WHY NEW DISTRIBUTED GENERATION UNITS MIGHT TRANSFORM POWER INDUSTRY'S ORGANIZATION ? THE CASE OF GAS MICROTURBINES

Sophie MERITET

C.G.E.M.P.
Centre de Géopolitique de l'Énergie et des Matières Premières
Université Dauphine - Paris IX

ABSTRACT

In this paper, we will focus on the relationship between innovation and industrial organization in electric power industry. With the deregulatory reforms, the influence of new generating technologies on the current evolution of the power sector seems to be relevant to study. Recent technological advances have resulted in the emergence of so-called distributed power generation system. One of the latest option of decentralised generation units is the gas microturbine which might transform the whole American electric power industry.

INTRODUCTION

Worldwide, for the last two decades, energy network industries have undergone major changes in terms of industrial organization and competitiveness. Led by a combination of economic, technological, political and ideological forces, these industries are now progressively less protected and controlled by governments. After restructuring reforms in the transportation, telecom and natural gas sectors, deregulatory initiatives have been taken in the electric power industry to eliminate traditional constraints and protectionism. A new era has emerged : in some segment of the value chain, electric monopoly activities are now open to competition. There is lively debate about whether these experiments will succeed and how they should be conducted.

In several industrial sectors, especially in networks industries, regulated monopolies are regarded as either directing or delaying innovations. There is an obvious link between the form of industrial organization and the dynamic of technological progress. Thus, one concern is raised : **the role of technology in the new emerging structure of electric industries** and more precisely, its contribution to change monopolistic situations in various activities. With the deregulatory reforms, the influence of new generating technologies on the current evolution of the power sector seems to be highly relevant. The electric power industry and its related R&D in the midst of a transition still have to be defined not only from a regulated industry to a deregulated one (partially or totally), but also from an old dynamic R&D to a new one. The role of generating innovations will be probably decisive.

In this paper, we will focus on the relationship between **innovation** and **industrial organization in electric power industry**. In the first part, we will briefly discuss the **theoretical impact** of new technologies on network industries' organization and vice-versa, keeping in mind that technological progress' dynamic is different in a regulated market than in a competitive one. Then, we will study the evolution of power generating system towards new highly efficient **distributed generation units**. These technological improvements might revolutionise not only generation activity but the whole power industry. Finally, we will present **the case of gas microturbines** to underline the drawing forces and obstacles of the development of some small generators on site.

INNOVATION AND MONOPOLY

Network industries such as natural gas, electricity and telecommunications are defined by the need to dispatch goods or services over a *network* that constitutes a natural monopoly. They have long been structured in accordance with the belief that a single company can provide services more efficiently. An industry is a natural monopoly "*if total costs of production are lower when a single firm produces the entire industry output than when any collection of two or more firms divide the total among themselves*".[1] This single firm is characterized by[2] economies of scale existing when the average costs of production decrease as output expands. In Economics, the old concept of "natural monopoly"[3] refers to an industry where the technological advantages of large scale production preclude efficient competition among smaller companies.

By the beginning of the twentieth century, it was recognized that railroads, telecommunication and local public utilities possessed to certain extend some degree the characteristics of a natural monopoly. For nearly a century, worldwide these sectors had been thought of as a natural monopoly industries where efficient production required reliance on monopoly suppliers subject to government control of prices, entry, investment, service quality and other aspects of firm behavior. Concerned for the public interest, these industries were regulated in the United States and publicly owned elsewhere. "*The essence of regulation is the explicit replacement of competition with governmental orders as the principal institutional device for assuring good performance*" (A.KHAN 1970, p.3). Regulation initially required detailed authority over the levels and type of services, revenue amounts, minimum and maximum rates in order to prevent sector concentration, to hinder destructive competition, to develop the infrastructure and to protect consumers.

Despite these goals, the reality of regulation became different. The lack of competition caused by the regulatory regime left firms and entire industry structures frozen over the decades. They had no incentive for innovation. In a regulated market, companies are not incited to invest in technology to improve operational efficiencies. For example, H.AVERCH & L.JOHNSON (1962) argued the rate-of-return regulation leads to an inefficient use of capital. When regulators set the allowed rate-of-return above the cost of capital, the utility uses more capital than if it were unregulated. This constraint creates an incentive for the utility to accumulate an excessive amount of capital relative to the cost-minimizing level. Excess capitalization (the so-called "*Averch-Johnson effect*") arises from the absence of competitive pressure on producers.
Conversely, technological performances can be stimulated by regulation. In some situations, protection and constraints imposed by regulators favor development of new technologies. Competitive firms could not afford to invest in some new technology. A regulated firm can be more able to support such costs. For instance, in France, during the mid-80s, E.D.F. innovated in building large efficient power plants (≈1400 MW).[4] But, regulation can also lead to technological excessive considerations : the French electric monopoly is sometimes perceived as "*over-engineered*".

The majority of **academic literature** has not focused on the regulated firm's incentive to adopt new technologies. The effects of regulation on technology are not so clear (R.VIETOR 1994). One intuitive reaction is that monopolies stifle innovation and are technologically obsolete. The general perception is that regulation discourages innovation. According to A. KAHN *"It seems a fair generalization that regulation has on balance been obstructive both of competition and the innovation that it helps stimulate and justify"* (1988, p.247). Although regulated companies operated under the regulatory constraints, their financial health was guaranteed. Authorities were careful to ensure financial viability of these firms by shielding them from competitive forces and other risks. In one of the few theoretical analyses of the issue, G. SWENNEY argues that "*in many circumstances a regulated monopolist can maximize the present value of profits only by delaying adoption of an innovation*" (1981, p.437). In the specialized press on energy, interviews with top executives indicate that they also believe regulated firms are slow to adopt new technology. Traditional electric utilities avoided to developing new technologies which could erode their situation.

As economists have recognized for many decades (F.SHERER & D.ROSS 1991, W.SHEPHERD 1996), monopolies tend to delay technological progress in a variety of industries. Different technologies would have been developed in the absence of regulation. AT&T would have digitized its network much earlier in a competitive environment. Similarly, prior to deregulation, airlines favorized large aircraft for trunk line operations which were dominant before 1978. Regulation did not require maximum of utilization of airplanes for continued service. After deregulation, hub-and-spoke operations called for smaller planes.

In a deregulation process, innovation can be the key to **erode or eliminate monopolies** by giving new comers special advantages as it has also occurred in many sectors[5]. The state of technology in the past must be considered as well. An important argument to defect regulated monopoly is its failure to recognize that new technologies evolve over time that they are efficient at much lower level of output than old methods of production. The dynamic of technological progress depends on the degree of competitive pressures (N.ROSE & P.JOSKOW 1990, R.VIETOR 1994 et W.SHEPHERD 1997).

In the American electric power industry, regulation is often thought not to incite innovations. Capital cost disallowance based on avoided costs, thus penalizing high costs or low performances outcomers, discouraged the adoption of new technologies which performance is uncertain. This issue is not obvious in electric utility behavior until the mid-70's, during which time utilities adopted various new generating technologies. Since, many arguments have evolved to explain the decline of power companies' innovations :

- Regulatory incentives for conservation and load management have displaced new construction (this argument does not explain the small role of new technology in the construction plans of utilities).
- Underlying steam turbine technology has exhausted improvements in scale economies and thermal efficiency[6] (this does not explain the reluctance of utilities to adopt new small scale technologies).
- Managerial culture within companies, which traditionally emphasized large-scale technologies, has been slow to accept smaller scale alternatives.[7]
- Changes in regulatory practice have undermined incentives for innovation.

In the past, significant speed variations with which American utilities have adopted new generating technologies have been demonstrated (P.JOSKOW & N.ROSE 1985). The electric power industry's organization has evolved through new technologies and progressive deregulatory laws. In 1978, the Public Utility Regulatory Policies Act (*PURPA*) helped to stimulate innovations in combined cycle generating technologies using natural gas as fuel. Ever since, independent producers, appeared with *PURPA*, have built most of the new generating capacities. During the eighties, smaller power plants with shorter construction cycle than traditional plants have been built by an increasing number of independent producers. The 1992 Energy Policy Act (*EPAct)* has promoted competition in the wholesale market by expanding opportunities for independent producers to sell electricity to utilities for resale. Competition and innovation have been increasing gradually.

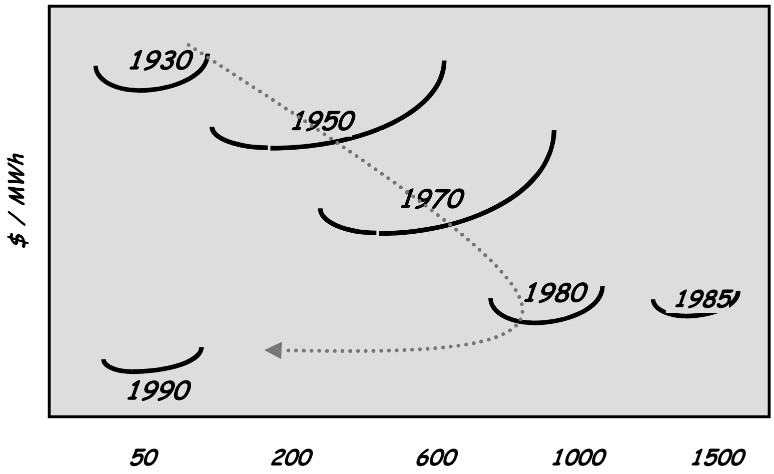
DISTRIBUTED GENERATION UNITS

For two decades, the electric utility industry has undergone a major transformation from a regulated market place to one exposed to the influence of market forces (JM. CHEVALIER 1997). It is still unclear what kind of organization will emerge from these changes. Potentially competitive segments are being separated from the natural monopoly segment. The changes are designed to foster competition in the power generating activity and to reform regulation of the transmission and distribution functions, which continue to be viewed in some extent as natural monopolies.

In the United States, the electric industry, likely the most stable structure in terms of growth forecasts, rates stability, earnings and methods of operation is about to experience a major upheaval. A "new age of competition" began at all three levels of operation. This new area also means opening of all significant markets to vigorous competition. Many states through their regulators are considering various initiatives of increased wholesale competition for electric generation and even direct access for retail customers. The power generation function will be driven primarily by cost minimization considerations. Transmission is likely to assume regulated common carrier status. And local distribution companies will emerge as full services suppliers of the energy need, both natural gas and electricity, to their customers. Since last year, some states (California, Illinois, Massachusetts, Pennsylvania,…) have programs that separate transmission activity and allow retail consumers to choose among several generation service suppliers. In the electric industry, these experiences are new steps towards competitive power generation and retail sectors.

Although claims about "natural monopoly" continue to influence public policies and academic discussions, this concept has become less relevant to some activities of modern power industries.[8] It is sometimes argued that creating a separate generation sector now makes sense : as a matter of fact the generation of electricity is no longer a natural monopoly due to technological change. The most important assumption underlying the proposal to deregulate electricity generation is that once deregulated, the electric generation market is expected to perform much more like a competitive market than one that has been historically plagued by natural monopoly. In the deregulation process, the power industry has virtually abandoned the idea of continuing to build large expensive central power plants which take years to build, require miles of distribution wires and take decades to pay off (see the discussions on stranded costs).

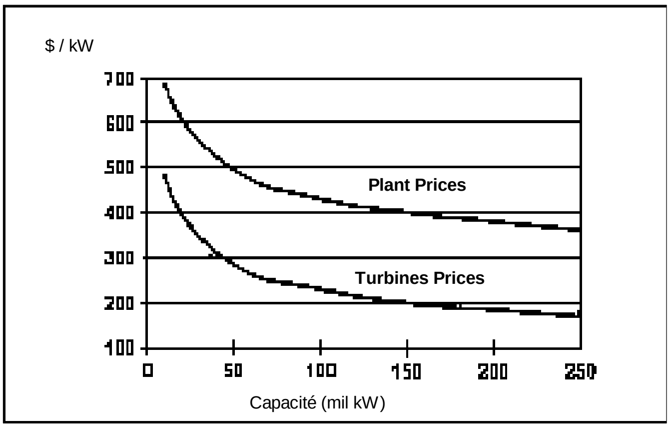
Figure 1 : Optimal plant size (per MW costs curves 1930-1990).



Source : Inspired of C.Bayless (1994)

A significant impetus for change in power generation processes is the loss of economies of scale. This has reversed the long trend towards ever larger central plants, back to smaller and modular capacity. Figure 1 shows the change of the short run average cost and size installed capacity over time. Optimum size has shifted from 1400 MW to smaller units over sixty years. In 1930, a 50 MW unit was cheapest to build. Thanks to technological progress, the cheapest unit produced 200 MW by the 50's, more than 1000MW (French nuclear units) in the 85's. The size of the cheapest plant dropped dramatically. Small generating system are most cost efficient (power at the end-user site). Today, the cheapest unit produces 100 MW. However, Figure 2 shows that there are still some economies of scale for turbines up to about 250 MW.

Figure 2 : Simply cycle turbines and plant prices.



Source : Linden H. (1997)

As soon as the total cost of new power plants became smaller than the operating cost of traditional plant, new units have been developed. Obsolete facilities have lost a lot if not all of their financial value. Thus, such facilities provide the bases for claims of **stranded costs**. For J.SCHUMPETER[9], obsolete investment (stranded costs) is the price that incumbent firms pay for technological progress. He deplored policies that slowed innovation or compensated those that it harmed. But in the absence of stranded cost recovery, some utilities might have to divest some assets in order to remain financially viable. Probably the most critical issue associated with new power technologies is : how to address stranded generation costs.

In power generation activity, current deregulation entails a fundamental shift from guaranteed cost recovery to open market competition. The need to reduce costs is the key driver of the present transition which has been furthered by a technology push. For the past years, result of generation research has been the evolution of thermally efficient technology for the production of electricity at much smaller unit sizes than those which dominated the industry. Recent research and development progresses have resulted in the emergence of so-called **distributed power generation system.** This is a term for a diverse group of technologies aimed at generating electricity close to the place where it is used, instead of generating at large centralized power plants and transmitting the power to users over long stretches of wire. Some of the technologies that can be placed near users include microturbine generators, windmills, solar cells, photovoltaic and fuel cells[10].

An advantage inherent in all of these technologies is a reduced reliance on the electric grid. Customers served by a neighborhood fuel cell or small gas turbines would not have to worry as much when the wind blew. Distributed generation could be especially valuable to customers who want to build new homes in remote areas without incurring the cost of building several miles of new wires. Distributed generation could also help utilities to keep down costs for customers by easing congestion on existing wires. If a new subdivision or industrial park threatens to overtax the existing wires, the utility could either upgrade the lines (the traditional choice) or put a small generator in the area of new growth. As the new technologies are refined, the latter choice will become much more cost-effective. These new technologies offer significant environmental benefits. They are clean, quiet and small. Many have no air emission, and even those involving combustion are insignificant sources of emission because of their size and location.

With these technological advances and the loss of significant economies of scale in production, a new generation market is emerging and is about to revolutionize the electric power industry’s organization. Distributed generation units have changed the fundamental premise that shaped electricity systems for more than a century. Small, prepackaged generating units give customers and competitors the technical ability to run their own power plants. History just might repeat itself : distributed generation units have the same relationship to large power plant that the PC had to the mainframe ; it puts the source of power at the user site. These new generating units can do more than reduce the costs of electricity. Some believe that distributed generation may be the "wave of the future" and even begin to displace large, central station generators. With or without less wires, the maintenance costs of the grid diminish. But what is the interest of a grid with units generating on site ? The functions of power transmission and distribution should be transformed as the whole network structure. The probability of this happening, the timing and the implications are difficult to forecast.

NEW GAS MICROTURBINES

Many analysts say that future demand will be met by smaller generators which are closer to where the electricity will be used. Gas microturbines are the latest distributed generation option. Small natural gas turbine plants can generate electricity at a lower cost and therefore more efficiently, than more traditional and considerably larger coal plants. At the current low prices of natural gas, these smaller units compete favorably with traditional coal units. Manufacturers of microturbines are promoting them as low-cost and low pollution method of generating electricity on site. While the generator may be a perfect fit in remote areas like oil rig sites and gas fields, where it can produce electricity from natural gas which is often simply burned up, manufacturers have come up with 300 other applications, from powering supermarkets to making pizza, and helping power companies meet peak demand. With generation on site without long lines, electric power transmission (not environmentally wanted) or might disappear. A transmission problem still persists : the natural gas supply which is costly is necessary to microturbines. Table 1 indicates how gas microturbines stock up against other energy sources currently available or under development

Table 1 : Comparison with gas microturbines.

	Gas Microturbine	Gas turbine	Fuel cells	Gas turbine combined cycle power plant	Existing coal power plant
Capacity	5 -50 kW	1-50 MW	200 kW - 2 MW	400 MW	30 MW- 40 MW
Efficiency (% converted to electricity)	20%-30%	21%-42%	40%-65%	60%	32%-35%
Cost (installation per kilowatt)	\$400-\$600	\$650-\$900	\$900- \$3000	\$350-\$400	\$900-\$1300
Maintenance (per kilowatt hour) *	0.2¢ -1.0¢	0.3¢ -0.8¢	0.5¢ - 1.0¢	0.2¢- 0.4¢	0.5¢ - 1.0¢
Emissions **(**nitrogen oxide, pounds /MW)	0.1-0.5	0.1-2.0	0.1-0.2	0.2	4.0-10.0

* Costs do not include price of fuel, which varies depending on source. ¢ = US$ cents

Source : Electric Power Research Institute (1998).

Rapid advances in microturbine technology with low gas prices have made it difficult for fuel cells and high-tech renewable sources, to find substantial market niches due to relatively high operating and fixed costs. The advantage of gas microturbines is its single moving part. Air heated by fuel drives a turbine, a generator and a compressor that spin on a single shaft[11]. Six main basis factors lead to the **growing use** of these new small microturbines generators :

- Low capital costs : a shorter construction cycle that minimizes risks.
- Prepackaged and relatively maintenance free[12] (which reduces capacity requirements for utilities)
- Very high efficiencies achieved
- Abundance of cheap gas
- High levels of availability and reliability
- Low impact on the environment

The optimism regarding microturbines may be premature because they have yet to be commercially proven. Over 10 000 MW of small generating units less than 1 MW in size have already being purchased and installed each year for use as a primary power supply (not just as a standby jet). However, costs of microturbines, the first generation scheduled for commercialization in 1997 in the United States, were almost four times what manufacturers expected. One of the most significant barriers to the adoption of distributed energy options is their perceived relative cost : purchase price and delivered cost of electricity. Today, the microturbines available to consumers are too expensive and inconvenient for most people to use as a day-to-day source. Markets for microturbines vary with geography, be reliant on favorable net metering policies and require extensive environmental and regulatory licensing. The price drop will likely prompt a wider range of cost-effective uses and be followed by greater availability on the market.

These changes in generation technology, combined with economic theory, suggest a move away from large companies to small units built by a host of new companies. In the United States, ten years from now, the list of generating companies will hold names that have not appeared yet. Microturbines and fuel cells, if powered by natural gas, promise to bring new players into the electricity market. These next technologies could prove that deregulation is not just for electric players but for anyone affiliate with natural gas. But plopping down a gas microturbine next to the local supermarket and connecting to the grid to sell excess power is not without its pitfalls. There is a number of states that are looking closely to the role distributed generation can play in bringing down electricity costs, increasing reliability and improving the environment. The California Public Utilities Commission (PUC) has issued and ordered an instituting rulemaking on distributed generation. Gas delivery infrastructure needs changes, according to comment filed in the PUC rulemaking on distributed generation. Gas companies say that they are…

Instead of implementing these technologies, some electric utilities are accused to have suppressed the researches and **strategically delayed deployment** of distributed generation technologies in order to maintain high profits, enable "stranded cost" recovery and position themselves to fully control distributed electricity generation in deregulated markets. Alternative energy advocate alleges industry collusion. Some analysts point out unlawful activities of the utilities (B.ALTHOUSE 1999) : withholding information, obstructing grid-interconnections (by imposing financial penalties on customers that attempt to self generate), bribing those entities that threaten to self generate with below cost rates, perjuring themselves by explaining the nature of stranded costs as something other than the obsolescence of central power generation… Leading independent producers of microturbines have been co-opted by utilities to prevent others from accessing these technologies. One of the most cost effective small power generator may be Allied Signal's new microturbines, but utility holding affiliates have already bought all of Allied's production even before the construction of their microturbines factor. In 1997, the Department of Justice (DOJ) settled out of court a lawsuit against a utility accused of preventing competition. According to the DOJ, faced with losing customer or being forced to lower rates to compete, the utility agreed to provide a customer with deep-discounted electricity. In return, the customer promise to keep its supplier for seven years and agreed not to study any alternative sources of electric power and gas supply.

CONCLUSION

As W. Shepherd (1997) notes « *US electricity is now often a laboratory to test the role of new technology in promoting or blocking new competition* ». While turbine generators have been in use for years, the microturbine is quieter, cleaner, relatively maintenance free and does not require long power lines. There is some alternative on the horizon in continuing to expand the thousands of miles of wires that deliver electricity to homes and businesses around the world. Many challenges faced by gas microturbines could cancel these technology's benefits. Clearly, the generation activity is undergoing **major transformation** which will affect the industrial organization of power industry. Not everyone sees the microturbines as a surfire blockbuster as there are skeptics who say small-scale generation will never be economically viable. Nevertheless, new technologies are one of the most potent drivers of industry change today. In the future, market demands will have a much stronger influence on R&D decision-making.

Distributed generation is an illustration of number of technologies which are about to transform the electric power industry's organization and competitive profile of the players. With these decentralized generation units, two barriers to entry (high costs and specific technical expertise) have evaporated : however the regulatory barriers still persist. Some regulators and utilities may be able to keep the barriers intact longer than others. Nonetheless, when private and independent producers pressure lawmakers to deregulate, the remaining barriers will fall. These innovations will be indeed capable of reducing much of the monopoly in the power sector : they will speed up the move. Technology has only started to make a difference.

The explosion of interests in gas microturbines over the last years has resulted in intense competition with new rent-seeking players. These new highly efficient small generators are eroding economic advantage of traditional plants generating electricity at lower costs. Some traditional American electric utility companies have chosen : they have shown agility and strength in controlling the new technology rather than letting their positions erode. New technologies can be captured by firms, such that their control is extended rather than ended. Future technological development can provide the strategic advantage needed by utilities to thrive in the newly competitive market place.

Traditional utilities, which are about to know competition, have to evolve in order to survive. As C. Bayless underlines, « *the winners will embrace competition early and learn to compete. But in the end, the* *message will be the same for all - change or die* » (1994, p. 25). Power companies have to adapt the newest technology and cut costs. Since 1992, a wave of large electricity mergers has arisen, tending to enlarge and strengthen the firm's monopoly position before the competition arrives. With the deregulation of the generation segment, many gas utilities are merging with electric power companies. Aeroderivative turbine technology has had the most visible impact on convergence of the electric and gas industries. However, as competition intensifies, vigilant enforcement of antitrust laws will be essential for the preservation of an open competitive industry.

ACKNOWLEDGEMENTS

I would like to thank Professor Jean-Marie Chevalier for his support and suggestions. I am also very grateful to Christine Huynh and Alberto Elizalde Baltierra for their helpful comments.

REFERENCES

ALTHOUSE B. (1999), *Are utilities suppressing distributed generation ?"*, The Public Utilities Fortnightly, April, pp. 20-22.

AVERCH H. & JOHNSON L.L. (1962), "*Behavior of the firm under regulatory constraint*", The American Economic Review, vol. 52, n°5, December, pp. 1052-1069.

BAUMOL W.J., PANZAR J.C. & WILLIG R.D. (1982),*Contestable markets and the theory of industry structure,* Harcourt Brace Jovanovich, New York.

BAYLESS C.E (1994), « *Less is more : why gas turbines will transform electric utilities* », Public Utilities Fortnightly, vol. 132, n°22, December, vol. 21, pp. 21-25.

BOITEUX M. (1996), « *Monopole ou concurrence dans l'électricité ?* », Le Monde, 3 Mai, pp. 14.

BOUTTES J.P.& LEBAN R. & LEDERER P. (1993), *Organisation et régulation du secteur électrique : un voyage dans la complexité,* Cahier de Recherche CEREM, Décembre.

CHEVALIER JM. (1995), « *Les réseaux de gaz et d'électricité : multiplication des marchés contestables et nouvelles dynamiques concurrentielles* », Revue d'Economie Industrielle, n°72, pp. 7-29.

CHEVALIER JM. (1997), "*Contestabilité des marchés et nouvelle dynamique concurrentielle : une nouvelle problématique économique de l'énergie*", Revue de l'Energie, n°486, Mars /Avril, pp. 209-216.

CLARK J.M. (1940), « *Toward a concept of workable competition* », American Economic Review, May, pp. 241-256.

HIRSH R. (1989), *Technology and transformation in the American electric utility industry,* Cambridge University Press.

JOSKOW P.L. & ROSE N. (1985), "*The effect of technological change, experience and environmental regulation on the construction costs of coal burning generating units",* Rand Journal Of Economics, vol. 16, n°1, pp. 1-27.

KHAN A.E. (1970),*The economics of regulation,* 2 vol. , New York, Wiley.

KHAN A.E. (1988), *The economics of regulation : principles and institutions,* MIT Press, Cambridge.

LINDEN H.R. (1997), « *Operational, technological and economic drivers for convergence of the electric power and gas industries* », The Electricity Journal, May, pp. 14-25.

MARSHALL A. (1890), *Principles of Economics,* 8th ed. (London Macmillan 1920).

MOURRE B. (1996), « *Ouverture à la concurrence des monopoles énergétiques : analyse générale et étude du cas britannique* », Économie et Prévision, vol 3, n°119, pp. 87-105.

SCHUMPETER J.A. (1942), *Capitalism, socialism and democracy,* Harper & Row, New York.

SHARKEY W.W. (1982), *The theory of natural monopoly,* University Press, Cambridge.

SHEPHERD W.G. (1996), *The Economics of industrial organization,* Englewood Cliffs, Prentice Hall.

SHEPHERD W.G. (1997), "*Control over technology by deregulated monopolies*", Revue d'Economie Industrielle, n°80, pp. 25-45.

SHERER F.M. & ROSS D. (1991), *Industrial market structure and economic performance*, Chicago Rand Mac Nelly, 3 ed.
SWENNEY G. (1981), "*Adoption of cost saving innovations by a regulated firm*", American Economic Review, vol. 71, pp. 437-447.
TRAIN K.E. (1992), *Optimal regulation, the economic theory of natural monopoly*, 2 ed, The MIT Press.
VIETOR R.H.K. (1994), *Contrived competition : Regulation and deregulation in America*, Cambridge, Harvard University Press.
ZUCKERMAN L. (1997), "*Tiny turbine : the next generator* ?", The New York Times, pp. 1-5.

FOOTNOTES

[1] Cf. pp.603 The New Palgrave, ed. Eatwell, Milgate and Newman (reprint 1994), McMillan Press Limited.

[2] Generally a natural monopoly is characterized by subadditivity of a representative firm's cost function. If all prospective firms in the industry have the same cost function, or if one firm has a uniformly better technology, then subadditivity implies that industry costs are minimized if only one firm is active in the market. While subadditivity is a purely technical condition, it is also possible for natural monopoly to arise from purely economic forces if imperfectly competitive outcome is inefficient.

[3] **A.**Marshall (1890) was one of the first to identify formally the technology in the form of the representative firm's cost function, as the fundamental determinant of industry structure. Industries with increasing average cost of production were generally competitive or monopolistic. J.Clark (1923) contributed to the understanding of natural monopoly through his careful analyses of the economics of overhead costs (economies of non convexities). He was also a pioneer in the empirical study of declining average cost industries.
About theory of natural monopoly, see Sharkey W.W. (1982), Baumol W.J., Panzar J.C. & Willig R.D. (1982) and Train K.E. (1992).

[4] See Bouttes J.P. & Leban R. & Lederer P. (1993).

[5] For instance, in the related services of microwave transmission, AT&T policies were deeply monopolistic and technologically slow. AT&T's failures in innovation strengthen the resolve of political agencies and the Courts to dissolve the monopolistic Bell System in order to increase innovation efficiency. The divestiture in 1984 was highly successful in all dimensions and was particularly effective in unleashing product and process innovations in the entire telecommunications sector.

[6] See Hirsh R. (1989) and Joskow P. (1989).

[7] See Hirsh R. (1989).

[8] See Boiteux M. (1996), Mourre B. (1996)...

[9] See Schumpeter J.A. (1934).

[10] One of the most intriguing new technologies is fuel cells, which use hydrogen to produce the electrons that constitute electricity. This is done without burning. The fuel can be natural gas, with the waste consisting in water and carbon dioxide. Fuel cells can be of any size.

[11] See Schuler F. Jr. (1996), Zuckerman L. (1997), and Linden H.R. (1997).

[12] Gas microturbine use a cushion of air making the machine virtually maintenance free.