DISTRIBUTED GENERATION

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INTRODUCTION: SOME HISTORY AND EVOLUTION TOWARDS DISTRIBUTED GENERATION

Distributed generation is generally thought of as small scale generation that is used on-site and/or connected to the distribution network. Historically, the type of technologies employed has varied, but are generally limited to small engines or combustion turbines fueled by diesel, gasoline, or natural gas and are expensive to run relative to grid supplied power [1]. More recently intermittent renewable resources such as solar photo-voltaic, small hydro, and wind have been thought of as distributed generation that is seen as being deployed to reduce overall emissions. Consequently, small-scale, fossil-fired generation was seen, and still is seen, as primarily providing reliable, back-up generation in the event of grid supplied power interruptions with an estimated 70 percent of diesel distributed generators in the United States being used for emergency purposes [2]. In contrast, the electricity industry was historically seen as possessing economies of scale in the production and delivery of power. Such economies of scale necessitated larger and larger generating facilities to meet the increasing demand. This brings us to the power system of today where we have large, centrally dispatched power stations that are connected to each other and to consumers by the high voltage transmission system eventually leading to lower distribution voltages and consumers of power.

However, there have been several developments that have made the idea of distributed generation not only possible, but potentially desirable. The first development is the technological change relating to costs and economies scale that came to fruition in the 1990's: combined cycle, natural gas technology. In Figure 1, the change in economies of scale compared to historical trends is a fundamental shift toward smaller, lower cost generating units.

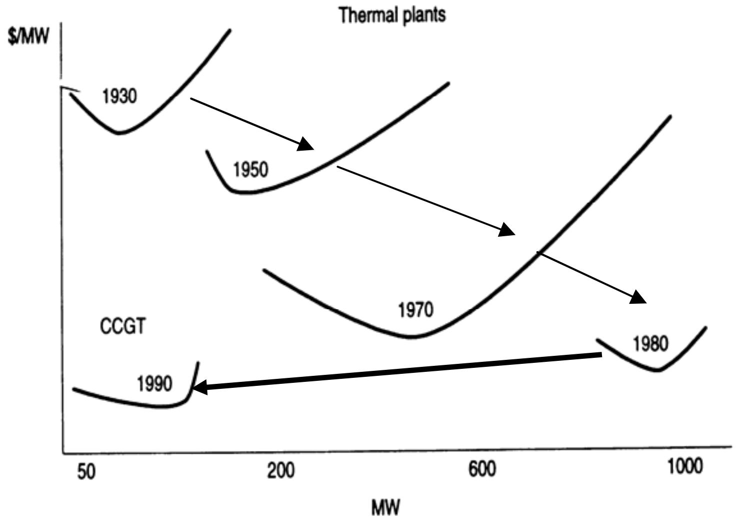


Figure 1: Generating plants costs curves concerning power (1930-1990). Source: Hunt, Sally and Shuttleworth, Graham. *Competition and Choice in Electricity*.(England, John Wiley & Sons, 1996).

The second development, as indicated by proponents of distributed generation in [3] was the availability of relatively inexpensive natural gas supplies which made potential distributed generation technologies more affordable to operate. Consequently, it would then be possible, as argued in [2,3], for distributed generation to operate at costs competitive to traditional central station power while avoiding, deferring, or reducing network costs.

The third development, aided by the previous two developments described above and described by [4], is the policy change around the world moving from vertically integrated monopolies toward more competitive market structures in the generation sector allowing for more diverse ownership of generating assets that would compete against each other to drive the price of electricity down.

The last development, driven by environmental policy that is currently ongoing, is the idea that distributed generation can help countries reduce emissions, especially carbon emissions [5]. Natural gas fired technologies have lower carbon emissions than traditional coal-fired technologies but higher emissions than renewable technologies which have zero carbon emissions.

The remainder of the entry is organized as follows. First, we will discuss how distributed generation is defined and contrast that with other notions of distributed resources. Next, we will briefly outline the types of technologies that are deployed as distributed generation along with a summary of their cost characteristics. Following that, we discuss the potential benefits attributed to distributed generation along with some cautions about overstating the benefits. Finally, we will discuss policies affecting distributed generation followed by concluding remarks.

WHAT IS DISTRIBUTED GENERATION?

Many terms have emerged to describe power that comes from sources other than from large, centrally dispatched generating units connected to a high voltage transmission system or network. In fact, there is not clear consensus as to what constitutes distributed generation (DG) [2,6].

CIRED Working Group N° 4 [6] created a questionnaire of 22 which sought to identify the current state of dispersed generations in the various CIRED member countries. Response showed no agreement on a definition with some countries using a voltage level definition while others considered direct connection to consumer loads. Other definitions relied on the type of prime mover (e.g. renewable or co-generation), while others were based on non-centrally dispatched generation.

This diversity is also reflected in the CIGRE Working Group 37.23 [3] definition, which characterizes dispersed generation as not centrally planned or dispatched, connected to lower voltage distribution networks, and is less than 50-100 MW.

The World Alliance for Decentralized Energy (WADE) [7] defines *Decentralized Energy (DE)* as electricity production at or near the point of use, irrespective of size, technology or fuel used - both off-grid and on-grid, including: 1) High efficiency cogeneration on any scale; 2) On-site renewable energy; and 3) Energy recycling systems, powered by waste gases, waste heat and pressure drops to generate electricity and / or useful thermal energy on-site.

The International Energy Agency (IEA) [2] defines distributed generation as the following:

> **Distributed generation** is a generating plant serving a customer on-site or providing support to a distribution network, connected to the grid at distribution level voltages. The technologies include engines, small (and micro) turbines, fuel cells, and photovoltaic systems.

The IEA definition excludes wind power, arguing that is mostly produced on wind farms usually connected to transmission, rather than for on-site power requirements. In addition to providing a definition for distributed generation, the IEA [2] has also provided nomenclature for other dispersed, distributed, or decentralized energy resources that we outline below for completeness and to alert the reader of the different terms that are often used with respect to distributed generation. It should be noted in each of the bulleted definitions below, distributed generation is a subset of the defined category.

- *Dispersed generation* includes **distributed generation** plus wind power and other generation, either connected to a distribution network or completely independent of the grid.

- *Distributed power* includes **distributed generation** plus energy storage technologies such as flywheels, large regenerative fuel cells, or compressed air storage.
- *Distributed energy resources* include **distributed generation** plus demand-side measures.
- *Decentralized power* refers to a system of distributed energy resources connected to a distribution network.

For the purpose of this work we will consider distributed generation as generation used on-site (and possibly unconnected to the distribution network) and/or connected to the lower voltage, distribution network irrespective of size, technology or fuel used. This nomenclature encompasses the definitions of [2] and [7].

DG Technologies

Reciprocating Engines

Reciprocating engines, according to [2] are the most common form of distributed generation. This is a mature technology that can be fueled by either diesel or natural gas, though the majority of applications are diesel fired. The technology is capable of thermal efficiencies of just over 40 percent for electricity generation, relatively low capital costs, but relatively high running costs as shown in Table 1. The technology is also suitable for back-up generation as it can be started up quickly and without the need for grid-supplied power. When fueled by diesel, this technology has the highest nitrogen oxide (NO_x) and carbon dioxide (CO_2) emissions of any of the distributed generation technologies considered in this entry as seen in Table 2.

Simple Cycle Gas Turbines

This technology is also mature deriving from the use of turbines as jet engines. The electric utility industry uses simple cycle gas turbines as units to serve peak load and they generally tend to be larger in size. Simple cycle gas turbines have the same operating characteristics as reciprocating engines in terms of start-up and the ability to start independently of grid-supplied power making them suitable as well for back-up power needs. This technology is also often run in combination for combined heat and power (CHP) applications which can increase overall thermal efficiency. Capital costs are on par with natural gas engines as seen in Table 1 with a similar operating and levelized cost profile. The technology tends to be cleaner as it is designed to run on natural gas as seen in Table 2.

Microturbines

This technology takes simple cycle gas technology and scales it down to capacities of 50-100 kW. The installed costs are greater than for gas turbines, and the efficiencies are lower as well as seen in Table 1. However, it is much quieter than a gas turbine and a much lower emissions profile than gas turbines as seen in Table 2. The possibility also exists for microturbines to be used in CHP applications to improve overall thermal efficiencies.

Fuel Cells

Fuel cell technology is also fairly new and can run at electrical efficiencies comparable to other mature technologies. Fuels cells have the highest capital cost among fossil-fired technologies and consequently have the highest levelized costs as seen in Table 1. Offsetting that, the emission footprint of fuel cells is much lower than the other technologies as seen in Table 2.

Renewable Technologies

There are three major types of renewable energy technologies we discuss here: Solar Photovoltaic (PV), Small Hydro, and Wind. Each of these technologies is intermittent in that they are dependent upon the sun, river flows, or wind. Consequently, these technologies are not suitable for back-up power, but also have no fuel costs and have a zero emissions profile as seen in Table 2. However, the capital costs vary significantly among the technologies and operating conditions over the year affect their respective levelized costs. Solar PV is by far the most expensive in both capital costs and levelized costs as seen in Table 1. Capital costs for small wind are much lower, but levelized costs are in the range of more traditional technologies as seen in Table 1. Small hydro capital costs can vary widely with levelized costs reflecting the same variation.

Table 1: Cost and Thermal Efficiencies of Distributed Generation Technologies Inclusive of Grid Connection Costs and Without Combined Heat and Power Capability

	Installed Cost ($/kW)	**O&M (c/kWh)**	**Efficiency Percent**	**Levelized Cost (c/kWh)**
Simple Cycle Gas Turbine	650-900	0.3 – 0.8	21 - 40	6 - 9
Microturbines	1000 - 1300	0.5 - 1.0	25 - 30	7 - 9
Diesel Engines	350 - 500	0.5 - 1.0	36 - 43	7-11
Gas Engines	600 - 1000	0.7 – 1.5	28 - 42	6 - 9
Fuel Cells	1900 - 3500	0.5 - 1.0	37 - 42	11 - 14
Solar PV	5000 - 7000	0.1 – 0.4	n/a	34.5 – 46.0
Small Hydro	1450 - 5600	0.7	n/a	3.5 - 8
Wind	790	n/a	n/a	7.6

Sources: IEA, 2002 except for the wind which is from AWEA, 2002 and Small Hydro from WADE, 2003. Levelized cost numbers assume 60% capacity factor except for Solar PV from WADE, 2003 at 1850 hours per year, Small Hydro from WADE, 2003 at 8000 hours per year, and wind at 39% capacity factor.

Table 2: Emission Profiles of Distributed Generation Technologies

Technology	lbs. NO_x/MWh	lbs. NO_x/mmBtu	lbs. CO_2/MWh	lbs. CO_2/mmBtu
Average Coal	5.6	0.54	2115	205

Boiler 1998				
Combined Cycle Gas Turbine 500 MW	0.06	0.009	776	117
Simple Cycle Gas Turbine	0.32 - 1.15	0.032 - 0.09	1154 - 1494	117
Microturbines	0.44	0.032	1596	117
Diesel Engines	21.8	2.43	1432	159
Gas Engines	2.2	0.23	1108	117
Fuel Cells	0.01 – 0.03	0.0012 – 0.0036	950 - 1078	117
Solar PV	0	0	0	0
Small Hydro	0	0	0	0
Wind	0	0	0	0

Source: Regulatory Assistance Project, *Expected Emissions Output from Various Distributed Energy Technologies*, May 2001 found at http://www.raponline.org/ProjDocs/DREmsRul/Collfile/DGEmissionsMay2001.pdf

The Role of Natural Gas and Petroleum Prices in Cost Estimates

The levelized cost figures in Table 1 above make assumptions about the price of natural gas and diesel. As can be seen in [10] the price of natural gas and petroleum products have risen substantially in recent years relative to the time the levelized cost estimates have been calculated. Consequently, if the forecasts in [10] are close, the levelized cost of all the fossil technologies will be greater than stated here.

Potential Benefits of Distributed Generation

Distributed generation has many potential benefits. One of the potential benefits is to operate DG in conjunction with combined heat and power (CHP) applications which improves overall thermal efficiency. On a stand-alone electricity basis, DG is most often used as back-up power for reliability purposes, but can also defer investment in the transmission and distribution network, avoid network charges, reduce line losses, defer the construction of large generation facilities, displace more expensive grid-supplied power, provide additional sources of supply in markets, and provide environmental benefits [11]. However, while these are all potential benefits, one must be cautious to not overstate the benefits as we will discuss as well.

Combined Heat and Power (CHP) Applications

CHP, also called cogeneration, is the simultaneous production of electrical power and useful heat for industrial processes as defined by [12]. The heat generated is either used for industrial processes and/or for space heating inside the host premises or alternatively is transported to the local area for district heating. Thermal efficiencies of centrally dispatched, large generation facilities are no greater than 50 percent on average over a year and these are natural gas combined cycle facilities [9]. By contrast, cogeneration plants, by recycling normally wasted heat, can achieve overall thermal efficiencies in excess of 85 percent [7]. Applications of CHP range from small plants installed in buildings (e.g. hotels, hospitals, etc.) up to big plants on chemical works and oil refineries, although in industrialized countries the vast majority of CHP is large, industrial CHP connected to the high voltage transmission system [2]. According to [3], the use of CHP applications is one of the reasons for increased DG deployment.

Table 3 shows the costs of DG with CHP applications and their levelized costs. When compared to the levelized costs of stand-alone electricity applications, these costs are lower, especially at high capacity factors (8000 hours) showing evidence of lower costs along with greater efficiency in spite of the higher capital cost requirements.

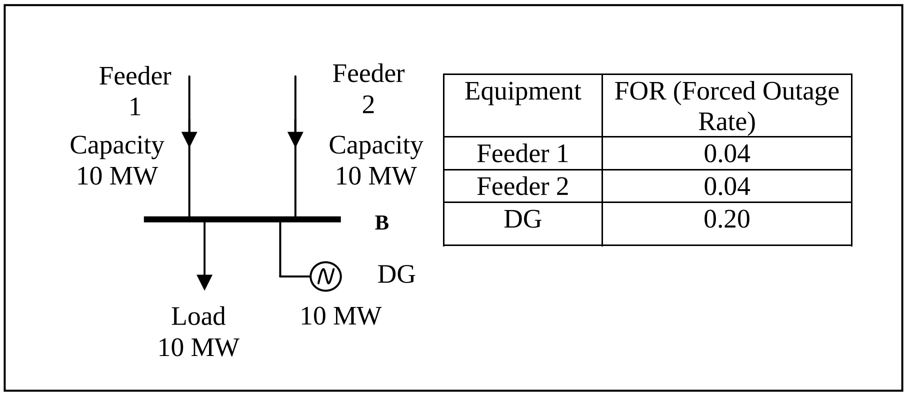
Table 3: Distributed Generation Technology Costs Inclusive of Combined Heat and Power Infrastructure

	Installed Capital Cost ($/kW)	**O & M (c/kWh)**	**Levelized Cost (c/kWh)**	
			8000 hrs/year	**4000 hrs/year**
Simple Cycle Gas Turbine	800 – 1800	0.3 – 1.0	4.0 – 5.5	5.5 – 8.5
Combined Cycle Gas Turbine	800 – 1200	0.3 – 1.0	4.0 – 4.5	5.5 – 6.5
Microturbines	1300 – 2500	0.5 – 1.6	5.0 – 7.0	7.0 – 11.0
Reciprocating Engines	900 – 1500	0.5 – 2.0	4.5 – 5.5	6.0 – 8.0
Fuel Cells	3500 – 5000	0.5 – 5.0	9.0 – 11.5	14.5 – 19.5

Sources: IEA, 2002 and WADE 2003

Impact of DG on reliability (Security of supply)

It seems quite clear that the presence of DG tends to increase the level of system security. To confirm this idea, the following example is considered:



Equipment	FOR (Forced Outage Rate)
Feeder 1	0.04
Feeder 2	0.04
DG	0.20

Figure 2: Security of Supply Example with DG.

Figure 2 shows a very simple distribution network. It consists of two radial feeders, each with 10 MW of capacity, which feed busbar B. A constant load of 10 MW is connected to B. The FOR of the two feeders is given in the table in Figure 2. Additionally, consider a 10 MW DG source with an availability factor of 80 percent.

To begin with, let us only consider the two feeders and assume there is no distributed resource connected to busbar B. The loss of load probability (LOLP), the probability that load is not served, is simply the probability of both feeders being out of service at the same time which can be calculated by multiplying the two probabilities of failure. Consequently, LOLP= (0.04 x 0.04) = 0.0016. The expected number of days in which the load experiences troubles can also be calculated multiplying the LOLP by 365, which results in 0.584 days/year. This number can be expressed in hours/year multiplying by 24, resulting in 14 hours/year.

Now let us consider including the DG source. It has an outage rate greater than the two feeders at 0.20, but it also adds a triple redundancy to the system. Thus we would expect the addition of the DG source to decrease the LOLP. The new LOLP is the probability that both feeders fail and the DG source is not available. Therefore, the LOLP = (0.04 x 0.04 x 0.20) = 0.00032. That is, the probability of being unable to serve load is five times less than before. This translates to an expected number of hours per year unable to serve load at just less than 3 hours per year in our example.

Impact of Distributed Generation on Network Losses, Usage, and Investment

The presence of DG in the network alters the power flows (usage patterns) and thus the amount of losses. Depending on the location and demand profile in the distribution network where DG is connected and DG operation, losses can either decrease or increase in the network. A simple example derived from [13] can easily show these concepts.

Figure 3 shows a simple distribution network consisting of a radial feeder which has two loads (D1 and D2 at point A and B respectively) and a generator (G) embedded at point C. The power demanded by the loads is supposed to be constant and equal to 200 kW. The power delivered by the generator is 400 kW. The distance between A and B is the same as the distance between B and C. In addition, the distance between T and A is twice the distance between A and B. Moreover, we assume the capacity of each of the sections is equal to 1000 kW. Impedances for sections AB and BC are assumed equal as are the distances. The impedance on TA is assumed twice that of AB and BC as the distance is double. We also assume constant voltages and that losses have a negligible effect on flows.

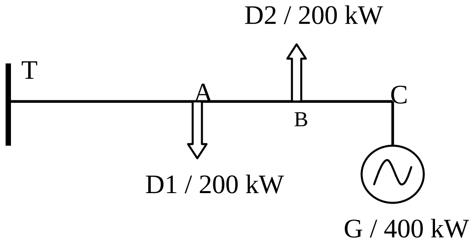


Figure 3: A simple distribution network.

From the hypothesis made it is easy to demonstrate that the line looses (*l*) can be calculated multiplying the value of line resistance (proxy for impedance) (*r*) by the square of the active power flow (*p*) through the line: $l = rp^2$

If distributed generator G is not present in the network (disconnected in Figure 4), then the loads must be served from point T with the resulting power flows, assuming no losses for the ease of illustration, of Figure 4.

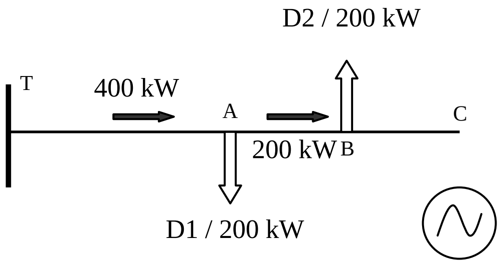


Figure 4: Power flows without DG

Losses in the network are $l = 4^2 x(2x0.001) + 2^2 x0.001 = 0.036\ p.u.$, or 3.6 kW. Additionally, the usage of the network is such that the section TA is used to 40 percent of its capacity (400kW/1000kW) and section AB is used to 20 percent of its capacity (200kW/1000kW).

Now, assume distributed generation G is connected at point C as shown in Figure 5. The resulting power flows, assuming no losses again for ease of illustration, are the following:

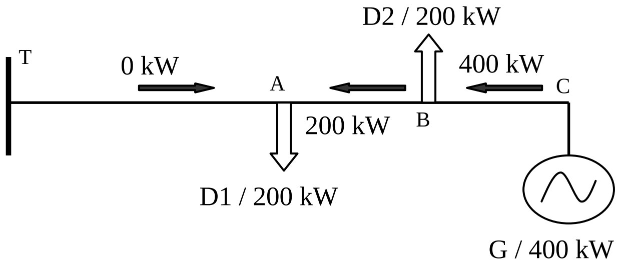


Figure 5: Power flows and usage with G producing 400 kW.

The losses are $l = 0.001\left[2^2 + 4^2\right] = 0.02\ p.u.$, or 2 kW, which is a 44 percent reduction in losses in the case without DG. The reduction from losses comes from transferring flows from the longer circuit TA to a shorter circuit BC. Moreover, since less power must travel over the transmission network to serves the loads D1 and D2, losses on the transmission system are reduced, all else equal.

Additionally, the pattern of usage has also changed. The usage on AB is still 200 kW but the flow is in the opposite direction from the situation without DG. The flow on TA has been reduced from 400 kW to 0 kW. In effect, the DG source at C has created an additional 400 kW of capacity on TA to serve growing loads at A and B. For example, suppose the loads D1 and D2 increased to 700 kW each. Without DG, this would require extra distribution capacity be added over TA, but with DG, no additional distribution capacity is needed to serve the increased load. In short, DG has the ability to defer investments in the network if it is sited in the right location.

Finally, depending on the distribution and transmission tariff design, DG can avoid paying for network system costs. This is especially true in tariff designs where all network costs are recovered through kWh charges rather than as fixed demand charges. This is another reason, according to [3] for DG deployment.

It is important to emphasize that the potential benefits from DG are contingent upon patterns of generation and end use. For a different generation and end use patterns, losses and usage would be different. In fact, losses may increase in the distribution network as a result of DG. Let us, for example, G produce 600 kW. For this case, losses are 6 kW, greater than the 3.6 kW losses without DG. Moreover, while DG effectively created additional distribution capacity in one part of the network, it also increased usage in other parts of the network over circuit BC. Consequently, one must be cautious when evaluating the potential for DG to reduce losses and circuit usage.

Potential to Postpone Generation Investment

In addition to the potential network benefits and reliability (security of supply benefits), distributed generation may bring other benefits to power systems. The first is the ability to add generating capacity in a modular fashion and that does not require building large power plants which will have excess capacity for some time and because of size, may be easier to site and permit and completed quicker. In this vain, [14] modeled DG in the PJM market and found the potential to displace some existing units as well postponing new combined cycle gas units. However, one must be cautious with this potential benefit as the overall costs of DG may be less than central station power.

Potential Electricity Market Benefits

In an electricity market environment, distributed generation can offer additional supply options to capacity markets and ancillary services market thereby leading to lower costs and more competition [15]. In the same vain, the owner of distributed generation has a physical hedge against price spikes in electricity markets which not only benefits the owner of distributed generation, but should also help dampen the volatility in the market [2].

Potential Environmental Benefits

Finally, distributed generation resources may have lower emissions than traditional fossil-fired power plants for the same level of generation as can be observed in Table 2, depending on technology and fuel source. Of course, this is true for renewable DG technologies. The benefits are potentially large in systems where coal dominates electricity generation as can also be seen in Table 2. [14] models DG in the PJM market and finds DG displacing generation on the system led to lower emissions levels. These reasons were cited in [3] as determining factors for some DG deployment. Moreover, since losses may also be reduced distributed generation may reduce emissions from traditional generation sources as well. Additionally, customer demand for renewable energy may be driving renewable energy deployment [16].

POLICIES AND CONCLUDING REMARKS

Distributed generation as defined in [2,7] can provide many benefits, though it is not yet quite competitive with grid-supplied power on its own. Current policies to induce DG additions to the system generally consist of tax credits and favorable pricing for DG provided energy and services that are subsidized by government [2]. While such policies may be effective to capture some potential benefits from DG such as environmental benefits, they do not address the network or market benefits of DG. Only recently has serious consideration been given to considering locational pricing of network services as a way to provide better incentives without subsidies [17, 18] as recommended by [2]. Moreover, only recently has DG been recognized as a potential player in wholesale power markets to provide market-wide benefits [15]. Finally, any barriers that prevent the efficient entry of DG should be reconsidered [1, 2].

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