# Distributed vs. centralized electricity generation: are we witnessing a change of paradigm?

## An introduction to distributed generation

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**Abstract:**

In this paper we study the reason for the current interest in distributed generation and the challenges to be faced while increasing its share in the electricity generation mix. We decided not put any restriction on the technologies used or plant size in the definition of distributed generation and based our research on the definition putting the emphasis on the connection to the distribution network and the proximity to the consumption point. We first describe the centralized generation paradigm to show that its failure to provide answers for niche generation markets combined with both electricity deregulation and the more stringent environmental constraints paved the way an increasing share of distributed generation over the past years. We then show that to be a credible alternative generation paradigm, distributed generation will have to overcome significant technical, economic, regulatory and environmental hurdles.

*Keywords:* distributed generation, decentralized energy production, cogeneration

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# Executive summary

Under the current centralized generation paradigm, electricity is mainly produced at large generation facilities, shipped though the transmission and distribution grids to the end consumers. However, the recent quest for energy efficiency and reliability and reduction of greenhouse gas emissions led to explore possibilities to alter the current generation paradigm and increase its overall performances. In this context, one of the best candidates to complement or even replace the existing paradigm is distributed generation where electricity is produced next to its point of use:

- historically, distributed generators have been able to act as a complement to centralized generation i.e. they provided solutions to overcome the shortfalls of the centralized generation paradigm;

- deregulation theoretically enabled distributed generators to enter the electricity market through market price signals and fewer barrier to entry; and

- environmental concerns led regulators to promote efficient generation technologies such as cogeneration. Cogeneration can be considered as distributed as heat and steam cannot be easily shipped.

The main aim of this study is thus to better understand what hurdles currently prevent distributed generation to play such a role. Based on recent research, we have identified X different categories of barriers:

- technical issues: distribution networks will have to be reinforced and partly redesigned to cope with new capacities. Besides, they will have to incorporate both control and protection software and hardware to coordinate the distributed generators and make.

- Price competitiveness: for such a move toward distributed generation to be efficient in terms of both performance and price, distributed generation will have to be used where it is more competitive than centralized generators i.e. at congested areas where it is uneconomical to build a centralized plant or as cogeneration facilities. This will also mean more research and development for new technologies such as fuel cells in order to reduce the cost per kWh.

- regulatory barriers: significant work has to be undertaken to alter the regulatory environment the distributed generators are facing: regulatory hurdles still impede the spread of distributed generation as distribution network operators have little incentive to give them access to the distribution network while distributed generators are unable to cash in the positive impact they have.

- environmental impact: distributed generation does not necessarily mean clean generation. Indeed, diesel reciprocating engines often used as back-up distributed generators tend to be the worst performers in terms of greenhouse gas emissions. Distributed generation, to be a sustainable alternative paradigm, will thus have to rely on the cleanest technologies or favour efficient uses maximising energy efficiency and reducing emissions such as cogeneration.

# Content

# Introduction

In the current context of high fluctuation in energy prices, concerns over fossil fuel depletion and increased awareness of greenhouse gas emission, the European Union sees energy efficiency as a major challenge for the years to come. In its communication, the Commission of the European communities (2006) estimates that the European Union can save up to 20% of its energy consumption over the period 2007- 2020. In several countries such as the United Kingdom, a wide range of possibilities are currently explored including distributed generation.

*"The Government's Energy Review Report of July 2006 highlighted the challenges we face in addressing climate change and ensuring security of energy supplies. A key part of responding to this challenge is to investigate to what extent DG could complement, or in the longer term potentially offer an alternative to, a centralised system."* (Ofgem, 2007)

To better understand the implication of such a statement, special care has to be given to the definition of distributed generation. As a relatively new field of research, several expressions are still currently used such as "decentralized generation", "dispersed generation", "distributed energy resources" etc. As show by Pepermans et al. (2005), the definition varies significantly in terms of characteristics of the generators mentioned. Dondi et al. (2002) define distributed generation as a generator with small capacity close to its load that is not part of a centralized generation system. Chambers (2001) puts a limitation on the maximum capacity of distributed generation (30kW). There is however no consensus in the literature on the upper limit to be set: this limit can range from 1MW to over 100MW (Ackermann et al., 2001). So as to define distributed generation in a way that could encompass a wide variety of technologies, capacities, the connection type and so forth, Ackermann et al. (2001) devised a definition applicable to the vast majority of distributed generators.

*"Distributed generation is an electric power source connected directly to the distribution network or on the customer site of the meter".* (Ackermann et al., 2001).

The key criteria in this definition are the connection to the distribution network and the proximity to the end consumer. Using such a definition will for instance rule out of the study large wind farms connected to the transmission network. In a weaker form of the definition, we will include large combined heat and power plants to the definition: large cogeneration facilities can be connected to the transmission network but are conceptually close to distributed generation as they need to be located in the vicinity of their heat consumers.

Put into an historical perspective, Ofgem's aim to promote research in distributed generation can come as a surprise as the past century has been driven by centralization and increase in scale of power plants: though born decentralized, electricity quickly moved to a centralized paradigm where electricity is produced, transmitted and distributed to the end consumers. As early as 1930s centralized generation was the leading form of generation in the US thanks to the advent of the AC grid (Carley, 2009). The main goal of this study will thus be to understand why we should reconsider an electricity generation system that was so easily dismissed in a past and to identify the drivers of such a trend reversal i.e. the key advantages of distributed generation that are at the outset of such a paradigm change. The first objective of the study is to describe the current state of the power market where centralized generation is dominant and distributed generation accounts for a relatively small share of the total generation on average. The paper will focus on the main assets of distributed generation, the technologies used and current and prospective penetration rates. We will there review the different classifications of distributed generators introduced in the literature to provide the reader with a consolidated view. The second part will show that distributed generation currently lacks the inner strength to become the dominant generation paradigm: increasing sustainably the share of distributed generation will mean lifting several barriers that currently impeded its spread. The hurdles are first of technical nature: the current network architecture is able to handle a limited number of distributed generators but will have to be revamped to accommodate a larger proportion. Second, given the current lack of cost competitiveness of some technologies on a $/kWh basis, generators will have to provide significant effort in research and development or favour use of distributed generation where they can prove more competitive than centralized generation. Third, the study will review the regulatory barriers to distributed generation expansion:

though deregulation had a positive impact on distributed generation, additional regulation will be needed to ensure a balanced growth. The study will rely on research results by Cossent et al. (2009) while conducting such a review. Last, based on recent research by Strachan et Farell (2006) on the emission levels for different distributed generation technologies, we will show that moving towards this new paradigm will not ensure clean generation for all uses. Increasing the performance of distributed generation with respect to emissions will necessarily mean a larger share of cogeneration in the short run and further development of fuel cells in the medium run.

# I. Current state of the power market

## *A. The centralized paradigm*

### 1. Description and definition

Since the 1990s, electricity production has been driven towards generation concentration and a higher degree of integration leading to the current centralized electricity paradigm. This move was driven by several factors (US DOE, 2007):

- Economies of scale: the advent of steam turbines made it possible to increase the size of the turbines while decreasing the marginal cost of electricity production. The rapid spread of this technology led to a surge in the overall plant capacities;

- The search for high energy efficiency: gains in efficiency were achieved through larger facilities capable of handling higher pressures and temperatures in steam used in electricity generation. At a certain point, the gains were however offset by the increase in operating and maintenance costs as materials were unable to sustain operation at high specification over the long run;

- Innovation in electricity transmission: the use of alternative current instead of direct current permitted to transmit electricity over long distances with a significant loss reduction;

- The search for reliability: so as to increase the reliability at the customer's end, large electricity production facilities were connected to the transmission networks. Pooling resources helped reduce the reliance of each customer on a particular generator as other generators were often able to compensate for the loss;

- Environmental constraints: the use of transmission networks made it possible to relocate the generation facilities outside the city centres thus removing pollution due  to exhaust from coal fired plants;

- Regulation favouring larger generation facilities.

In the sector's layout resulting from this move towards concentration and integration, electricity is generated, transported over long distances through the transmission network and medium distances through the distribution network to be finally used by the end customer. This can be summed up as follows:

*"Traditional electrical power system architectures reflect historical strategic policy drivers for building large-scale, centralised, thermal- (hydro-carbon- and nuclear-) based power stations providing bulk energy supplies to load centres through integrated electricity transmission (high-voltage: 400, 275 and 132 kV) and distribution (medium-, low-voltage: 33 kV, 11 kV, 3.3 kV and 440V) three-phase systems."* (Mc Donald, 2008).

Though dominant, centralized generation has always been operating along a smaller distributed generation capacities that were never phased out of the market. The persistence of the first historical form of energy generation whereby energy is consumed near its generation point seems puzzling in the light of the properties of centralized generation mentioned above. The significant size of distributed generation in countries such as Denmark (detailed in section B) clearly implies that it is capable of overcoming shortfalls of the centralized generation paradigm.

## 2. The main drawbacks of the centralized paradigm

Several studies were conducted to emphasize the main shortfalls of the centralized generation paradigm and to explicit the motivation of the agents in keeping distributed generation as a primary source of electricity or as a back up generator (El-Khattam et Salama, 2004; Perpermans et al., 2005). The main drivers listed in the literature are summarized below:

Transmission and distribution costs: transmission and distribution costs amount for up to 30% of the cost of delivered electricity on average. The lowest cost is achieved by industrial customers taking electricity at high to medium voltage and highest for small customers taking electricity from the distribution network at low voltage (IEA, 2002). The high price for transmission and distribution results mainly from losses made up of:

- line losses: electricity is lost when flowing into the transmission and distribution lines;
- unaccounted for electricity; and
- conversion losses when the characteristics of the power flow is changed to fit the specifications of the network (e.g. changing the voltage while flowing from the transmission network to the distribution network) (EIA, 2009).

The total amount of the losses is significant as shown in Table 1. In addition to the cash cost, these electricity losses have an implicit cost in terms of greenhouse gas emissions: fuel is consumed thus generating greenhouse gases to produce electricity that is actually not used by the final consumer.

**Table- 1. Transmission, distribution losses and unaccounted for electricity in the U.S.**

| Date | Net Generation -Bn kWh | T&D losses and unaccounted for | In % |
|---|---|---|---|
| 1973 | 1864 | 165 | 8.9% |
| 1975 | 1921 | 180 | 9.4% |
| 1980 | 2290 | 216 | 9.4% |
| 1985 | 2473 | 190 | 7.7% |
| 1990 | 3038 | 203 | 6.7% |
| 1995 | 3353 | 229 | 6.8% |
| 1996 | 3444 | 231 | 6.7% |
| 1997 | 3492 | 224 | 6.4% |
| 1998 | 3620 | 221 | 6.1% |
| 1999 | 3695 | 240 | 6.5% |
| 2000 | 3803 | 244 | 6.4% |
| 2001 | 3737 | 202 | 5.4% |
| 2002 | 3858 | 248 | 6.4% |
| 2003 | 3883 | 228 | 5.9% |
| 2004 | 3971 | 266 | 6.7% |
| 2005 | 4055 | 269 | 6.6% |
| 2006 | 4065 | 266 | 6.5% |
| 2007 | 4157 | 264 | 6.4% |
| 2008 | 4115 | 241 | 5.9% |

Source: Energy Information Administration, 2009

Rural electrification: in an integrated power system, rural electrification is challenging for two reasons. As large capital expenditures are required to connect remote areas due to the distance to be covered through overhead lines, connecting remote areas with small consumption might prove uneconomical. This effect is amplified when taking into account transmission and distribution losses because both tend to increase with the distance covered. Rural electrification is thus costly. It often proves more economical to rely on distributed generation in such cases (Carley, 2009). This has often been the case for mountain areas or low density areas remote from the main cities.

Investment in transmission and distribution networks: over the next 20 years, significant investment will be required to upgrade the transmission and distribution networks. The International Energy Agency (2003) estimated the total amount to be invested in generation, transmission and distribution up to 2030 for the OECD countries to stands between 3,000 and 3,500 billion dollars (base case predictions). In order to cut these costs, distributed generation can be used as a way to bypass the transmission and distribution networks. In its alternative scenario – under this scenario distributed generation and renewable energy are more heavily supported by policy makers- the IEA forecasts the overall amount to be invested to be lower than 3,000 billion dollars (electricity generation investments remaining constant).

Energy efficiency: in the 1960s, the marginal gains in energy efficiency through size increase and use of higher temperature and pressure started to diminish. Higher temperatures and pressure resulted in high material wear and tear leading to lower than expected operating life for steam turbines (Hirsch, 1989). In order to increase energy efficiency without requiring to higher pressure, cogeneration systems have been developed to reuse the waste steam in a neighbourhood heating system or cooling system through district heating and/or cooling district. The total energy efficiency achieved when combining both electricity and heat goes up to 90% (IPPC, 2007). Comparatively, the sole electricity generation hardly goes above 40%. The main problem, however, is that steam and heat are even less easily transported than electricity, thus justifying the use of distributed generation through production next to the point of consumption.

Security and reliability: The persistence of distributed generation contributed to energy security through two effects:

- Fuel diversity: as distributed generation technologies can accommodate a larger range of fuel that centralized generation, distributed generation has been used to diversify away from coal, fuel, natural gas and nuclear fuel (IEA, 2002). For instance, distributed generation has been used at landfills to collect biogas and generate energy;

- Back up generation: the main use of distributed generation is for back up capacities to prevent operational failures in case of network problems. Back-up generators have been installed at critical location such as hospitals, precincts etc.

Electricity deregulation and cost control device: in a deregulated electricity market, the diminution of reserve margins or the failure of generators to supply the network (due for example to unplanned outages etc) can lead to capacity shortfalls resulting in high electricity prices to the consumers. In order to hedge against negative price impacts, large electricity consumers have developed acquired distributed generation capacities. Such a move was possible thanks to the increase in flexibility in the market regulation following the deregulation including, among other, reducing barriers to entry.

Environmental Impact: the environmental impact of the centralized energy system is significant due to the heavy reliance on fuel, coal and to a lesser extent natural gas. The electricity sector is responsible for ¼ of the $NO_x$ emissions, 1/3 of the $CO_2$ emissions and 2/3 of the $SO_2$ emissions in the United States (EPA, 2003). Distributed generation has been used to mitigate the impact both in terms of emissions associated with transmission and distribution losses, to increase efficiency through cogeneration and distributed renewable energy.

As distributed generation has been able to overcome the aforementioned shortfalls of the centralized generation paradigm, it kept on average a small share in the overall generation mix. The following subsection will focus on the main features of distributed generation and why it has been the source of an increased attention recently.

### *B. The main characteristics of distributed generation*

#### 1. The main drivers behind the revival of distributed generation

As seen in the previous part, distributed generation has been historically used in several ways to complement centralized generation. The reason behind the recent revival of distributed generation is two-fold: the liberalisation of the electricity markets and concerns over greenhouse gas emissions (Perpermans et al., 2005).

The electricity and gas deregulation process started in Europe following the application of two directives (Directive 96/92/EC and 98/30/EC) aimed at providing a free flow of gas and electricity across the continent. These directives and the subsequent legislation created a new framework making it possible for distributed generators to increase their share in the total electricity generation mix. The effect of deregulation is two-fold (IEA, 2002):

- thanks to the reduction of barriers to entry and clearer prices signals, distributed generators were able to move in niche markets and exploit failures of centralized generation. Theses new applications took the form of standby capacity generators, peaking generators (i.e. producing electricity only in case of high price and consumption periods), generators improving reliability and power capacities, generators providing a cheaper alternative to network use or expansion, provision of grid support (i.e. provision of ancillary services permitting better and safer operation of the network and/or shortening the recovery time) (Pepermans et al., 2005).

- as distributed generators tend to be of smaller size and quicker to build, they have been able to benefit from price premiums. Geographical and operational flexibility made it possible to set up distributed generators in congested areas or use it only during consumption peaks. Besides, for small excess demand, it is often uneconomical to build an additional centralized generation plant whereas with lower CAPEX and capacities, distributed generation might come in handy (IEA, 2002).

The second driver behind the rebirth of distributed generation is to be related to environmental constraints. As shown by Pepermans et al. (2002), environmental and economic constraints led to look for cleaner and more efficient use of energy. Distributed generation has been able to achieve this target through:

- combined heat and power generation: using heat for central heating and other applications makes it possible to reduce emissions and increase energy efficiency to high levels. Cogeneration relies heavily on distributed generation as heat transmission and storage is the source of significant energy losses;

- use of alternative fuel: distributed generation technologies make it possible to accommodate a broad range of fuel. Typical applications involve collecting waste gas from landfills and use it to generate electricity on site.

## 2. Technologies used for distributed generation

The variety of end-use is to be related to an even greater variety in technologies. The range of technologies used for distributed generation and described by the International Energy Agency (2002) includes:

- <u>Reciprocating Engines</u>: this technology uses compressed air and fuel. The mixture is ignited by a spark to move a piston. The mechanical energy is then converted into electrical energy. Reciprocating engines are a mature technology and largely spread thanks to their low capital investment requirement, fast start-up capabilities and high energy efficiency when combined with heat recovery systems. Most reciprocating engines run either on fuel or natural gas with an increasing number of engines running on biogas produced from biomass and waste. On the rolling year June 2007- May 2008, most of the reciprocating engines ordered were used as back-up or stand-by generators (45%[1]), the remaining being divided between peaking generators (30%) and continuous generators (25%) (DGTW, 2008). Reciprocating engines perform, however, poorly in terms of noise, maintenance and emissions (IEA, 2002);

- Gas Turbines: gas turbines are widely used for electricity generation thanks to the regulatory incentives induced to favour fuel diversification towards natural gas and thanks to their low emission levels. Conversely to reciprocating engines, gas turbines ordered over the period covered by the survey were widely used as continuous generators (58%), 18% were used as standby generators and 24% as peaking generators (DGTW, 2008). Gas turbines are widely used in cogeneration;

- Microturbines: microturbines are built with the same characteristics than gas turbines but with lower capacities and higher operating speed;

- Fuel cells: instead of converting mechanical energy into electrical energy, fuel cells are built to convert chemical energy of a fuel into electricity. The fuel used is generally natural gas or hydrogen. Fuel cells are a major field of research and significant effort is put in reducing capital costs and increasing efficiency which are the two main drawback of this technology;

- Renewable sources: renewable technologies have been used as a way to produce distributed energy. Renewable sources range from photovoltaic technologies, wind energy, thermal energy etc. These sources qualify as distributed generation only if they meet the criteria of the definition which is not always the case. Distributed generation is therefore clearly distinct from renewable energy. For example, offshore wind farms do not qualify as distributed generation.

[1] The numbers are expressed in percent of unit orders and not in percent of total capacity

The table below summarizes the main characteristics of the technology used as presented by Perpermans and (2005).

**Table- 2. DG technologies**

| | General information | Application range | Electric conversion efficiency | Application | Fuel | Comments |
|---|---|---|---|---|---|---|
| Reciprocating engines | | Diesel: 20 $kW_e$–10 + $MW_e$ (IEA) | Diesel: 36%–43% (IEA) | Emergency or standby services | Diesel, also heavy fuel oil and biodiesel | |
| | | Gas: 5 $kW_e$–5 + $MW_e$ (IEA) | Gas: 28%–42% (IEA) | CHP | Gas, mainly natural gas, biogas and landfill gas can also be used | |
| | | By far most common technology below 1 $MW_e$ | | | | |
| Gas turbines | | 1–20 $MW_e$ (IEA) | 21–40% (IEA) | CHP<br>Peak power supply units | Gas, kerosene | |
| Micro turbines | | 30 $kW_e$–200 $kW_e$ (IEA) | 25–30% (IEA) | Power generation, possible with CHP added | Generally uses natural gas, but flare, landfill and biogas can also be used | |
| | | 35 $kW_e$–1 $MW_e$ (A)<br>Small-scale applications up to < 1 $kW_e$ | | | | |
| Fuel cells | Molten carbonate: MCFC | 50 $kW_e$–1 + $MW_e$ (IEA) | 35–60% (IEA) | PEMFC: low temperature applications in transport and stationary use | Methanol | |
| | Proton-exchange membrane: PEMFC | PAFC: 200 $kW_e$–2 $MW_e$ | MCFC: ± 50–55% (IEA) | MCFC: high temperature | Hydrogen or natural gas. Reforming of $CH_4$ to $H_2$ leads to decreased efficiency | |
| | Solid oxide: SOFC | MCFC: 250 $kW_e$–2 $MW_e$ (A) | PAFC: ± 35% (IEA) | Transport sector is major potential market | | |
| | Phosphoric acid: PAFC<br>Direct Methanol : DMFC | PEMFC: 1 $kW_e$–250 $kW_e$ (A)<br>SOFC: 1 $kW_e$–5 $MW_e$ (A) | PEMFC: ± 35% (IEA)<br>SOFC: ± 50–55% (IEA) | SOFC: high temperatures<br>Power generation is the most likely immediate application | | |
| | Only PAFC is currently commercially available | | Electric efficiency of small-scale applications : ~ 25% | CHP, UPS | | |
| Photovoltaic | Generates no heat | 1 + kW (IEA) | not applicable | Household and small commercial applications | Sun | Non predictable output; capacity factor ~ 10–15% in Western Europe |
| | | 20 + kW (A);<br>Every range possible when using more cells | | Off-grid applications<br>Developing countries | | |
| | | | | Small scale applications | | |
| Wind | On shore and in-land | 200W–3 MW (A) | Not applicable | | Wind | Non-predictable output<br>Capacity factor on shore ~ 20–25% |
| Other renewables | Includes thermal solar, small hydro, geothermal, ocean… | | Not applicable | | | |

Source: Pepermans et al., 2005

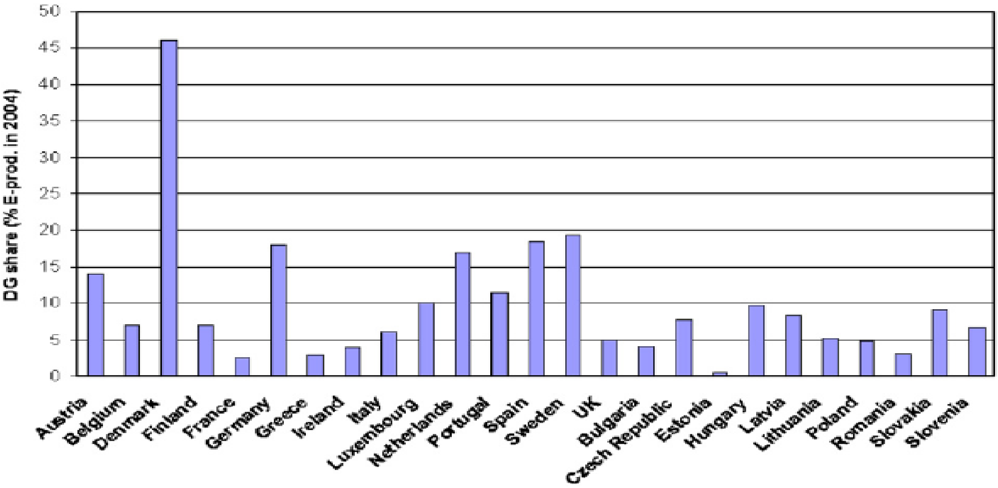
## 3. Current share of decentralized energy and prospective penetration rate

Estimating the worldwide share of distributed generation can lead to significant divergence in results due to the differences in the definitions used. The differences mentioned in the introduction can yield to significant adjustments in the estimate of the total share of distributed generation. The inclusion or exclusion of large cogeneration facilities can significantly affect the results. For instance, the total share of distributed generation is of 2.5% in California if cogeneration capacities larger than 20MW are excluded. If included, the share goes up to 17% of the total net peak demand (Rawson and Sugar, 2007). The bone of contention here is whether this large cogeneration capacities often connected to the transmission grid can be considered as distributed generation. The impact on the result is even more significant as the capacities of such facilities tend to be high.

A survey conducted by WADE in 2006 led to an estimated 25% share of distributed generation (WADE, 2006). The definition used by WADE does not take into account project size, the technology used or whether or not the facility is connected to the distribution grid. It thus includes large cogeneration facilities. The International Energy Agency's model (2003) estimates that distributed generation will account for between 20 and 25% of additional capacities to be built up to 2030 in the reference scenario and 30 to 35% in the alternative scenario. This will add up to approximately 30 to 35% and 40 to 45% of power generation investments over the period 2001 - 2030. The strong incentive to support distributed generation will be driven, among others, by the size of investment in transmission network to be avoided. It is estimated at $130 billion (IEA, 2003).

While focusing on the EU-25 countries, we see that distributed generation accounts on average for around 10% of the total electricity production. As stressed out in the chart below, the pattern significantly differs from one country to the other. In Denmark, for instance, distributed generation accounts for more than 45% of the total electricity produced (Cossent et al., 2009).

**Figure- 1. Distributed generation shares in the total electricity production of the EU-25 countries (2004)**




Cossent et al., 2009

The difference across countries can be explained by regulatory aspects, political decisions – e.g. France heavily promoted large nuclear power plants -, and the way the electrical sector was historically built. In Denmark for instance, nuclear power has never been an option for long term electricity generation due to public concern over the risks and environmental impact related with this technology. Instead, between 1970 and 2000, the government embarked in a vast program to promote cogeneration, energy efficiency and renewable energy through wind power. The implementation of such a program was done through a bottom up approach involving a large number of small firms, municipalities and cooperatives working in close cooperation (Lethonen and Nye, 2009).

## II. The challenges to be faced while increasing the share of distributed generation.

To sustain the forecast penetration rate, the architecture of the electricity sectors needs to be altered. The current infrastructures were not originally built to accommodate a large proportion of distributed generation. For the moment, only necessary adjustments are undertaken in order to accommodate these new capacities. The difficulties experienced by front-running countries such as Denmark give a flavour of the problems to be faced as distributed generation is increasingly used.

*"For along time, western Denmark managed to increase DG connection apparently with only minor changes in network control.* […]. *It was not until the early 2000s that the reliability problems, created by the sudden increase in wind generation, grew acute—notably the blackouts in eastern Denmark in 2003 were a wake-up call."*(Lethonen and Nye, 2009)

Over the long run, however, increasing significantly the share of distributed generation will necessarily mean revamping the whole physical and regulatory architecture of the electricity network and more precisely the distribution network.

### *A. Technical constraints:*

The first difficulties to overcome are related to technical improvements necessary to ensure high system reliability with distributed generation. The following section gives an overview of the technical issues caused by distributed generation. The classification and description are derived from a study by Pehnt and Schneider (2006). The issues can be classified as follows:

<u>Capacity:</u> adding distributed generators at the distribution level can significantly impact the amount of power to be handled by the equipment (cables, lines, and transformers). In order to avoid overload problems, reinforcement work will have to

be undertaken. As shown by Pehnt and Schneider, the critical piece will often be the transformers (converting medium voltage to low voltage or high voltage to medium voltage): if power generated exceeds by far consumption, power will have to flow back from the low voltage network to the medium voltage network or from the medium to the high voltage network and be directed to other consumption areas. The transformer will have to be able to handle this reverse flow i.e. being able to convert it back and have specification to cope with potential oversupply. This is of major issue at peak hours: at that time both continuous and peaking distributed generators will operate to cash in the price premium. Production forecast from peaking distributed generators is key while determining the specifications of the equipment, as capacities will be added when the total power flow is already significant.

<u>Voltage:</u> distributed generators are often connected to low voltage networks. When power is carried over long distance, voltage tends to drop due to resistance in cables. As generators connected to the distribution network tend to increase the network voltage, they may help keep the voltage within the specifications over the distance and have a positive impact on the network. This positive impact is however strongly dependent on the number of generators connected to the distribution network and their concentration: above a certain threshold, adding another distributed generator might negatively impact the network by increasing voltage above the specifications.

<u>Protection:</u> while using distributed generation, additional protection systems are required to avoid internal faults, defective distributed network and islanding (Jenkins et al., 2000). Islanding occurs when part of the network is still operating with the distributed generators delivery electricity to customers while the rest of the network has been disconnected. It can be useful to operate the network in such a way to ensure steady supply of consumers with critical need for electricity or ensure that the majority of the network is still operating while a section is under maintenance. The main issue comes from undetected islanding as network operators might undertake repair work and thus incurs significant risk for staff members.

<u>Voltage and current transients:</u> short term abnormal voltage or current oscillation may occur as distributed generators are switched on or off. The result of these oscillations can have a destabilizing effect on the network.

Transmission and distribution losses: one of the key advantages of distributed generation is that it helps reduce transmission and distribution losses as distributed generators are not connected to the transmission grid and some of them might even choose to operate as captive plant for a client with thus limited use of the distribution grid. Recent research has however shown that above a threshold (at very high penetration rate and with generators concentrated in a specific area and all of them feeding the distribution grid), the size of the transmission and distribution losses goes up again (Mendez et al., 2002).

Ancillary Services: as of today all the ancillary services positively impacting the quality of electricity delivered are provided by centralized generators. For example, centralized generators are requested to keep capacities in excess of peak load to adjust production in case of demand surge, to hold voltage control devices… As the share of distributed generation increases, distributed generators will have to provide a larger share of these services.

In addition to the technical issues mentioned above, two fields of research will have to be further investigated: “active” network and “virtual power plants” and microgrids.

Historically, distribution networks have been less sophisticated than transmission network as they were passively distributing energy from the transmission networks to the customers. The coordination between the generators and the adjustments in outputs were done directly at the transmission level. The integration of distributed generation on a large scale will however require the distribution network to be *active* in the sense that they will have to manage the flow coming from centralized generation through the transmission lines, forecast the levels of output from distributed generators (and especially peak generators), collect information, devise start-up procedures in case of system failures, automation…. This increased level of complexity will require the development of management and control procedures necessary to ensure quick and safe operation (McDonalds, 2008). The change in network control and management can either rely on a centralized control entity or several local controlling entities coordinated together. The latter architecture was adopted in Denmark where the Cell Architecture project has been launched. The aim of such a venture is to build a decentralized control system where the grid management is handled by semi-autonomous entities. These entities will then be able to operate jointly or as island in case of failure on part of the network thus ensuring a minimum impact on a located system failure (Lethonen et Nye, 2009).

An extension of this idea is the concept of *virtual power plant*. A *virtual power plant* is the coordination of several distributed generators in order to act as an integrated plant (Feldmann, 2002; Jänig, 2002; Stephanblome et Bühner, 2002; Arndt et Wagner, 2003). The plant is "virtual" as it is not in one place but made of the aggregation of several units. The operation of such a plant required a strong integration of information, communication and management systems (Pehnt, 2006). One way of integrating small scale distributed generators is through a microgrid. As of today, distributed generators are mainly integrated though medium voltage grids. Significant research is however underway to facilitate the integration in low voltage grids with local coordinating functions or microgrids (Costa et al., 2008).

### B. Cost competitiveness: the economics of distributed generation

One key hurdle to overcome in a deregulated power market is the cost competitiveness of distributed generation. This parameter varies, however, a lot from one technology to the other mainly. One of the main reasons for such a difference is the age of the technology and its current state of development. For example reciprocating engines have been used for decades and are a mature technology while fuel cells are still subject to significant research and development in order to become a credible source of generation. According to Pehnt (2006) more than 5 years of research and development will be needed for it to become a mature technology to be adopted on a large scale. Table 3 below gives an indication of the capital costs, operating and maintenance costs and fuel cost of the different technologies. These parameters indicatives as they are highly sensitive to inputs (Strachan et Farell, 2006). Data for fuel cells are also high sensitive to the progress in research and development linked with this technology. All costs measures are in $2000. The following analysis draws its results on key research results presented by Strachan and Farell (2006).

**Table- 3. Cost comparison between DG technologies**

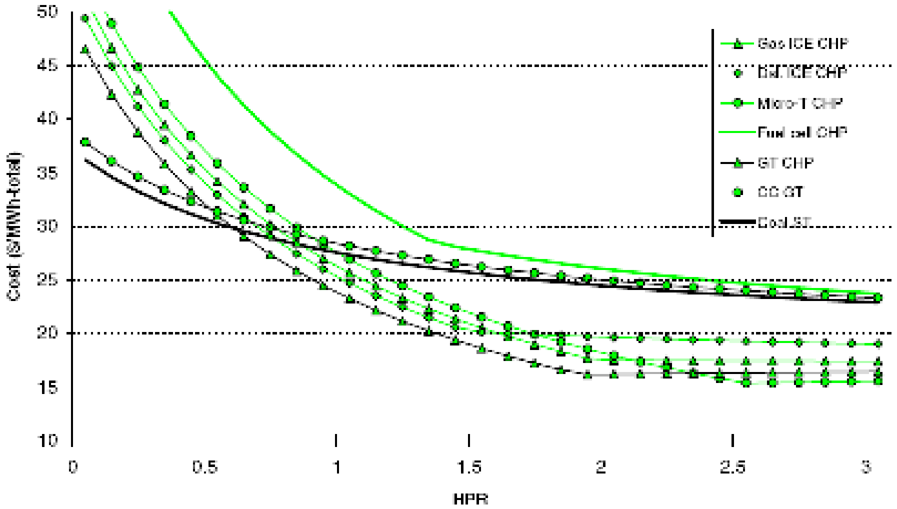
| | Efficiency (%HHV) | Unit size (MWe) | Capital cost ($/kW) | Fixed O&M cost ($/kW-yr) | Variable O&M (c/kWh) | Fuel production costs (c/kWh) | |
|---|---|---|---|---|---|---|---|
| | | | | | | 1999 average | 2001 average |
| Gas reciprocating engines | 29 | 0.2 | 750 | 15 | 1 | 0.68 | 1.19 |
| Diesel reciprocating engines | 35 | 0.2 | 700 | 15 | 1 | 1.05 | 1.44 |
| Micro-turbine | 25 | 0.06 | 800 | 15 | 0.6 | 0.68 | 1.19 |
| Fuel cell | 38 | 0.1 | 3000 | 15 | 0.6 | 0.68 | 1.19 |
| Gas turbine | 29 | 10 | 480 | 15 | 0.55 | 0.68 | 1.19 |
| CCGT (centralised generation) | 50 | 200 | 550 | 15 | 0.55 | 0.68 | 1.19 |
| CST (centralised generation) | 33 | 500 | 1100 | 15 | 0.4 | 0.38 | 0.42 |

Source: Strachan et Farell, 2006

As shown in the table, for most of the costs (all the capital costs, fixed and variable operating and maintenance costs), distributed generation technologies are less or as competitive as combined cycle gas turbines. Coal steam turbines tend to have higher capital costs but remain highly competitive due to their cheap fuel costs. On a pure cost per kilowatt basis, distributed generation is clearly not the cheapest source of generation.

The only way to tweak the picture and make distributed generation competitive is to price in some of the key characteristics and positive externalities of this generation technique. For instance, taking into account the ability of distributed generation to produce both electricity and heat can modify the hierarchy. In this case cogeneration will compete against production of centralized energy and costs related to the use of an additional boiler to provide heating for a facility (Strachan et Farell, 2006). On the chart below, internal combustion engine (ICE) is a proxy for reciprocating engines.

**Figure- 2. Indicative cost comparison between technologies**




Source: Strachan et Farell, 2006

The HPR ratio used in the chart above is defined as:

$$\text{HPR} = \frac{\text{Energy produced (or consumed) as heat}}{\text{Energy produced (or consumed) as electricity}}$$

A heat to power of 0 is thus related to a case where electricity only is produced while a heat to power ratio of 2 is achieved under a situation whereby the facility needs twice more heat than electricity. An increase in heat to power ratio has a positive effect on the cost of distributed generation until the maximum steam generation output of the technology is reached. The curves converge as when the HPR is high: at this point cogeneration is no longer sufficient to produce heat and additional boilers should be added. At high HPR ratios, the marginal cost is quasi only influenced by the marginal cost of an extra boiler and no longer by the marginal cost of the distributed generation technology (Strachan et Farell, 2006).

Cost competitiveness of distributed generation today is thus heavily impacted by the capacity of the regulation to price its impact on the electricity network and on its ability to provide specific services to the end consumer such as heat generation or ancillary services. The diffusion rate of distributed generation will thus be driven by the ability of the regulator to lift the regulatory barriers. This issue will be of major importance as it will strike the balance between a market driven diffusion model whereby the distributed generators will be able to increase their return on investment through prices (incorporating factors such as avoidance of use of the grid, investment deferral, emission abatements etc) and a subsidized model with the state or electricity regulator imposing higher tariffs for distributed generators when the price signal fails.

### *C. Regulatory barriers*

In addition to technical and cost issues mentioned above, distributed generation's share is still negatively impacted by the lack or the inappropriateness of regulation. In a recent study, Cossent et al. (2009) made a review of European regulation and analysed the key factors that might impede the spread of distributed generation in Europe. The classification and main issues mentioned below are derived from this study. The main issues identified are:

Network tariffs: when getting connected to the electricity for the distribution network, distributed generators have to pay to the distribution network operator charges as a remuneration of work undertaken. The charges are divided between connection charges for the physical connection to the network (paid at once) and use-of-system charges (paid on a recurring basis).

Connection charges can be divided between deep connection charges and shallow connection charges. Deep and shallow connection charges can be defined as follows:

*"Under deep connection charges, DG pays for all the cost of connection, including upstream network reinforcements. On the other hand, under shallow connection charges DG pays only the direct costs of connection"* (Cossent et al., 2009).

The choice between deep and shallow connection charges is bound to have a major impact on the penetration rate of distributed generation. Deep connection charges will be detrimental for small scale distributed generators and to some extend peaking distributed generators: the investment needed for connection will significantly reduce the net present value of the investment and can to some extent make it become negative. The differences in regulation across European countries thus make investment more or less attractive in member state countries when taking into account this criterion (Table 4). The term shallow-ish refers to a situation where the distributed generation pays for direct connection costs and part of the reinforcement of the system proportional to its system use.

Use-of-system charges are generally not a major issue for distributed generators: the regulation is generally favourable to them as they are not required to pay it. This feature is bound to change if distributed generation accounts for a large share of total generation.

## Table- 4. Review of distributed generation regulation

| Country | Connection charges | | | DG pay UoS charges | | Treatment of DG incremental costs | | | | Incentives to reduce losses | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Deep | Shallowish | Shallow | Yes | No | Cost of service | Incentive based regulation | | | None | Penalties for non-compliance with regulated values | Losses bought at the market | Incentives and penalties plus regulated values |
| | | | | | | | DG-related incremental costs not considered | DG-related incremental CAPEX considered | DG-related incremental CAPEX and OPEX considered | | | | |
| *New MS* | | | | | | | | | | | | | |
| Bulgaria | | | ✓ | | ✓ | | | ✓ | | | | | ✓ |
| Czech Republic | ✓ | | | | ✓ | | | | ✓ | | | | ✓ |
| Hungary | ✓ | | | | ✓ | | | | ✓ | | | | ✓ |
| Lithuania | ✓ | ✓[a] | | | ✓ | | | ✓ | | | ✓ | | |
| Poland | | | ✓ | | ✓ | | ✓ | | | | | | ✓ |
| Romania | ✓ | | | ✓ | | | ✓ | | | | | | ✓ |
| Slovakia | ✓ | | | ✓ | | | ✓ | | | | | | ✓ |
| Slovenia | | | ✓ | | ✓ | | ✓ | | | | ✓ | | |
| *EU-15 MS* | | | | | | | | | | | | | |
| Austria | | | ✓ | ✓ | | | ✓ | | | ✓ | | | |
| Denmark | | | ✓ | ✓ | | | | | ✓ | | | | ✓ |
| Germany | | | ✓ | | ✓ | ✓ | | | | ✓ | | | |
| The Netherlands | ✓ (>10MW) | | ✓( <10MW) | | ✓ | | ✓ (>10MW) | ✓(<10MW) | | | | ✓ | |
| Spain | ✓ | | | | ✓ | | ✓ | | | | | | ✓ |
| France | | | ✓ | | ✓ | ✓ | | | | | | ✓ | |
| Italy | | | ✓ | ✓ | | | | ✓[b] | | | | ✓ | |
| UK | | ✓ | | ✓ | | | | | ✓ | | | | ✓ |

| Country | Incentives to improve quality of service | | | Incentives for innovation | | | Type of DSO unbundling | | | | DSO may own DG | | | Number of DSOs | | Share of connections by small DSOs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | No | Regulated targets | Non-regulated targets (contracts) | No | Implicit incentives given by regulation | Specific innovation incentives | Legal | Functional | Ownership | Public DSO | No | Yes | Only small DSOs (less than 100000 connections) | Total | Small DSOs | |
| *New MS* | | | | | | | | | | | | | | | | |
| Bulgaria | | ✓ | | | ✓ | | ✓ | | | | ✓ | | | 4 | 1 | 0.1% |
| Czech Republic | ✓ | | | | ✓ | | ✓ | | | | ✓ | | | 3 | 0 | 0% |
| Hungary | | ✓ | | | ✓ | | ✓ | | | | ✓ | | | n.a. | 0 | 0% |
| Lithuania | | ✓ | | | ✓ | | ✓ | | | | | | ✓ | 2 | Small number | 13% |
| Poland | ✓ | | | | | ✓ | ✓ | | | | | ✓ | | 18 | 4 | 1% |
| Romania | | ✓ | | | ✓ | | ✓ | | | | ✓ | | | 8 | 0 | 0% |
| Slovakia | | | ✓ | ✓ | | | ✓ | | | | | ✓ | | n.a. | 250 | 0.5% |
| Slovenia | | ✓ | | ✓ | | | | | | ✓ | ✓ | | | 1 | 0 | 0% |
| *EU-15 MS* | | | | | | | | | | | | | | | | |
| Austria | ✓ | | | ✓ | | | ✓ | | | | | ✓ | | 135 | 119 | 12% |
| Denmark | | ✓ | | | ✓ | | ✓ | | | | | | ✓ | 120 | 112 | 43% |
| Germany | ✓ | | | ✓ | | | ✓ | | | | | ✓ | | 950 | 900 | n.a. |
| The Netherlands | | ✓ | | | ✓ | | ✓ | ✓ | ✓(1 small DSO) | | ✓ | | | 11 | 6 | 3% |
| Spain | | ✓ | | ✓ | | | ✓ | ✓ | | | | | ✓ | 329 | 321 | 3% |
| France | ✓ | | | ✓ | | | ✓ | ✓ | | | | ✓ | | 166 | 160 | 5% |
| Italy | | ✓ | | | ✓ | | ✓ | | | | | ✓ | | 170 | n.a. | n.a. |
| UK | | ✓ | | | | ✓ | ✓ | | | | ✓ | | | 14 | 3 | 1% |

[a] Used occasionally
[b] Fixed rate of return for CAPEX

Source: Cossent et al., 2009

Planning: one of the main benefits of distributed generation is to defer costly investments in distribution networks (upgrade or capacity increase) by producing electricity where it is most needed. Though cost effective, these economies are often not realised due to the structure of the revenues of the distribution network operators. As regulated natural monopolies, distribution network operators are often remunerated on a cost plus of rate of return basis with adjustment for reaching performance tests. This structure gives them little interest in favouring distributed generation as they do not directly benefit from this improvement: operators will choose to invest in the costly solution that gives them a safe income (i.e. the network extension or upgrade with a guaranteed rate of return) instead of a less costly solution with no gain. This is even more pronounced as since the electricity market deregulation, transmission network operators cannot hold generating capacities. In some countries, regulation has been adapted to take into account this potential cost reduction.

Incremental distribution costs caused by distributed generation: though in the long run distributed generation defers investment in the network, reinforcement work has to be undertaken to accommodate this new form of generation. This additional distribution costs (incremental CAPEX and OPEX) caused by distributed generation is seldom accounted for in the current compensation of network operators. Operators are thus less inclined to favour this option.

Energy losses: the treatment of energy losses varies greatly across countries. With a low penetration rate and low concentration, distributed generation has a positive impact on these losses. Regulation on this specific point affects the profitability of the distributed generators. In countries such as Italy, the network operator pay for the loss avoidance to the distributed generators connected at the transmission level. In France however, the operator has incentive to encourage distributed generators to enter the market as he pays for the losses through the purchase of electricity to a centralized generator (Cossent et al. 2009). The network operator thus has a financial gain in letting distributed generators enter the market and reduce this amount of losses. This is however less advantageous to the centralized generators. The adoption of such solution will thus be significantly affected by the relationship between centralized generators and network operators. When both, though legally independent from one to the other, are owned by the same entity, the operator might not be willing to favour the distributed generators.

Ancillary services: distributed generators can help improve the quality of services provided through voltage control (connecting a distributed generator to a low voltage network makes it possible to reduce the drop in voltage over the distance), providing additional peaking power capacities …. These potential services to be rendered are not a source of revenues for distributed generators under the current regulation. Regulatory change might be phased in this impact. One of the key hindrances here, besides regulation, is the lack of long term historical data to assess the overall impact of these generators.

Incentives for innovation: integrating distributed generators into the distribution network will trigger a major change in the management and control process. The replacement of traditional grids by "smart" grids is a prerequisite for a larger share of distributed generation. The results of the regulatory incentives given for innovation are mixed.

Unbundling activities: The operator's independence with respect to centralized generators is key for distributed generation. Electricity deregulation ensures legal independence of the two entities. Legal independence is, however, not sufficient to ensure that network operators will not act in favour of centralized generators. The problem is even more acute when ownership structures are the same (Praetorius, 2006). Studies even report unfair discrimination towards distributed generators (Jörss et al. 2003). This problem is of major importance as distributed generators are often in a critical phase of their investment process when encountering such difficulties. Due to their relative small size, unjustified delays or procedures might significantly affect their financial strength.

In addition to these regulatory barriers, Ofgem (2007) reported in its review of distributed generation additional regulatory burdens in the form of:

- licensing requirements that were devised for large centralized generators: the requirements are often irrelevant for small scale generators or come at a high cost;

- difficulties in getting permissions and delays;

- issues with exported electricity: one key complement of distributed generators is to be able to supply the grid when needed or when consumption at the nearest point is too low. The lack of visibility on the tariffs or the low tariffs for the electricity fed back to the grid has been a major source of concern for distributed generators. This problem has a major impact on the economic profitability of the project.

Last, network operators lack incentives to take into account heat in the case of distributed cogeneration. Operators will favour project having a positive impact on the system stability regardless of the increased efficiency to be achieved through production of electricity and heat (Woodman et Baker, 2008). This is unfortunate as cogeneration is one of the key assets of distributed generation.

### *D. Impact on climate change and global warming*

As previously mentioned, distributed generation does not necessarily mean clean generation. The aim of this section is to better understand the environmental impact of the main technologies used in distributed generation.

Strachan and Farell (2006) analysed the performance with respect to emissions of distributed generation operating either for the sole production of electricity or as cogeneration units. Renewable energies were left off the sample as for those technologies the main concern is less emissions than cost per kWh. Table 5 gives the emissions comparison between gas and diesel reciprocating engines, microturbines, fuel cells, combined cycle gas turbines and coal steam turbines. The emissions produced by a boiler have been added to make it possible to compare the emission of centralized generation with an extra boiler used on site for heat and distributed cogeneration.

**Table- 5. Emission factor for distributed and centralized generation**

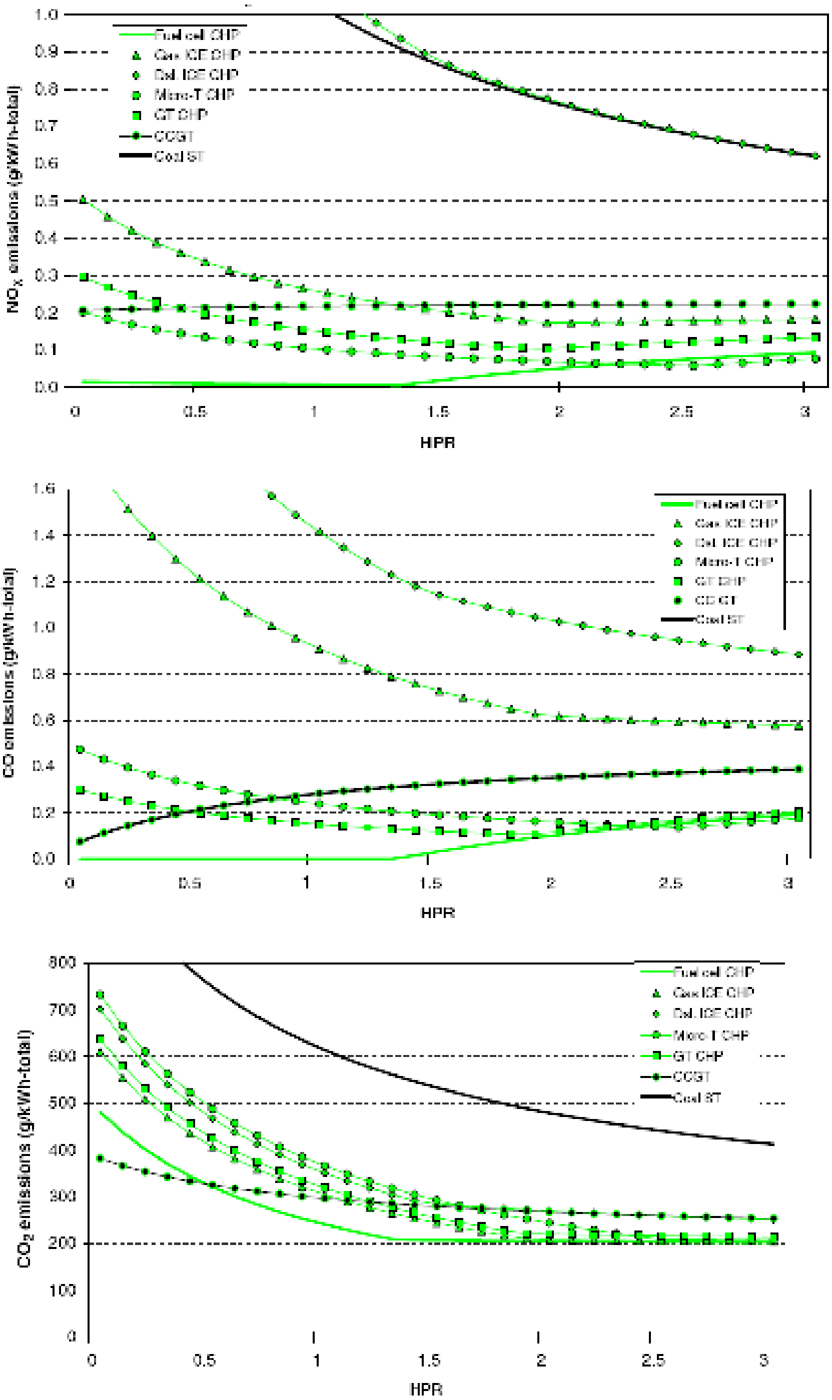
| | $CO_2$ (g/kWh) | $SO_2$ (g/kWh) | $No_x$ (g/kWh) | CO (g/kWh) | $PM_{10}$ (g/kWh) | HC (g/kWh) |
|---|---|---|---|---|---|---|
| Gas reciprocating engine | 625 | 0.032 | 0.5 | 1.8 | 0.014 | 0.54 |
| Diesel reciprocating engine | 695 | 1.25 | 2.13 | 2.8 | 0.36 | 1.65 |
| Micro-turbine | 725 | 0.037 | 0.2 | 0.47 | 0.041 | 0.14 |
| Fuel cell | 477 | 0.024 | 0.015 | 0 | 0 | 0 |
| Gas turbine | 625 | 0.032 | 0.29 | 0.42 | 0.041 | 0.42 |
| CCGT | 363 | 0.019 | 0.195 | 0.07 | 0.041 | 0.05 |
| CST | 965 | 5.64 | 1.7 | 0.07 | 0.136 | 0.05 |
| Gas-fired boiler | 201 | 0.01 | 0.12 | 0.12 | 0.01 | 0.014 |

Source: Strachan and Farell, 2006

As already mentioned above distributed generators are not best in class when it comes to emissions. Diesel reciprocating engines are the worst emitters in terms of nitrogen oxides ($NO_x$). Combined cycle gas turbines tend to be the best performers in terms of carbon dioxide ($CO_2$), sulphur dioxide ($SO_2$) while fuel cells are the lowest emitters when it comes to $NO_x$, CO, particulate matters ($PM_{10}$) and hydrocarbons (HC).

Starchan and Farell then complete the analysis taking into account the possibility to use the heat produced by distributed generators for heating a facility. The charts below plot the emission against the heat to power ratio. Heat to power ratios tend to vary significantly across the regions and seasons with for instance a heat to power ratio for aggregated seasonal demand of 3 for New York in Winter and 0.82 for Florida in Summer as shown in the study. The optimal technology to be used here is thus a function of costs, emissions and heat to power ratio.

**Figure- 3. Emissions comparison between centralized and distributed generation when both electricity and heat are needed**




Source: Strachan and Farell, 2006

As shown in the charts above, the results are somewhat mixed. The highest emitters tend in general to be the diesel reciprocating engines and the coal steam turbines. This fact has been known for a long time and is at the heart of regulation implemented to reduce the emissions at CST plants while imposing more stringent conditions on the use of diesel reciprocating engines as back-up generators. The lowest emitting technology is the fuel cell but at high HPR as to little heat is produced additional boilers have to be used. As shown in the cost comparison figure, this technology is still crippled by high costs.

Distributed generation is not always the best performer in terms emissions. Though some technologies such as fuel cells seems promising for future application, the absence of implementation background and the costs of this technology are still hindering its diffusion on a large scale. To be used in the cleanest way possible, distributed generation will thus have to use the less emitting technologies and favour cogeneration.

# Conclusion and future research

The recent attention paid to distributed generation is not surprising in many ways. The flaws of the centralized generation paradigm led to look for a complement generation technique, a role that was endorsed to the extent possible by the distributed generators before the energy deregulation. The drastic change in the environment of the electricity generators in the 1990's laid the foundation for an increasing use of distributed generation. As shown by Pepermans et al. (2005), energy deregulation and concerns over human impact on climate change created a context in which the revival of distributed generation became possible: clearer price signal and fewer barriers to entry made it possible for small scale generators to enter niche markets while environment concerns positively impacted efficient generation methods such as cogeneration. The renewed interest for the oldest generation paradigm (at the beginning of the electricity industry all plants were distributed), made us wonder if it can account for a larger share in the total generation. Forecast penetration rates are high but rely on strong assumptions on the future state of the electricity market (regulation, government backing of a distributed generation policy etc). Besides, though front-running countries such as Denmark made it clear that it can account for a large fraction of generation, we were still wondering if such an example was not in the end an exception: the size of distributed generation increased to such levels mainly through cogeneration due to the high demand for heat related to the low temperatures in winter.

The in-depth study of the electricity market structure and of the key characteristics of distributed generation demonstrated distributed generation can consider becoming an alternative paradigm provided it can overcome significant obstacles. First technical issues will need to be solved: better understanding of the impact of a high number of distributed generators need to be developed and network management procedures will have to be overhauled to fully exploit its implicit benefits. From an economic perspective, distributed generators will have to go on more research and development to lower the cost per kWh while specialising in end-use where they can prove more competitive than centralized generators. Besides, the growth of distributed generation will be closely linked to the capacity of the generators to monetize their positive impact on the overall electricity sector. This will only be possible if the sector' and price's regulation integrates this effect through an adjustment in the price of electricity paid to the generators. The new legislation to be implemented will thus be crucial in defining a diffusion of model of generation (a market model or a subsidized model). As the revival was partly driven by environmental concerns, effort on total emissions from distributed generators will have to be the object of more scrutiny. Distributed generation is not the cleanest and the most efficient source of generation, at least for non renewable generators. The best solution to increase its performance is to use if for cogeneration which implies a greater integration on electricity heat and cooling network. Though a widely used technology, cogeneration still faces difficulties as there is in general no link between regulators for electricity and heat (Woodman et Baker, 2008). Further research will thus investigate the change needed to ensure better use of cogeneration. This will also require questioning the impact on a third driver currently reshaping the energy sector, the search for supply security: most of the cogeneration facilities are currently running on natural gas.

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