 kg/MW h, and oil-fired boiler = 240 kg/MW h.

By 1997, due to DG penetration, the Netherlands realized an annual CO_2 reduction of between 4.4 and 6.7 million tonne, which accounts for 2.4–3.8% of national CO_2 emissions. The UK reductions were limited to 0.07–0.11% of national CO_2 emissions.

3.2. DG adoption: overview of DG units installed

Figs. 5a and b compare annual DG installations by sector in the Netherlands and UK. In the UK, the most active sectors have been commercial buildings (e.g. leisure centers, hotels, hospitals). Without higher electricity buy-back tariffs, base-load applications are limited by demand variability and restricted utilization to smaller and less profitable DG units. The Netherlands also has many installations in the various commercial buildings sectors. However, provided a large heat load is available (or with limited heat dumping), electricity export from these sites would allow larger unit sizing. The largest sector for IC engine cogen in the Netherlands is horticulture. Greenhouses with very large heat loads are an excellent DG application, with a proportion of electricity used for predictable on-site demands for artificial lighting and the remainder available for export.

In comparing overall adoption of IC engine cogen in the two countries, we have assumed that the overall potential is the same on a per capita basis. Is this a valid assumption?

The greater population density[7] of the Netherlands (384/km^2) could benefit DG compared to the UK (242/km^2). However, England's population density (376/km^2) is close to the Netherlands, urban population densities are similar, and geographical patterns of investment relative to population density did not show any significant differences.

For many sectors (e.g. health, leisure, education, sewage) it is reasonable to assume that two countries with comparable social organizations, cultures, GDP/capita and climate have similar numbers of potential DG sites. Country specific factors could skew other sectors (e.g. multi-residential housing). This was investigated using national statistics (CBS, 1999; ONS, 1999)

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[6] In 1997, UK electricity capacity was 55.9% steam turbine (of which 66.7% is coal fired), 18.9% nuclear, 17.5% CCGT, 2.1% gas turbines and engines and 5.6% hydro-electric (source: UK DTI, 1998).

[7] *Sources*: OECD, 1999; ONS, 1999.

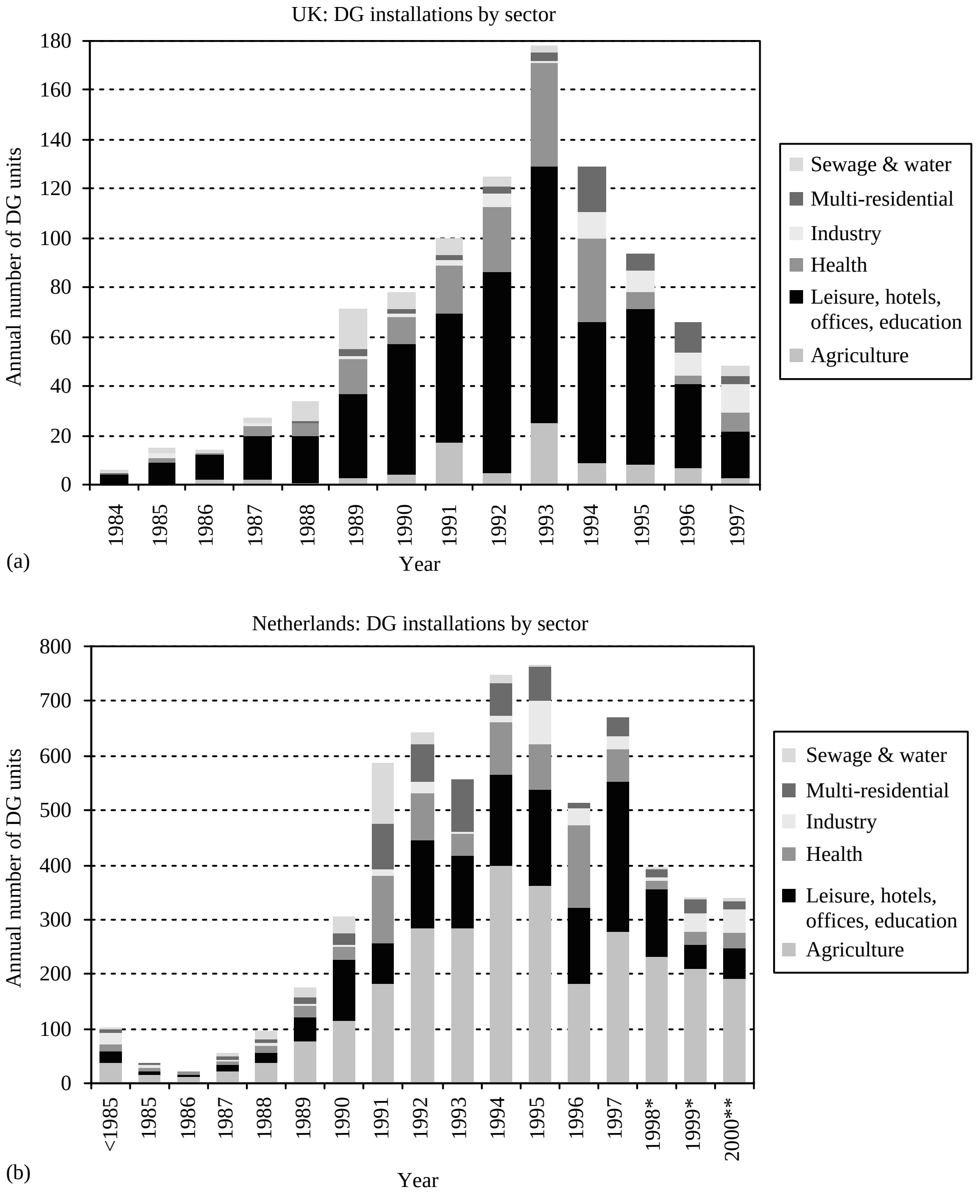

Fig. 5. (a) UK: IC engine cogen installations by sector. (b) Netherlands: IC engine cogen installations by sector.

for buildings and industrial facilities, and energy demands within these sub-sectors. No evidence of major disparities was uncovered. Particular attention was paid to estimate the horticulture sector of both countries. As of 1997, there were 2286 DG units in the Netherlands horticulture sector, with only 86 in the UK (i.e. a ratio of 27-to-1). However, there is a substantial greenhouse industry in southern England. Overall, there are as many potential sites for DG investment in UK horticulture as in the Netherlands.

3.3. *Market similarities*

This paper was motivated to explain the stark difference in the adoption level of IC engine cogen in the UK and Netherlands. A number of commonly proposed explanations of DG investment, detailed in Table 2, can be ruled out due to similarities between the two markets.

Additional explanations for country differences in DG investment were discarded following the initial investigation. Newell et al. (1999) suggested that lower energy prices (possibly due to market liberalization) weaken the drive to implement energy efficiency measures. However, econometric analysis found that energy prices (with and without lags) were a poor explanatory variable for installation rates. Furthermore, market liberalization reduced both electricity and natural gas prices, and investment return from a DG unit was fairly constant through time. Another

Table 2
Common explanations for DG investment ruled out by Netherlands–UK market and institutional similarities

Known barrier to adoption	Market and institutional situation in the UK and Netherlands
Supply constraint on input fuel for DG	Extensive natural gas networks
Decision-makers are not aware of the technology (Morgenstern, 1996; DeCanio and Watkins, 1998)	Government information programs, supported by cogen/DG trade groups
Idealized engineering-economic projected savings never being achieved (Metcalf and Hassett, 1998)	Case studies and operation data on actual installations
Investors are wary to invest their own capital, or capital for energy related investments is not available (Owen and King, 1997)	Availability of supplier financing
Additional costs that organizations face to change their method of operation (Cebon, 1992) deterred them from making the investment	Proven packaged[a] technology, and technical standards for interconnection with the electricity network
Regulatory restrictions on DG investments and electricity sales	Separation of electricity generation and distribution, with open third party access to the distribution network and power purchasing based on avoided costs
Government imposed moratoriums on new power generation facilities	DG exempt from moratoriums on new power generation facilities (1994 in the Netherlands, 1998 in UK)
Concern over the spatial and temporal impacts of DG on local air pollution	DG support was given for reduction in CO_2 emissions. IC engine cogen was exempted from regulations controlling NO_X, CO or hydrocarbons (HC) emissions[b]

[a] IC engine cogen is packaged as a single unit, with generator, heat exchangers, control panel, and acoustic enclosure for simple connection to a building's electricity and hot water systems.

[b] IC engines can be catalytically controlled. Alternative DG technologies (e.g. fuel cells) offer very low NO_X, CO and HC emissions if this issue is a priority.

proposed contributing factor is the role of social networks (Valente, 1995), as the diffusion process is categorized by information flows (Bass, 1969). However, temporal and spatial analysis via a Geographical Information System (GIS) did not reveal any trends or a diffusion pattern consistent with contagion models. In addition, it would be difficult to separate the effects of networks of adopters, and suppliers' efforts to set up a high geographical density of DG units for reduced maintenance costs (see Section 2.3).

A final potential explanation for energy efficiency investments could be option values due to uncertainty in investment return (Hassett and Metcalf, 1993). The UK electricity and gas markets were liberalized in stages from 1990 to 1994,[8] and were characterized by greater volatility[9] in energy prices than the Netherlands where liberalization only began in 1998. In addition, short term prices for emergency back-up electricity in the UK could rise by more than an order of magnitude above average prices during peak demand periods (Electricity Pool, 2000). However, electricity and gas prices in the UK were correlated (correlation co-efficient of 0.82) and DG investment contracts typically shared risk between adopters and suppliers for movements in base energy prices. In addition, various hedging mechanisms were available for back-up electricity requirements, and spot market price spikes of <50 h/yr would have little overall effect on overall profitability of units designed for operation for thousands of hours per annum. Thus the magnitude of the option effect is too small to explain the large differences observed between the two countries (as found for a different problem by Sanstad et al., 1995).

3.4. Importance of subsidies

Similarities in the markets for DG in the Netherlands and UK leave two explanations for the difference in adoption level: subsidies and institutional factors. Section 2 showed that differences in investment return between the Netherlands and UK were heavily influenced by both subsidies and economies of scale.

As noted in Section 3.1, DG was promoted in both countries as an effective measure for reducing CO_2 emissions. However, in the Netherlands the target for IC engine uptake was directly linked to policy support actions. The Netherlands government financial support measures were extensive. UK capital subsidies were limited to 'kick-start' DG in targeted sectors. Table 3 details DG promotional measures.

Table 4 illustrates the available subsidies in both the Netherlands and the UK. Each country recouped a similar proportion of installed IC engine capacity per subsidy (in \$/kWe terms). A cursory examination of Table 4 confirms that subsidies were an important factor for DG investment. However, sizing and utilization of DG plants are also key in determining economic operation. This is suggestive of different modes of plant

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[8] Gas and electricity competition for residential consumers was implemented from 1996 through 1999.

[9] Coefficients of variation for energy prices (1988–1998): UK, electricity 0.5, natural gas 0.1. Netherlands, electricity 0.06, natural gas 0.01.

Table 3
Promotion of IC engine cogen in Netherlands and UK

	The Netherlands	The UK
Part of government policy on climate change	√	√
Support measures directly linked to climate policy goals	√	no
Capital subsidy	√	Limited
Fuel subsidy	√	no
Information office	√	√
Coordination of suppliers, utilities and users	√	no
Restructured gas and electricity industries	√	√
Performance in meeting DG/cogen target	Exceeded	Failed

Table 4
IC engine cogen subsidies and installed capacity

	Netherlands	UK
Capital subsidy	\$M 167	\$M 10
Information gathering and dissemination	\$M 17.7	\$M 9.5
Fuel subsidy	\$M 137	0
Energy tax exemption	\$M 3.9	0
Utility incentives for CO_2 controls	~0.15¢/kW h	0
Installed distributed generation capacity	1500MWe	160 MWe
Subsidy per unit capacity installed	\$220/kWe	\$155/kWe

operation and decision making. Clearly a closer examination of the evidence is in order.

3.5. Sizing and utilization of DG units

All else being held constant, the subsidies offered in the Netherlands lowered the size threshold for economic investments. However, the majority of DG investments in the Netherlands were in much larger units. The UK (with a higher size threshold) had relatively many more small units. This evidence contradicts the centrality of subsidies as the prime motivation for DG investments. This is why we turn to institutional factors to explain how so many large DG units were installed in the Netherlands, including sites with limited base-load energy requirements.

This disparity between reduced economic size thresholds and larger unit sizing in the Netherlands is illustrated in Fig. 6. As discussed in Section 2.2, the economic size threshold for IC engines was lower in the Netherlands at 100 kWe, and lowered further to 70 kWe by public subsidies. But Fig. 6 illustrates that the average size of DG units installed in the Netherlands was substantially larger than the UK.

Even if average DG unit sizes were larger in the Netherlands, significant numbers of DG units would still be expected at the lowest sizes. That is, the full range of economic schemes would be expected to be exploited. However, as shown in Fig. 7, only 7% of Netherlands schemes were from 50 to 100 kWe. Subsidies lowered the size threshold below 100 kWe, but relatively few investors exploited the benefits of installing DG on these smaller sites. Returns to investment cannot have been the key to their decision-making. If it had been, the subsidy would have motivated their involvement.

In comparison, more than 50% of DG units in the UK were <100 kWe, well below the economic size threshold (140 kWe) there. From our analysis of IC engine investments, an investor in the UK wanting to limit the probability of a loss to 15% would install units of 200 kWe or larger. Seventy-seven percent of units installed in the UK are smaller than this threshold. Fig. 6 shows that since 1995, UK unit sizes have dramatically risen, helped by a more proactive role of UK distribution utilities in partnership with Netherlands owned supply firms, who have brought their mode of DG operation to the UK.[10]

In Section 4 we argue that the support of utilities is key for operating DG in a way that takes advantage of economies of scale. Exploiting these economies is central to development of a healthy supply and maintenance industry and widespread diffusion of this technology.

4. Distribution utilities: enabling institution for DG

The Netherlands government encouraged distribution utilities into promoting DG (discussed in Blok and Farla, 1996). Regulatory reform in the Netherlands separated generation and distribution, and restricted distribution utilities to invest in generating units of <25MWe per plant. In response to a national target of reducing CO_2 emissions with corresponding financial supports, distribution utilities formulated their own environmental action plans (EnergieNed, 1993). Under these plans, DG became the most important measure for meeting CO_2 reduction targets, and by 1998 gas-fired IC engines accounted for 1500MWe or 6% of installed electric capacity in the Netherlands.

4.1. Innovative utilization of DG

In both the Netherlands and UK, distribution utilities were under obligation to accept electricity export by self-generators with buy-back tariffs being set by the avoided costs to the utility. Tariffs are based on alternative

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[10] A separate paper is being prepared analyzing the role of UK suppliers and financing of DG installations of uncertain economic profitability.

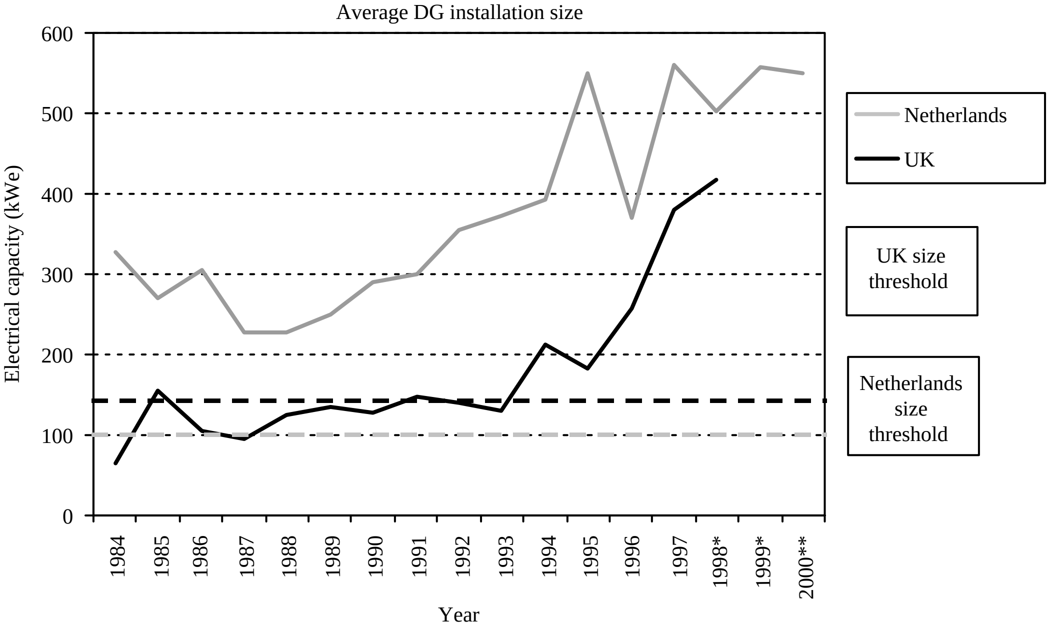

Fig. 6. Average size of Netherlands and UK DG units by year. [Years marked (*) are provisional data, years marked (**) are supply firms' market estimates.]

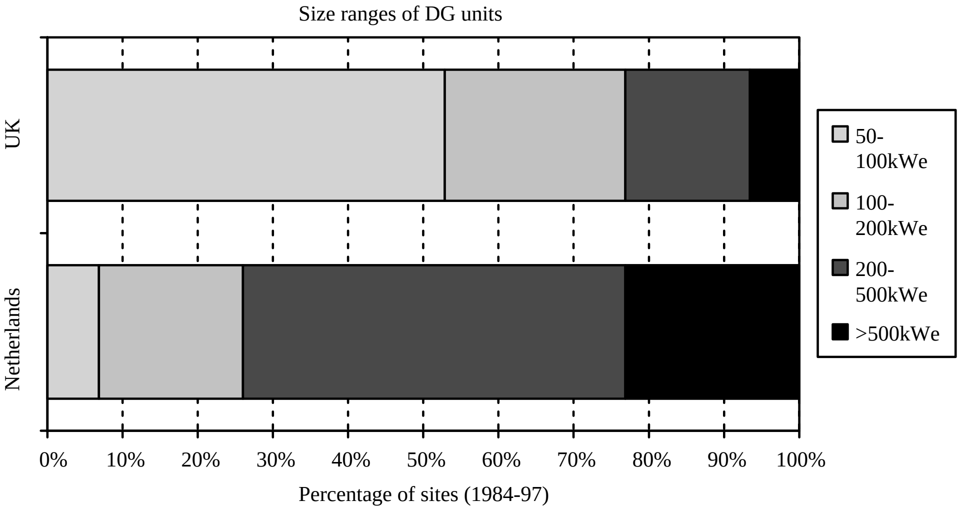

Fig. 7. DG units by size range.

generation costs together with some representation of the costs and benefits from the distribution of this electricity, including capacity charges for supply at peak times. Thus there is considerable latitude in buy-back price determination. Fig. 8 illustrates how Netherlands utilities have purchased DG electricity at typically 75% of relative grid sale price[11] making electricity export attractive.[12] In contrast, UK utilities paid DG ventures only 40% of relative grid sale price.

The buy-back tariff is critical for flexible operating modes, and hence larger sizing of DG units. High buy-back tariffs also allow installation opportunities at the much larger set of sites with variable electricity demands.

4.2. Benefits for adopters of new modes of DG operation

In Section 2.2, size thresholds for IC engine cogen were calculated assuming that unit outputs were used to meet base-loads of both electricity and heat. This limits the size of DG units to available base-load requirements *and* to a smaller set of potential sites. If heat demand is

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[11] Relative grid sale price is predominately averaged end user tariff, plus a much smaller annual capacity charge.

[12] Some DG units in demand constrained areas have enjoyed tariffs over 100% of relative grid price.

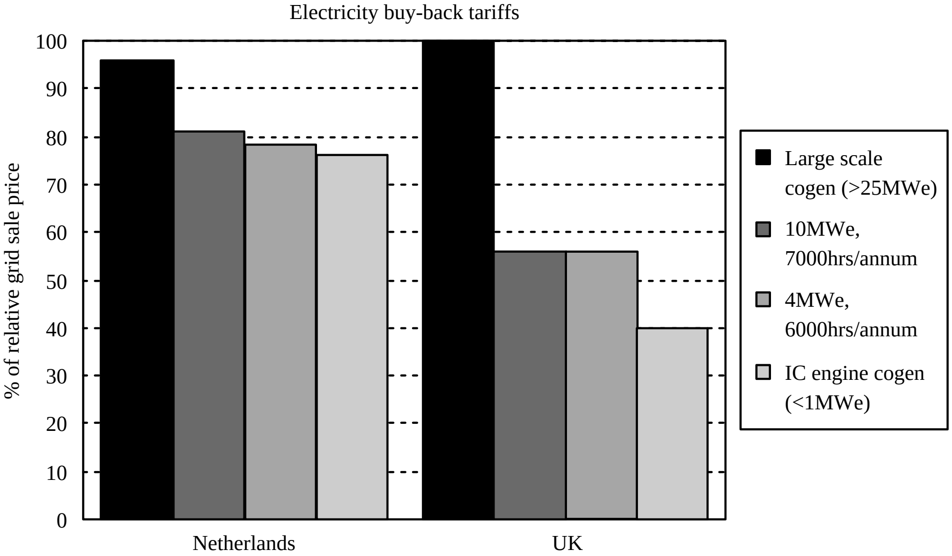


Fig. 8. Electricity buy-back tariffs for self-generators (source: Cogen Europe, 1995).

variable, excess heat can be stored, or rejected to the atmosphere via a dump radiator. However, excess electricity is difficult to store or reject and represents a valuable income stream when exported to the grid. Electricity export allows larger sizing of DG units on sites with limited base-loads, but the buy-back tariff offered will determine whether to export electricity.

Figs. 9a and b give returns on investment for IC engine cogen in the Netherlands and UK, using these buy-back tariffs of 75% and 40%, for cases ranging from no electricity export to all export. Heat is used on-site, although 20% rejection of available heat is now factored in to account for possible variable heat demand (i.e. the DG units would now operate at only 82% overall efficiency). In the Netherlands, the higher buy-back tariff supported larger unit sizing, even if all electricity was exported. This was not the case in the UK. Low prices for electricity export gave less incentive for investing in a larger DG unit. Furthermore, if the majority of electricity could not be used on-site then a positive NPV could not be achieved with any size of unit.

Therefore, the higher buy-back tariffs resulted in electricity export from large units to be worth the extra capital investment in the Netherlands. Economies of scale applied both to sites where the DG unit met base-load energy requirements and sites with variable electricity requirements. In the UK, a lower buy-back tariff restricted DG units to the far fewer sites that have sufficient base-load demand.

4.3. Benefits to distribution utilities of new modes of DG operation

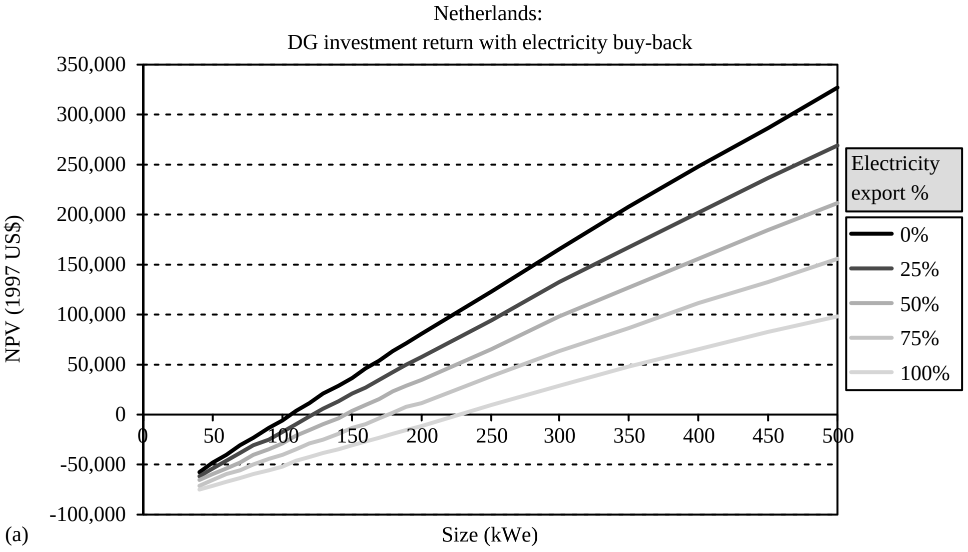
The above analysis shows that buy-back tariffs offered by Netherlands distribution utilities made DG more attractive for investors through innovative operation and larger sizing. What benefits did this utilization of DG give to the distribution utilities?

DG ventures were win–win partnerships between adopters and Netherlands distribution utilities. Firstly, even with buy-back tariffs at 75% of relative grid sale price, distribution utilities were making a 25% profit from electricity purchased from DG operators. Low cost electricity from DG also allowed Netherlands distribution utilities to become players in the liberalizing generation market.

DG also gave Netherlands distribution utilities the potential to improve management of their power networks, including postponement of new network infrastructure. Distribution utilities were involved in DG ventures, facilitated through a standard contract process (Cogen Nederland, 1994). This also included financing in many cases. Therefore, utilities obtained prior knowledge and a degree of control (depending on the contract details) over electricity exports to the grid. This knowledge and control of electricity exports gave distribution utilities the potential to use DG as a tool to improve management of electricity networks. Twenty-three percent of electricity produced by the installed DG capacity was exported to the distribution network to meet off-site demand (EnergieNed, 1999). Future work seeks to determine the monetary value of DG electricity to distribution utilities and relate this to buy-back tariffs.

4.4. Additional consequences of new modes of DG operation

Distribution utilities in the Netherlands aided the development of an embryonic DG market. In the early



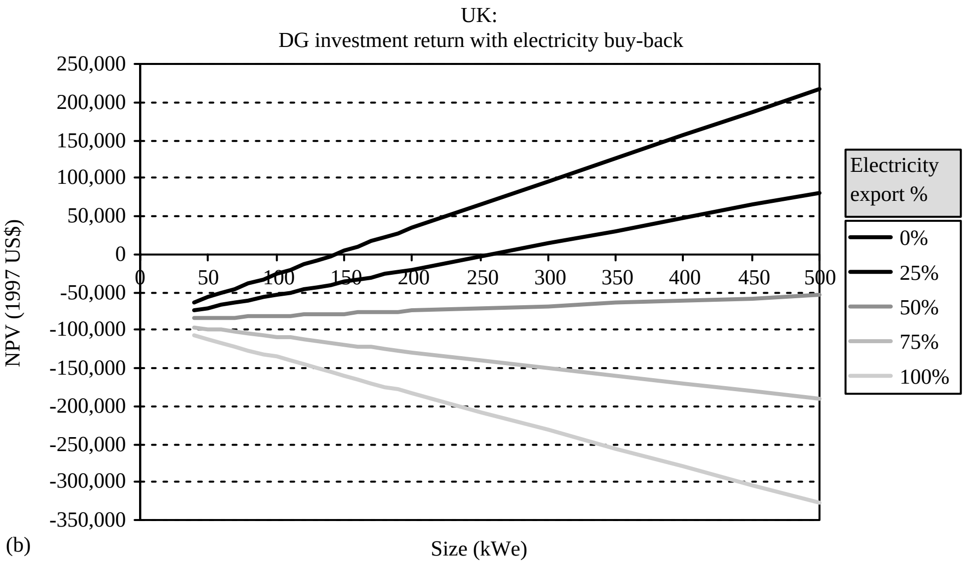


Fig. 9. (a) Netherlands: median NPV of investments in DG units of various capacity, given different percentages of electricity export. (b) UK: median NPV of investments in DG units of various capacity, given different percentages of electricity export.

1990s, utilities were partners in a majority of IC engine schemes. For potential adopters, distribution utilities could overcome reluctance for this discretionary investment through provision of capital, expertise and reputation. From 1996 onwards, the share of DG investments by distribution utilities declined, partly due to the increasing focus by utilities on the upcoming liberalization of the Netherlands electricity sector. However unit sales, believed to be predominately to private investors, remain strong in the Netherlands at around 350 per annum (see Fig. 5b).

With the experience of over 5000 installations in their home market, the Netherlands have realized technology export benefits as their DG suppliers became leaders in all major European markets. The innovative modes of DG operation that were developed in conjunction with distribution utilities in the Netherlands, are now being deployed in other countries including the UK

Netherlands utilities as partners in DG ventures also improved economic return on DG units through reduced interconnection costs to the distribution network. Typical connection costs in the Netherlands ranged from 6% to 10% of overall capital costs. In the UK a higher range of 10–15% adversely affected the economics of schemes (Cogen Europe, 1999). The technical requirements of DG interconnection were clearly specified in both countries.

Lastly, the Netherlands had much lower maintenance costs than the UK (Section 2.2). The technology was identical in both countries and a number of Netherlands supply firms operate in the UK. We suggest that economies of geographic concentration from a higher density of DG units are the underlying cause of the Netherlands maintenance cost reduction. As the DG market develops further, supply firms in both the Netherlands and UK are working with distribution utilities to set up 'clusters' of DG units to benefit from economies of geographic concentration. Distribution utilities are interested in DG clusters in order to provide significant amounts of pre-arranged electricity export for network management.

5. Conclusions

This paper has investigated the stark difference in adoption of IC engine cogen in the Netherlands and UK. On a per capita basis, the Netherlands realized 20 times as many DG units, and 40 times as much DG capacity compared to the UK. By 1997, due to DG penetration the Netherlands realized an annual CO_2 reduction of between 4.4 and 6.7 million tonne, which accounts for 2.4–3.8% of national CO_2 emissions. DG became the major tool of distribution utilities in meeting industry CO_2 reduction targets.

Many of the common hypotheses for explaining the level of adoption of a new technology were shown not to apply in this case. Subsidies undoubtedly improved the economic return from DG units. However, institutional factors are shown to be more important in explaining the details and pattern of DG adoption.

IC engine cogen exhibits economies of scale due to fixed components in maintenance costs. The economic size threshold for IC engine cogen was lower in the Netherlands due to reduced interconnection charges as well as lower maintenance and capital costs. This size threshold was further reduced by public subsidies. However, DG installations in the Netherlands were much larger in size, indicative of a different mode of operation.

Netherlands distribution utilities offered higher electricity buy-back tariffs. Electricity buy-back allows larger unit sizing and promotes use of DG on sites with limited electricity base-load demand. Low buy-back tariffs in the UK made electricity export much less attractive. Therefore in the UK, DG installations were confined to smaller less profitable units on the reduced sub-set of sites with sufficient base-load demand for electricity.

For distribution utilities, DG provided low cost electricity and gave access to liberalizing generation markets. DG also offers the potential for improved network management. At a minimum this requires knowledge of projected electricity production, and is greatly enhanced by distribution utilities having some control over electricity exports. As Netherlands distribution utilities were partners in DG schemes, prior knowledge and control of electricity exports could be arranged through standard contracts co-ordinated by the cogen/DG trade body. As well as meeting on-site demands, 23% of DG electricity was available for improved management of distribution networks.

The win–win partnership for DG between adopters and distribution utilities allowed the development of an installed base of DG units. This enhanced DG uptake through economies of geographic concentration in maintenance costs. Increasing numbers of DG units creates a virtuous circle of lower maintenance costs, improved economic return and increased sales. In addition the Netherlands realized technology export benefits as their DG suppliers became leaders in all major European markets, utilizing their experience in working with distribution utilities.

Future work investigates additional impacts of DG adoption. This includes quantifying the benefits of DG electricity to distribution utilities and relating this to buy-back tariffs, determining the diffusion ceiling of DG under different operational modes, and investigating the development of a supply industry of a newly commercialized energy technology.

Acknowledgements

The authors would like to thank David Green and Wim Jochem for data provision, the UK and Netherlands energy experts interviewed for this paper, and Simon Minett, Granger Morgan, Scott Farrow, Kathleen Carley, Alex Farrell and Lester Lave for insightful comments. This research was made possible through support from the Center for Integrated Study of the Human Dimensions of Global Change. This Center has been created through a cooperative agreement between the National Science Foundation (SBR-9521914) and Carnegie Mellon University and a grant from the MMIA program at NSF (SBR-9711498). It has also benefited from additional grants from the Exxon-Mobil Foundation, and the American Petroleum Institute.

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