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Fuel cells – a new contributor to stationary power

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Abstract

Stationary power generation historically started as distributed generation near the user, with the configuration of a very open market, where a lot of small competing utilities were offering electricity to the customers. At a second time it became a 'monopolistic' business because of technical reasons. Big steam turbines and electric generators, allowing better efficiencies, were more conveniently installed in very large power plants, necessarily located in sites far away from where the power was needed, and the transmission losses were bounded by AC high voltage technology. The Governments were, therefore, trying to balance the power of monopolies, that were limiting the economical development of the countries, by strengthening the concept of electrical energy price public control and, alternatively, by establishing rules to allow a free flow of electricity from one region to the other, or taking direct control through ownership of big and small utilities. The most effective way of making the electric energy system competitive has proved to be the opening of a partial competition in the generation field by forcing the utilities to compare the cost of their energy, produced with new centralised plants, to the price of the available energy, coming from combined heat and power dispersed generators. In fact, with reference to this cost, all the peculiar features of large central stations and dispersed generators were taken into account, like the widespread use of natural gas, the investment risk reduction with single smaller increments of capacity, the transmission and distribution siting difficulties and high costs, the improved system reliability, and, finally, the high quality electric power. Fuel Cells are a recently become available technology for distributed electrical energy production, because they share the main typical aspects, relevant for a distributed power system, like compatibility with other modular subsystem packages, fully automation possibility, very low noise and emissions release, high efficiency both directly as fuel cell (38–55%) and in integrated cycles (50–65% with fossil fuels), delivered 'power quality' and reliability. Focus is principally kept on the impact fuel cells could have on electrical grid management and control, for their voltage support and active filtering capabilities, for their response speed and for quick load connection capabilities. The cost for the moment is high, but some technology, like phosphoric acid, is in the market entry phase. Cost analysis for the main subsystems, that is fuel cell stacks, fuel processors, and power electronics and controls, indicates that the prices will be driven down to the required levels both through technology refinements and increase of production volumes. Anyhow, a new phase is beginning, where centralised power plants are facing the competition of distributed generators, like fuel cells, small gas turbines and internal combustion engines, and of other renewable energy generators, like photovoltaics and wind generators. They all are modular, dispersed throughout the utility distribution system to provide power closer to end user, and are not in competition with existing transmission and distribution systems, but they improve the systems' utilisation. The plants will initially be directly owned and operated by gas or energy distributors, and the customers could easily supersede their mistrusts by only paying for the energy they are really utilising, leaving away the worries about the investment costs and the risks of a bad operation. An 'intelligent grid', delivering high quality electrical energy to millions of electrical household consumers, which, a second later, become non-polluting energy producers, appears to be giving a very relevant contribution to 'the town of the future', envisaged also by the European Commission, where the quality of our lives is mainly depending on the quality of the energy. Published by Elsevier Science S.A.

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1. The stationary power generation market

Power generation is a business which, no doubt, has accelerated its rate of change in the last years.

The reasons for this are very numerous, and, certainly, along this Fifth Grove Fuel Cell Symposium, multiple interpretations of this change will be analysed, mainly with reference to fuel cell generation.

To our purposes of clarifying which type of contribution to stationary power generation fuel cells could and will give, it is, therefore, necessary to sketch our vision of the stationary power generation, trying to point out some historical insight of the electric systems and of its evolution in most countries of the world.

In fact, the electric systems have been, since the very first diffusion of electrical energy, a very open market, as many

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small utilities were offering to supply energy to any specific customer. Just as a confirmation, the city of Chicago used to have, at the turn of the century, almost 50 utilities, delivering electrical energy in the same areas of the town.

A second phase, that lasted till the recent past, in spite of any economical push, has been highly monopolistic, with the energy market into the hands of a small number of companies, delivering energy to entire towns or regions. The reasons for this were, first of all, technical. The trend towards increasingly bigger power generation stations has been based upon the fact that bigger steam turbines and electric generators, allowing better efficiencies, were making it more convenient to produce power in very large power plants. The power plants were, of course by need, located in sites not so close to where the power was needed, but the high voltage technology; connected to the adoption of alternating current as energy carrier, instead of direct current, made it convenient to transfer electrical energy to very far away locations with limited dispersions or losses by the adoption of high voltage overhead lines, fed through high voltage transformers.

Also the cost of kWh, heavily affected by the investment cost level, was taking direct benefit from the reduction of the unit cost of the investment ($/kW), which was decreasing with the size of the plant. Each electric power producer was compelled to install its own transmission lines and this need became, very soon, a point of strength in relation to the energy market. In fact, no other electric energy producer was allowed to sell its energy in a certain area, if not with the consent of the owner of the transmission lines. The creation of monopolistic situations was, therefore, inevitable.

Generally speaking, the big utilities have been vertically highly integrated, directly owning and operating generation, transmission and distribution systems. Excess electricity has been generally sold or acquired to or from the other monopolistic companies.

Almost at the same time, the big utilities, pushed by the public opinion, had to face the decision to shoot down nuclear power stations and polluting fossil fuels power stations, or investing a huge amount of money for the installation of pollution control devices. The big amount of money involved was only available through the increase in the energy price.

Also, the trends in energy consumption increase in the industrialised world, which developed at a rate lower than in the previous years, made the electric utilities more careful and cautious in their forecasts, because they were burdened with investment engagements in big plants, which were not in full operation or were operating at very low utilisation factor. The simplest ways for the Governments to overcome these difficulties and dismantle the limitations to economy development, represented by an high energy selling price, have been, alternatively or jointly, in different countries:

- the concept of public control of the price of electrical energy;
- the definition of rules for allowing a free flow of electricity from one region or State to the other, trying to counterbalance by (the power of the owner of the transmission lines;
- the opening of a partial competition in the generation field, through the public control of transmission lines;
- the public control or the ownership of the big as well as of the small utilities.

Particularly the choice of the last option has proved to be an indirect, but very effective way of rendering the electrical energy system very competitive.

In other words, some utility analysts have theorised that the situation of large central stations, being supplemented by a multitude of smaller generating units, located closer to utility customers, is becoming a grid similar to the one already settled for large mainframe computers, where a lot of personal computers is integrated in the information network.

A new technical aspect entered into the field, related to a different way of producing energy, that is the wide spreading of cogeneration power plants or of renewable sources. Independently from the size of the utility and of its plants, has been the opening of a partial competition, forcing the utilities to compare the cost of the energy produced with their new centralised plants, to the price of available energy, coming from new technology based dispersed generators, under the assumption of an already reached high degree of efficiency of production.

This reference cost is a measure of:

- all the peculiar features of large central stations and dispersed generators – their mix in a specific grid;
- the more or less widespread use of natural gas and of other fuels;
- the investment risk reduction with single smaller increments of capacity;
- the transmission and distribution siting difficulties and high additional costs for their extensions;
- the improved system reliability, and, finally – the high quality of electric power.

The fact that small municipal owned utilities are usually reciprocally selling or buying excess or lacking energy from or to their corresponding utility, has eased the creation of some pricing criteria, related to where and to when the electricity is available, and so on.

As an example, in recent times, the Independent Power Producers (IPP) in the US have been in a stable growth situation because they have been very fast reacting companies in applying emerging technologies, like combined heat and power (CHP), biomass, geothermal energy, wind and photo voltaic (PV).

The competition has therefore increased, because an IPP is authorised with the Energy Policy Act (1992) to sell its electricity to a distributor, by making use of a third company's grid, located between its energy production sites and the final customer. This fact, deriving also from the obligation of the owner of the transmission line not to deny this possibility, IPP have therefore reached in 1993 a significant amount (7%) of the total national energy generation.

2. Small scale distributed generators (DG)

2.1. Definition

Distributed generation (DG) is generally intended as any modular technology that is sited throughout a utility's service area, interconnected to the distribution or sub transmission system, to lower the cost of service. DG in a strict term comprises diesel and internal combustion engines, small gas turbines, fuel cells, photovoltaics, batteries and other types of storage technologies. Someone includes in DG also locally targeted demand-side management programs, that have the final goal of reducing energy demand and making available a 'virtual' DG.

A certain amount of DG already exists in every grid under the form of conventional technologies (diesel electric and turbine gen sets) and of advanced technologies (PV, batteries, FC), serving either as on-site power generators (or cogenerators) for large industrial or commercial customers, or as their back-up, to ensure power reliability.

2.2. Economical aspects

The DG concept under development and diffusion today has to be seen by utilities as a business opportunity, with the final goal of lowering the overall cost of serving customer loads and to enhance service quality. This is a very key issue in a market whose competition is heating up today.

Utilities are also encouraged in investing in smaller generation because of lowering of the investment risk connected to the big sizes of units, if compared to the slow rate of growth of the electrical energy demand. The need to increase the capacity of generating, transmitting and distributing can therefore be deferred.

Even if big units have a still lower cost per installed kW, nevertheless the cost of DG conventional technologies – such as aeroderivatives gas turbines – has declined sharply in recent years, as the high volume of fabrication for use in aircraft led to technological advances, improving both cost and performances. In other words, the economies for utility systems are shifting from economies of scale to economies of mass production.

A direct consequence of this experience, and of the different investment costs for the kW, is the different ranges for the cost of electrical energy (from 8 to 12 c$/kWh for geothermal, wind and biomass to 4 c$/kWh for gas turbines). These figures are very similar to the kWh costs of nuclear and big coal plants.

At least at the beginning of the development, the DG plant will be directly owned and operated by the power or the gas distributor, and the mistrust of the customer about reliability and operability of the new technologies is avoided by the fact that the customer is only paying for the energy he is really consuming, at a price in line with the market price of the power, and he is not facing the risk of a bad operation of the new system.

2.3. Technical challenges

What is here of interest is to see which are the additional factors, apart from size, that make more or less acceptable each DG technology.

First of all, the generator set has to be non polluting because its siting in the middle of urban areas needs not to add pollution to the basic levels, which are already existing.

Secondly, the distributed generators have to be modular systems, independently from the technology, so to reach a fast installation possibility.

Then, the fast response capability and the wave harmonic content are features that could satisfy the power quality needed by the present typical customer, by opening a lot of new applications.

Additionally, the possibilities of electrical grid management and control, of its voltage support and of its active filtering are making the grid very sound and able to provide additional opportunities of good quality power.

Finally, the efficiency of small generators has to favourably compare with the mean efficiency of a set of big generators, present in the grid.

3. Effects of DG on electrical grids

Let us evaluate the impact of small scale distributed generators, and, therefore, also of fuel cells on the overall grid behaviour, on the grid sizing, and the impact on the billing systems for the electrical energy to the final consumer.

There is an ongoing debate on the technical effects of widespread implementation of DG on the electrical grids.

- Traditionally, a utility has the obligation to ensure that at any instant in time the total product being produced for its customers is equivalent to the total demand from the customers. The system dispatcher ensures that the grid operates at a stable frequency. If the generation is greater than the load required, the frequency increases; and if the generation falls short of the load, the frequency decreases. Both situations can cause a variety of power quality problems to the customers, and to avoid this by keeping the frequency, utility dispatchers adjust power production according to the load. The automatic generation control system does not track generation at the small power fluctuations of the distribution level.

- Today, in general, the DG units are not dispatchable, that is they are not under the direct control of the utility dispatcher. Thus the utilities have to accept the power whenever it is generated. DG penetration is probably the key factor on existing networks, as far as their behaviour in terms of thermal loading, power flows and reliability. The technology for providing the required level of control at the distribution level is the necessary solution;
- At the other end, a real revolution is taking place, because the difference between energy customer and energy producer is becoming smaller and smaller. Probably today there is not any difference at all, when an industry or a small community is operating a power generation plant in some hours of the day and is selling to someone else, or generically to the grid, electric) energy in different hours of the day;
- The integration of distributed generators into an electric grid has to be greatly facilitated by bi-directional communication techniques for monitoring and controlling. At the lowest level, it is envisaged that the single house micro generator is connected to a very wide grid. The grid acts as an 'intelligent system', able to activate and deactivate single generators and appliances, according to the present needs, and the optical fibre cables, already present for thousands of kilometers, mainly along the high voltage lines, easily put into communication power generation plants with distribution plants and final appliances. The optical fibers connections, originally hired for the excess capability to communication companies, or viewed as a diversification mean for entering into the communication business, should today be directly utilised for connecting power generators to end users, equipped with home computers to properly manage the power consumption.

A real-time pricing systems has to be put into operation, taking into account the different value of energy, according to the different times during the day.

As a reference, in specific situations and locations, the fares can have a fluctuation from 4 c$/kWh to as much as 24 c$/kWh, and the advantage for the customer with the capability of properly programming its home appliances through microcomputers is sizeable.

Computer models simulating given networks have evaluated that the peak installed power is decreased by a factor of 1.5 kW for each family, by application of the pricing system and of the new technologies implied. It means $1500 of minor investments for the utility for every family connected to the grid.

The new situation, envisaged as a progressive 'vertical disintegration', referring to the fact that the link between the grid and the customer could be less stringent than before, looks to be a very effective measure for increasing energy production competitivity. Some monopolistic situations will be, anyhow, left in the transportation and distribution sectors, even if weakened by the decreasing monopolistic protection for the long distance transmission lines.

4. The fuel cell contribution to stationary power

4.1. The technologies and their applications

In a brief and schematic overview, for non specialists, of the main features of FC, various technologies are available, at a different degree of development, and, from the functional viewpoint, they pertain to two categories:

- high temperature, where the high grade heat availability gives the possibility of incorporating them in a combined cycle arrangement (thus producing additional electrical energy) or simply utilising the high grade heat for direct applications;
- low temperature, where the simplicity and the lifetime are more attractive.

A general view of the present status of them is reported in Table 1.

There is a gap in technologies' maturities and in commercial availabilities, in the dynamic performances, related to operating temperatures, and, finally, in the overall efficiencies, and in the combined cycle efficiencies (55–65%).

Table 1

FC technology status [3]

FC technology	Operating temperature (°C)	System efficiency (%)	Commercial availability	Start up time (h)
PEM	70–90	32–40	Post 1999	<0.1
PAFC	205	36–45	Started 1993	1–4
MCFC	650	43–55	Post 1999	5–10
SOFC tub	800–1000	43–55	Post 1999	5–10
SOFC planar	800–1000	43–55	Post 2000	unknown
High temperature FC integrated cycles	Various	55–65	Post 2000	5–10

Nevertheless, all the FC technologies have favourable performance parameters for applications in DG; just to mention a few of them not included in Table 1:

- fuel flexibility (hydrogen, natural gas, biogas, gassified coal, other fossil fuel);
- low emissions, without any specific cleanup or control; NO_x <5 ppm; CO <5 ppm; SO_2 negligible; noise <60 dB;
- CO_2 low, and directly related to the high efficiency;
- wide modularity, from 5 kW to 10 MW;
- reliability and low maintenance (for the commercial technologies).

FC are very favourable compared with other DG systems, as far as efficiency is concerned at full power operation, and, more important, at partial loads.

Fuel cells can therefore contribute to increase the mean level of efficiency of our energetic systems; and win the game against the efficiencies of large power plants.

About one third, but the figure is controversial, of the costs connected to the sale of electricity to the final customers is due to the transmission and distribution of this energy.

If the utility builds a FC power generator directly at the user's premises, these costs are completely avoided, and, when the plant is producing energy in excess of what is needed, it can be sold to the grid, taking advantage of the price differential vs. the one of the big power plant. As an alternative to this operation, one could take advantage of the efficiency versus load very favourable behaviour, utilising them in an high efficiency load following applications.

Additionally, FC electrical response speed is characterised by:

- the regulation of active and reactive power in each point of the grid, because of the presence of a solid state inverter in the FC DG;
- the speed for adapting to reactive power requirements, by far quicker than the one of rotating generators;
- the speed to comply with sudden load connections or disconnections(1/10 of a s).

Therefore, the emission levels give the possibility of siting FC practically everywhere and add a variable value for the overall environmental benefits of the technology – and mainly for the possibilities of electrical grid management and control, of its voltage support, and, finally, of its active filtering.

4.2. The 'newness ' of FC contribution to the stationary power generation

Let us now try come to the main issue of this presentation, the role fuel cells are foreseen to cover, similar to other DG systems, in the stationary power generation field, and according to which reasons should an utility buy fuel cells power generation plant, instead of other small size distributed generator systems.

FC in the stationary power generation field have a 'new' role for the combination of many factors, that became mature and relevant at the same time in recent years, and they are now aiming at special application niches:

1. distributed generation is today a growing aspect for every grid, and it is provided that it will boom in the near future, as it is already in a few regions of the industrialised world, where every new addition of power is only possible through DG. DG could either be conventional (small gas turbines and internal combustion engines) or renewable energy generators (like photovoltaics and wind generators), and they are not in competition with existing transmission and distribution systems, but improving the systems' utilisation;
2. because of their high efficiency, low emissions, high reliability and fast response to sudden electric loads, FC are ideal candidates to make DG more widespread;
3. fuel cells, that traditionally were considered for basic power generation, are today more and more foreseen for commercial generation and light industrial cogeneration. This aspect is outlined, among many others, by Arthur D. Little qualitative studies (Table 2 from [3]);
4. many FC types are very likely candidates for such applications, with the only exception of planar SOFC, because of their characteristics and economy, that need more developments;
5. the FC cost for the moment is high, but cost analysis for the main subsystems, that is fuel cell stacks, fuel processors, and power electronics and controls, have indicated that the prices will be driven down to the required levels both through technology refinements and increase of production volumes.

4.3. FC economics and competitivity

In general, FC cost for the moment is relatively high, but, as already discussed, some niche applications exist, particularly for the phosphoric acid technology, which is in the market entry phase.

Cost analysis for the main subsystems, that is fuel cell stacks, fuel processors, and power electronics and controls, as other DG technologies have already demonstrated, indicates that the prices will be driven down to the required levels both through technology refinements and increase of production volumes.

Not all the technologies have either the same needs for fuel processing or the same costs: fuel processor has a low/medium complexity for MCFC and SOFC because reforming process can be developed on the anode or on the anode flow fields; on the contrary, has a high/medium complexity for PEMFC and PAFC, where an external fuel processing is required.

Table 2
Matching of fuel cell characteristics with applications

Application/technology	PEMFC	PAFC	MCFC	SOFC (tub)	SOFC (plan)
Central generation	♣	♣	♥	♥	♦
Distributed generation	♦	♥	♥	♥	♦
Repowering	♣	♥	♥	♥	♦
Residential generation	♥	♣	♣	♣	♦
Commercial generation	♥	♥	♦	♣	♦
Light industrial cogeneration	♦	♥	♥	♥	♦
Heavy industrial cogeneration		♣	♥	♥	♦

♥The application is very likely.
♦The application could be considered.
♣The application is unlikely.

On the other end, each market segment has its own allowable prices/costs, that is total installed system costs, including all owners costs, vs. assumed:

- typical load factors for the facility;
- typical power capacity of the system;
- O&M costs (linked to the technology);
- availability;
- equipment life;
- payback requirements.

Here again the different analysts differ one from the other as far as their conclusions are concerned, but, taking the assumptions of 20 years equipment life, 95% availability, 18% capital charge rate, and increase of 0.01 $/kWh for O&M, it appears from market potential models, developed in [3]), that:

- commercial cogeneration and self-generation, in the range from 200 kW to 2 MW, and with a facility load factor ranging between 35 and 45%, give the highest allowable prices: 1300–2000 $/kW) (in 1997 US $);
- light industrial cogeneration and distributed power, in the range from 100 kW to 20 MW, and with load factors of 45 to 75%, have encouraging allowable prices of 1000–2000 $/kW;
- heavy industrial cogeneration, repowering and central stations are, with some significant exception, in the lower range of allowable prices, and, therefore, reflect low value markets, with wide market potential.

The heat recovery aspect has, of course, a very variable impact on the economics of the annual cost saving, according to the typology of commercial applications and of the different locations. Just as an example, heat recovery in hotels and hospitals could give an annual energy cost saving in 1997 US $/kW of installed capacity of as much as $200.

Many examples are available on how evaluating the economics of a FC Distributed Generation towards alternative competing systems.

Taking into consideration the 'classical' case of evaluation of FC distributed generators against an existing distribution network, it is necessary to consider typical values for capital costs of the transmission lines in respect of generation and distribution, which appear to be applicable to many utilities in industrialised world.

ADL made the calculation for a FC system versus the upgrading an existing distribution network, accounting:

- for capital costs according to [4], valid for Italy:

  – 42% (3350 billions lire) of the total construction expenditures for generation;
  – 17% (1320 billion lire) for transmission;
  – 41% (3200 billion lire) for distribution;

- for the O&M costs of the existing T&D 0.01 $/kWh and got the following results:

  – T&D avoided construction cost savings:

  – 100–300 $/kVA for transformer and substation upgrade;
  – 350–1000 $/kW for a 10 Km distribution line;

- T&D avoided capacity cost savings:

  – 10–100 $/kW for capital and O&M costs of the existing T&D;

- Transmission and Distribution avoided energy losses from central power station to DG interconnection:

  – 3–10% based on the system (but they could be as high as 20%);

- Reactive power support, produced by the FC by reducing current;
- It could be estimated as a benefit by using the avoided cost of shunt capacitors or through a load flow analysis;

  – 40 $/kVAR or 50 $/kW according to utility.

5. The town of the future

It is worthwhile briefly mentioning wider visions of what will be the future for the towns, where the large majority of European people are living today, under the impact of Distributed Generation, and, specifically, of FC.

The direct link is between the expected quality of life in towns and the level today reached, and how is the EU evaluating this possible improvement.

To minimise the gap between what people expect and what is really achievable, the EU is willing to launch a key action, whose name is 'the town of the future', to let people living in non-polluted conditions, having available energy clean, abundant, low cost, and of a high 'quality'.

The conventional, or 'historical' way of solving this equation has been to enter into the city with a distribution grid, having the power generation located – in general – very far from the point where the power is needed, and having solved more or less completely the problem of pollution at the generation site. The quality of electricity has been satisfactory for the time being, but an increased improvement in the quality is required by the extended application of small computers and sophisticated control systems applied in the everyday life.

The solution for the town of the future is today viewed as an 'intelligent grid' connecting non polluting power generators, not only of big size, but also very small, dispersed near the final users, or directly owned by the user/producer, delivering high quality and reliable electrical energy, to millions of electrical household appliances, capable of improving the quality of our lives, and, at the same time, activated only at appropriate times, when the power is available.

A new electrical network configuration is envisaged, where centralised power plants and a significant percentage of distributed generators, like fuel cells, small gas turbines and internal combustion engines, and of other renewable energy generators, like photovoltaics are operating at the same time. They all are modular, dispersed throughout the utility distribution system, to provide power closer to end user, and are not in competition with existing transmission and distribution systems, but they improve the systems' utilisation.

At the beginning the plants are likely to be directly owned and operated by gas or energy distributors, and the customers could easily supersede their mistrusts by only paying for the energy they are really utilising, leaving away the worries about the risks of a bad operation.

Finally, the 'intelligent grid' concept, delivering high quality electrical energy to millions of electrical household consumers, which, a second later, become non-polluting energy producers, appears to be giving a very relevant contribution to make possible the idealised 'town of the future', where the quality of our lives is mainly depending on the quality of the energy.

6. Conclusions

The competition increase in power generation and the new now available technologies give wide opportunities of business to quick acting companies, capable of facing dispersed generation issues and the difficulties associated to monopolistic situation and legislative dispositions.

Among the many dispersed generating systems, fuel cells can offer an important challenge because their characteristics are matching, better than any other system, to what is ideally required from any distributed generator system, and make possible to convert into reality the 'town of the future' concept.

References

[1] C. Flavin and N. Lenssen, *Technology Review, 86*, (1995).
[2] L. Lamarre, *EPRI J., April/May* (1993).
[3] A.D. Little, *Various Workshops.*
[4] ENEL 1994, *Financial Statements*: Director's Report on Operations.