Prospects for the hydrogen transition based on the network economic approach : Insights from the electricity and gas experience in Europe

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Abstract

This paper aims to investigate the transition to a new energy system based on hydrogen in the European liberalized framework. After analyzing the literature on the hydrogen infrastructure needs in Europe, we estimate the size and scope of the transition challenge. We take the theoretical framework of network economics to analyze early hydrogen infrastructure needs. Therefore, several concepts are applied to hydrogen economics such as demand club effects, scale economies on large infrastructures, scope economies, and positive socio-economical externalities. On the examples of the electric and natural gas industry formation in Europe, we argue for public intervention in order to create conditions to reach more rapidly the critical size of the network and to prompt network externalities allowing for the market diffusion of and, thus, an effective transition to the new energy system.

Keywords: Economics of regulation; network economics; technological change; energy economics; hydrogen; electricity; natural gas.

Introduction

Hydrogen produced from renewable sources and used in fuel cells for different applications has the potential to revolutionize the future energy sector in a sustainable way. Even though hydrogen production is still more costly than for other fuels—particularly gasoline for transportation—recent technology improvements in production and high oil prices have improved its economics. Many fuel cell producers have recently announced the cost of the fuel cells is approaching a competitive level, and some demonstration projects are already on the road all over the world. Although, without the infrastructure it is not likely that hydrogen and fuel cell technology can be diffused into the market (especially for transportation). Without infrastructure there will be no demand for hydrogen and fuel cell technology, and in that situation automotive companies will be unwilling to supply fuel cell cars. On the other hand, without demand there will be no private agents interested in building up the infrastructure. This is the so-called “chicken-or-egg” dilemma.

The infrastructure problem is not new in the history of the network industries. Several examples in history show that new infrastructures were built when they were required to overcome a national “strategic need.” This was the case of interconnections for telecommunications, railways for trains, and even the electricity grid and natural gas pipelines in the energy sector. Each of these infrastructures has in common high initial costs with large uncertainties in demand uptake and the recovery period, which makes it unlikely that private agents will be interested in pursuing the investments. Hence, traditionally the State built the networks under the argument of the common interest.

In the newly liberalized European framework, financial burdens and international competition rules make it almost impossible for the government to build a new energy infrastructure on its own. At the same time, it is still unclear how the market will provide the investment needed to build the infrastructure and who will organize it.

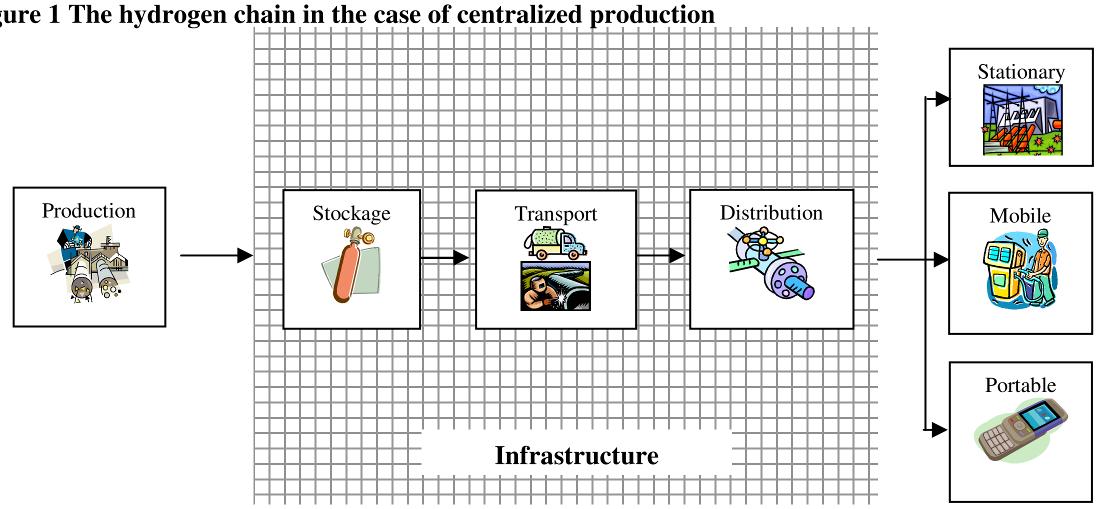
This paper aims to discuss the early hydrogen infrastructure transition in a market framework. More precisely, we focus on the following questions: How does the infrastructure evolve? ; What should be the role of public authorities leading up to the transition? . For answering those questions, in section one, we present the challenges of building up a hydrogen infrastructure in Europe and the likely transition pattern according to the literature. In sections two and three, we develop the network economic approach and we apply it to the evolution of the electric and natural gas industry in Europe. Finally, in section four, we use the insights from the early points to prospect the hydrogen transition. We argue that a strong intervention of public authorities is required in order to promote the new energy system.

1. Hydrogen infrastructure challenges

Unlike oil, natural gas or coal, hydrogen is not an energy source but is rather an energy carrier. Like electricity, it must be produced and transmitted to the consumption place in order to deliver an energy service (stationary, mobile, portable) using fuel cells technology. Hydrogen transmission requires an infrastructure. (Figure 1) In the case of mobile applications, hydrogen stations should be provided in a sufficient number and appropriately distributed.[1] The problem is that there is no demand if the network is not available; and there is no agent (energy companies, equipment manufacturers,…) providing infrastructure and technology until there is no sufficient demand. This is the so-called "chicken-or-egg" dilemma. Therefore, a transition must be organized in order to make both sides (supply and demand) evolve at the same time, reducing their risks and costs.

In the case of centralized production, the overall hydrogen cost at the consumption point includes the cost at each stage of the chain: production, storage, transport, distribution and finally, the hydrogen station. Otherwise, production can be decentralized by creating stations equipped with natural gas reformers for hydrogen production. Even though forecourt production costs may be more expensive (diseconomies of scale, more expensive inputs,...), it is not necessary to build up an infrastructure. At the end, the pathways choice will depend on resources availability (inputs prices), quantity flow, demand density (transmission cost), and forecourt production costs. Hence, the choice of the pathways must take into account the local specificity and there is no unique solution to any problem.[2]

Figure 1 The hydrogen chain in the case of centralized production



However, the transition strategy would follow more or less the same pattern regardless of the context given that it's always a matter of setting up an infrastructure with high uncertainty on the demand response. On the one hand, if there are already energy infrastructures in place - particularly for the natural gas - they should be used for hydrogen transmission when it is possible. On the other hand, where new infrastructure must be fully implemented, first networks should be decentralized and

[1] cf. Melaina, 2003.
[2] Ogden, 1999 ; Padró & Putsche, 1999 ; Amos, 1998 ; Simbeck & Chang, 2002 ; Yang & Ogden, 2004.

hydrogen produced in site. As the forecourt production is less intense in capital, it can respond more effectively to the demand growth. Later on, demand can expand and thereafter justify building up a large production unit and the establishment of the infrastructure. The infrastructure should be built basing on an incremental approach, as demand increases and becomes sufficiently large, in order to avoid investing in overcapacity. However, even if there is no sufficient demand in the transport sector at the beginning, the economics of a large hydrogen plant can still be improved if there are other uses for hydrogen such as ammonia manufacturing or market for heat and power.

In Europe, the official goals for the hydrogen and fuel cells market penetration reflect the conclusions of the report of the High Level Group (HLG, 2003) charged to create a vision for hydrogen in Europe. Particularly for the transport sector, the targets usually considered are: 5% of all new cars by 2020 (or 2% of the fleet by that time); 25% by 2030 (or 15% of the fleet); and 35% by 2040 (or 32% of the fleet). Since that, many studies have tried to estimate infrastructure costs and discuss the best strategies to get from here to there.

The project "HyWays" is the largest analysis of the hydrogen infrastructure already done for Europe. In 2007, the roadmap of the hydrogen introduction in Europe was presented by the consortium. The project aimed to: identify the first consumption centers in Europe; analyze the development of the infrastructure at the regional level; and assess the necessary investments in infrastructure over time. The analysis take into account, primarily, the profile of member states in terms of infrastructure, domestic resources, socio-economic actors, etc. ; and secondly, the objectives of the European policy particularly in terms of hydrogen penetration, CO2 emissions reduction, diversification of the energy mix, and incorporation of renewable resources. According to the assumptions made by "HyWays", hydrogen market deployment follows three phases: Phase I, pre-commercialization (up to 10,000 vehicles), characterized by a few large center demonstrations in Europe; Phase II, initial marketing (10 .000-500.000 vehicles), there are two to five hydrogen consumption centers by country, and hydrogen stations start to build up in the main roads; phase III, large-scale commercialization (500,000 to 16 million vehicles), hydrogen infrastructure expands and enter into new areas. Hence, initially hydrogen starts in main consumption spots, and expands from there to other spots. Later, those spots interconnect themselves and hydrogen keeps extending to other areas increasing both geographical and population coverage. The total investment cost at the end of Phase III (2027) was estimated at 60,000 million euros. It was also reported that hydrogen has the potential to halve CO2 emissions and reduce by 40 % oil consumption in transportation in Europe by 2050. However, a strong policy support would be necessary starting as soon as possible (e.g. R&D development, tax incentives, market niches, partnerships between government, manufacturers, and suppliers).

Other studies were performed in order to estimate the cost of the hydrogen infrastructure for Europe. These analyses confirm the need for large investments. (see table below)

Table 1 Synthesis of results of hydrogen infrastructure studies for Europe

	Countries	Usage	Demand	Type of modeling	Cumulated Investments
HyWays (2007)	10 countries (Finland, France, Germany, Greece, Italy, Netherlands, Norway, Poland, Spain, UK)	Transport	HLG (2003) 500.000 vehicles (2027)	Scenario modeling : demand ; "policy support", "technological learning" ; type of production (forecourt and centralized)	60,000 M€ (2027)
Tzimas et al. (2006)	EU25	Transport, stationary	HLG (2003)	Scenario modeling (% market penetration)	700,000 – 2,200,000 M€ (2050)
Wietschel et al. (2006)	EU25	Transport, stationary	Sc.A « high » 20% Sc.B « low » 5%	Scenario modeling (demand ; type of production)	60,000 M€ (2030, sc.A)
E4Tech (2005)	Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Portugal, Poland, Sweden, Spain, Switzerland, UK	Transport	« High » 40million vehicles (2030) "low" 20million vehicles (2030)	Scenario modeling (demand ; type pf production; « population density »; « automotive areas»)	(High uptake; « automotive » ; centralized prod.) H² fueling stations : 6,000 M€ Production & distribution : 11,000 M€

In addition, technology costs must be substantially reduced in the coming years so as to make hydrogen competitive with energy substitutes. This is the conclusion of the hydrogen prospective study, WETO-H2 (2007), which in his reference scenario (maintaining of the current trends) forecasts that hydrogen will not exceed 2% of global energy consumption in 2050 (3% in Europe). In the "hydrogen" scenario, characterized by carbon constraints and very optimistic assumptions concerning costs reductions in the hydrogen technologies, the proportion of hydrogen in the final energy consumption will not exceed 13% and 7%, respectively. This gives an idea of the challenges faced by the hydrogen today. In effect, both infrastructure and technology challenges must be overcome before hydrogen can finally assume its role in the market.

In conclusion, entry and penetration of the hydrogen into the market depends on the availability of the infrastructure. The necessary investments are very expensive especially as uncertainties persist on technology and on demand behavior. In this too risky context, it seems unlikely that private companies (oil, gas, electricians, etc.) are interested to take over the investments alone. The involvement of the State seems to be therefore necessary for the creation and development of the hydrogen industry as it was the case in the past with the electric and gas industry in Europe.

2. The economics of network industries

Network industries often appear in the economic literature as a typical example of the application of the Walras-Pareto's ideas on the role of the State in the economy. Under this approach, the market is the most efficient allocation of goods and factors. However, in the presence of externalities, public goods, or natural monopolies, the market does not obtain an optimal equilibrium in the sense of Pareto. Therefore, neoclassical economics argues that the State should intervene in areas where the market is "failing."[3]

2.1 Network externalities

Network is a spatial interconnection of activities and equipments technically compatible.[4] Networks goods are types of goods which value depends on the interaction created among economic agents. It raises the notion of externalities or external effects not captured by the market mechanism. An externality or external effect always happens when the activity of an economic agent benefits or imposes additional costs to another agent, without a payment for the benefits or a compensation for the added costs. Given that the complete amount of costs and benefits is not taken into account for the market equilibrium, this private equilibrium does not coincide with the social optimum.

Network industries are characterized by the existence of network externalities. These external effects can be generated *directly* by increasing demand (the club effects), or *indirectly* by declining commodity prices through scale economies, or improved quality by the diversification of the service.[5] Finally, the development of networks leads to positive effects on the overall economy.

2.1.1 Club effects

The definition of club effects was first established by Buchanan (1965) for those goods and services whose utility consumption depends on the number of users.[6] In the case of club goods, individuals increase their utility when the number of consumers of the club growth (up to the saturation point beyond which club effects are not anymore acting).

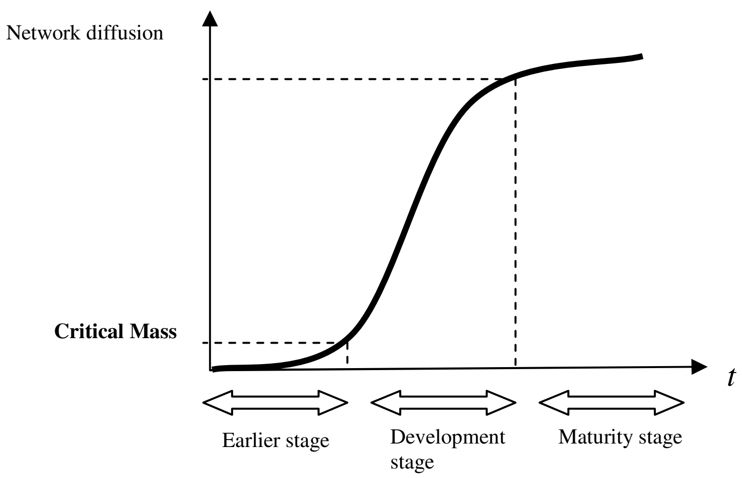
Network goods are characterized by club effects. Katz and Shapiro (1985) noted that network user's satisfaction increases with the number of members of the network.[7]

[3] cf. Guesnerie, 2006, p. 137.
[4] cf. Angelier, 2005, p.16.
[5] cf. Economides, 1995, p.6-7.
[6] "For any good or service, regardless of its ultimate place along the conceptual public-private spectrum, the utility that an individual receives from its consumption depends upon the number of other persons with whom he must share its benefits." (Buchanan, 1965, p.3)
[7] "The surplus that a consumer derives from buying a unit of the good depends on the number of other agents who join the network associated with that product. When the good is durable, an individual's consumption benefits will depend on the future size of the relevant network. Consumers will base their purchase decisions on expected network sizes." (Katz et Shapiro, 1985, p.426)

Also, the authors pointed out expectations on the future size of the network as a determinant of the network attractiveness. So, an expected wider size of the network provides a highest satisfaction among its users.

Network development is conditioned by club effect dynamics. On the one hand, network externalities are the source of increasing returns in the adoption, which means that the spread of network goods does not follow a linear path, but rather an S-curve (Figure 2). On the other hand, in the presence of such externalities, multiple stable equilibriums are possible. Club effects can explain the rapid diffusion of the network as well as the failure in the diffusion, always when the network can not reach the critical mass and spread out from there.

Figure 2 Typical diffusion of a network with club effects



The spread of a network usually follows a succession of three different stages: (i) a slow start period until a minimum level is reached (critical mass); (ii) once the critical mass is reached, the "installed basis" membership increases the attractiveness of the network. The arrival of new users improves the network attractiveness contributing to more adhesions, in a feedback effect, conducing to a fast diffusion rate of the network; (iii) in the third stage, the potential for growth is exhausted, the network reaches the saturation point and the industry maturity is attained.

Diffusion and survival of the network depends on whether the critical mass is reached or not. So, promoters of a new network should aim to reach the critical level as a minimum target, which must be achieved in one jump step. Otherwise, the only stable equilibrium will be the absence of the network.[8]

2.1.2 The effects of scale and scope

The high capital intensity of network industry is a source of many effects at the operational level that can be fully exploited by chain integration. We will consider two of those effects: scale economies and scope economies. Scale economies are the basis for the classic explanation of natural monopolies. Scale economies exist when

[8] Voir Katz et Shapiro, 1985; Economides, 1994. Curien (2000) points to the importance of not overpricing the network in early years.

the increase of all production factors in the same proportion (increase in the scale of production), generates a proportionally higher increase in the production. Thus, the average production costs decrease with the scale of production or the production volumes.[9]

This feature is present in network industries such as telecommunications, electricity and natural gas. Indeed, the development of networks often requires the establishment of a heavy technical structure requiring high initial investments. So, the initial fixed costs (sunk cost) are very important for the final price of the service. Moreover, the marginal cost of providing services is often constant or even decreasing for the relevant economic quantities. The bulk of the network being established, the adhesion of a new membership contributes to expand club effects and sharing costs rather than increasing exploration costs.

Scope economies are achieved by joint production of different goods or services, within the same company, through various production processes sharing a common input. In the presence of scope economies, producing *n* different goods or services separately becomes more expensive than producing them together given synergies in the production.

Network industries are heavily influenced by scope economies. Indeed, a large network can attract the creation of several related activities, strengthening the utility of the network. A recent example of scope economies in network industries is the emergence of multi-utilities. For example, utilities of telephone, gas, electricity, etc., propose a multitude of services beyond their core product. This allows the utility to optimize the use of its infrastructure, as well as to expand the range of services offered to the clients.

2.1.3 The dynamic effects on the economy

Investing in public infrastructures such as transport infrastructure, telecommunication interconnections, water networks, energy networks, etc…, is also justified by the positive externalities generated for the economy. Thus, investment in infrastructure affects the product directly by increasing total investments, particularly because public investment can be seen as an additional production factor in the economy. On the other hand, new infrastructure generates positive externalities in terms of aggregate output of the economy. Indeed, it allows for a more efficient functioning of markets, which benefits to all business and citizens. Finally, investing in new infrastructure entails indirect effects for the economy through the increase of factors productivity (*e.g.* capital and labor). Even though public expenses in infrastructure can provoke a crowding out effect by decreasing demand of private factors, it also contributes to increasing their productivity. Hence, a reduction in costs and an increase in the overall production would be expected.[10]

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[9] cf. Angelier, 2002, p.70.

[10] See, per example : Hulten C.R. et Schwab R.M. (1993), « Infrastructure Spending : Where Do We Go From Here ? », National Tax Journal, 46(3), September, 261¬-273; and Barro R. (1990), "Government Spending in a Simple Model of Endogenous Growth", Journal of Political Economy 98, 5, p.103-125.

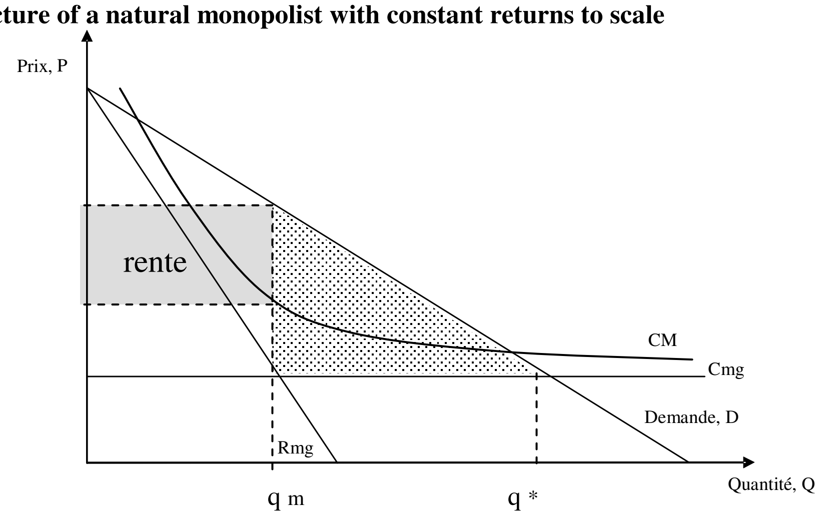
2.2 Natural monopoly

An industry operates in a natural monopoly situation if a single company produces with lower costs than a combination of smaller companies.[11] In the case of the electric power industry, for example, duplication of transmission networks to challenge the monopoly of transportation is not economical. In this case, competition (when possible) does not lead to a cost-effective solution and results in rather perverse effects in terms of price volatility. In this situation, we observe market failures in providing an efficient allocation. Therefore, a public intervention is necessary.

The natural monopoly may have different sources, most of them related to technological externalities. Thus, it may be associated to the existence of strong scale economies (due to the weight of fixed costs and lower average costs induced by the growth of the scale of production); scope economies (relating to variable costs and reduced average costs with the diversification of final production); and network economies (related to interconnection and size effects); or even a combination of all these effects.[12]

Efficiency can be severely affected in the case of a stable natural monopoly (decreasing costs for all relevant quantities). The monopolist maximizes its profit by producing until marginal revenue equalized the marginal cost. Thus, the monopolist restricts the amount of market (q m) for a price higher than the competitive price, which would guarantee a rent. (Figure 3) However, this amount is below the level that optimizes the social surplus (q *). So, from a social point of view, it would be desirable to increase production until the cost of the last unit evened the willingness to pay of the society, thus increasing social surplus by the gray area.

Figure 3 Cost structure of a natural monopolist with constant returns to scale



[11] Lévêque , 2004, p.51; Braeutigam, 1989, p.1294.
[12] cf. Baumol et al., 1982 ; Curien, 2000.

In this context, the public authority must intervene in order to increase the social surplus. It can take one of the two modalities: regulating the private monopoly or through creating a public monopoly.

3. The historical development of the electric and gas networks in Europe

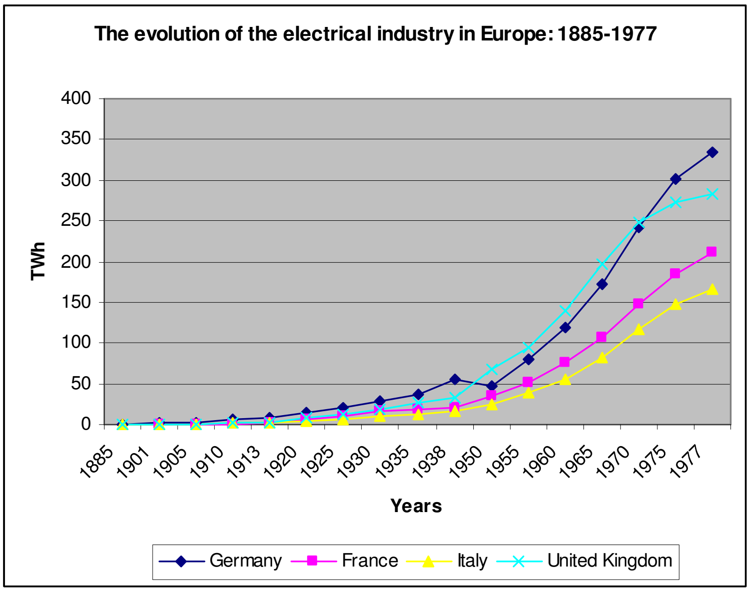
The following sections analyze the evolution of the electricity and natural gas in Europe. This analysis illustrates the effects of the network externalities on the development of those industries, and more precisely, the role of the State on the development. Moreover, hydrogen introduction would have multiple interactions with both industries, particularly the natural gas one.

3.1 The electric industry

The evolution of systems such as electrical ones is not a mere question of technical change. The socio-political context also influences its development. Hughes (1983) points to the role of *sociotechnological systems* to highlight the interplay of internal and external factors within the evolution of the electric industry.

The electric industry emergence in the four main countries of the Western Europe (Germany, France, Italy and Great Britain) began in the early 1880s. The period of major diffusion occurred before the 1980s. Until the 1980s, its development can be analyzed by the succession of three distinct stages: (i) the emergence of the industry, from the 1880s until the beginning of the First World War; (ii) enlarging markets and the beginning of the electricity policy in the period between the two World wars; and (iv) the operational harmonization and growth of domestic industries after the Second World War. (Figure 4)

Figure 4 The evolution of the electrical industry in Europe



Source : Angelier and Lalanne, 1979, from B.R. Mitchell, European Historical Statistics, 1750-1970, London, The Mac Millan Press, 446 p.

Since the beginning, the evolution of the electric power industry has experienced different rhythms and paths depending on the country. These national specificities lie in the basis of different performances of the national electrical industries. Angelier and Lalanne (1979) explain these differences by the influence of three factors: physic-economic country conditions; the origin of the capital and the means of its valorization; and the role of the States in the development of the industry.

The emergence of the industry: 1880-1913

Initially, the electric power industry was based on thermal and hydropower production. The initial purpose of electricity was to convert thermal energy into a form of energy more suitable for certain energy needs such as lighting. Moreover, governments aimed to replace imported energy by maximizing national resources such as hydro. Until the First World War, the main markets for electricity were lighting and public transportation.

On the eve of the First World War, the power industry remains generally confined to major urban centers and industrial areas of high consumption, where consumption is spread over the whole day. The industry structure varies from one country to another: concentrated in Germany and Italy; atomized in the United Kingdom; and highly concentrated in major consumer centers in France. The German electric industry is the most developed as compared to other electric industries in terms of electricity production, costs and electricity prices, geographically widespread network and diversification of the production mix.[13]

The enlargement of the industry: 1913-1938

The second stage corresponds to the period between the two World wars. During this stage, the electric industry had realized substantial progress in transportation and production. From now on, electricity can be transported over long distances and in more economical conditions. This allowed for a geographic expansion of local networks into the regional framework, and later on, in a national framework with the interconnection of various regional electricity grids. The expansion of the market is also associated to the growth of the production scale and the introduction of new power generation technologies (e.g. turbine), improving therefore the efficiency in the use of the fuel in the generating station.

During this period, electricity energy integrates the country energy consumption and contributes to economic competitiveness and growth. Firstly, electric power was mainly used for industrial needs. Industrial demand accounts for more than two thirds of the electricity consumption (except in the United Kingdom where it provided only 50%) between the World wars.[14] In fact, the growth in electric industries was linked to the electric motor ability to replace the steam engine in industrial use.

Technological advances in electricity transport and removal of market constraints allow exploitation of the economic benefits of the production in large size units.

[13] cf. Angelier et Lalanne, 1979.
[14] cf. Angelier et Lalanne, 1979.

However, the establishment of a transport network and large power plants requires a huge amount of investments. This situation will influence the structure of the industry (towards greater concentration) and the need for the State intervention.

The State intervention in the electricity industry in the period between the World wars took several modalities and different rhythms depending on the country. In Germany, public authorities, such as states and municipalities, are very active and hold large stakes in electric enterprises (strengthened after the economic crises of 1919 and 1923 when public entities intervene in order to rescue companies in difficulty), or through greater federal State control over the industry. In Italy, the State is required to redeem industrial assets (including electrical assets) from three major Italian banks in order to avoid their bankruptcy after the financial crisis of 1933. In the United Kingdom, the State puts the basis for the creation of the electric transport system. Similarly, it restructured the industry aiming to introduce greater competition between municipalities and private companies. In France, the State does not intervene directly in the resources allocation. The intervention stays more at the administrative level in order to guide business decisions.

The performance of the national electric industries in this period can be measured by the cost and the price of electricity, as well as by the extent of transmission and distribution. The prices in Germany were among the lowest in Europe. On the eve of the World War II, Germany has a national interconnected network as well as a wider distribution network. The United Kingdom also possesses a wide transmission and distribution network, one of the best in Europe.

The growth of national electric industries: 1945 - 1977

After the War, the demand for electricity has been progressing. The share of the tertiary sector and the domestic demand for electricity increases by about one fifth in 1950 to half in 1977.[15] This structural change is due to the extension of the distribution networks covering a larger portion of the population, on the one hand; and by the increasing importance of services in the western economies, on the other hand.

The third stage of the electric industry evolution is characterized by large and very capital intensive power plants. Hence, national organizations under increasing control of the State were created in Europe aiming to harmonize the operation and the growth of electric industries.

In the aftermath of World War II, electric companies were nationalized across Europe. Different factors explain that decision: the strategic importance of the electric power industry; electric industry characteristics approaching to a natural monopoly; the role of the industry as an instrument of the national economic policies. The power industry is nationalized in France and in the United Kingdom. In Italy, the State "nationalizes" the industry through a process of gradual redemption of financial investments in electricity companies. By contrast, the former West Germany, and particularly its

[15] cf. Angelier et Lalanne, 1979.

central State, sold a part of its stake in public electric holdings to private companies, particularly to banks.

The emergence and the "take-off" of a network industry such as the power industry have taken more than 60 years in the Western European countries. Before the World War II, national electric industries experienced different conditions of demand, supply (structure and technology) and of institutional environment. The State had traditionally had an important role in the network development. This role was central in Germany and in the United Kingdom for the studied period, both countries having the best performing electric industry in Europe. After the World War II, the State becomes the central player in the industry across Europe. It coincides with the strongest growth rates that electrical industry ever knew. Public authorities integrated the entire chain in order to avoid bottlenecks for growth (e.g. standardization of the technology), to maximize the benefits from club effects and scope economies, and to overcome the critical size more rapidly. More recently, with the arrival of the industry to maturity, these positive effects being exhausted, the disadvantages of vertical integration become more clear (decrease of the specificity nature of the assets and bureaucratic organization inefficiencies). At this time, the merits of the integrated model are questioned and conditions are created for opening up the industry to private companies.

Table 2 Summary of the historical development of the electric power industry in Europe: 1880 - 1977

	Principal usage	**Utilization technologies**	**Actors**	**Production technologies**	**Network evolution**
The emergence stage: 1880-1913	Lighting Public transportation	Electric bulb Electric motor	States Communes Electromechanic companies Industry Banks	Thermal (coal) Hydropower	Small urbain networks
The enlargement stage : 1914-1938 *« take –off »*	Industry	Electric motor	States Communes	Thermal Hydropower (large scale)	Network interconnection and regional networks
The growth stage : 1945-1977 *Diffusion*	Domestic Services	Electronic	States Communes (public and private stakeholders in Germany)	Thermal Hydropower Nuclear	National transport network and large distribution network

3.2 The natural gas industry

The natural gas industry has its origin in the town gas developed in the nineteenth century and the first half of the twentieth century. The gas mains for the town gas were firstly built in the major cities and then in smaller towns. Public and private lighting became the first major outlets for the gas. In the late nineteenth century, this outlet was already threatened by the introduction of the electric lighting. The gas industry responds to the electricity competition by increasing horizontal and vertical integration. The competition with electricity continued until the gas industry found its next impetus for growth in calorific usage. In the 1920s, technological progress and excess production contribute to concentrate the production in more efficient large-sized plants, putting basis for the creation of first transport networks at the regional level. Nonetheless, after the 1930s, the production modernization was not sufficient to prevent the decline of the manufacturing gas due to coal scarcity and the competition from electricity and petroleum.

This context marks the emergence of natural gas. Cleaner and having a better gross calorific value, natural gas was also a cheap energy source grace to the major deposit discoveries of the 1950s and the 1960s across Europe. Furthermore, in the end of the Second World War, the European economic reconstruction required significant amounts of energy. The first transmission and distribution networks of natural gas were built in Europe by that time. The transportation networks kicked off linking the producing areas with the main consumption. In large cities, the introduction of the natural gas was facilitated by the town gas infrastructure already in place, allowing a more rapid progress of the "new" gas in the city.

While the town gas industry was generally limited to a local level, the natural gas industry was developed at a national scale. In fact, the government intervention played a decisive role in the development of the natural gas industry. Hence, the natural gas experience in Europe is an illustration of the concurrence weakness during the growth stages of network industries. Indeed, in a competitive environment, the search for a solvent demand - in order to maximize the return on investments - is often done without taking into account network externalities and long-term investment needs.[16] This behavior constraints the rhythm and the scope of the network industry evolution (e.g. energy, telecommunication, railways).

The natural gas industry in the 1950s and 1960s

Natural gas appears in a difficult context for the town gas. Since the 1930s, and after World War II, town gas does not stop of losing market share for electricity and oil. Natural gas comes to revival the gas industry. More clean, efficient and reliable, natural gas is also cheaper because of the discovery of large deposits in Europe.[17] In the late 1950s, Italy was ahead France, Austria and Germany in terms of the natural gas production.[18]

The resurgence of the gas industry thanks to natural gas is accompanied by a radical institutional change which facilitates the transition. In fact, the major gas national firms were created after the Second War. In 1953, the Italian government created the national oil and gas company ENI (*Ente Nazionale Idrocarburi*) which reorganizes the

[16] cf. Angelier, 2007, p.65.
[17] Between 1938 and 1952, natural gas was discovered in the Po Valley, Italy. In 1951, the Lacq deposits were found in France, and the Slochteren in Groningen (Netherlands), in 1959. In 1965, the reservoir West Sole was discovered in the British side of the North Sea. In 1969, the reservoir Ekofisk was discovered in the Norwegian continental shelf of the North Sea.
[18] cf. Williot, 2005a, p.69.

sector by incorporating the firm already in charge of the transportation and the distribution of natural gas, SNAM (*Società Metanodotti Nazionale*). In France, the nationalization law of electricity and gas 1946 set up a national company for electricity (*Electricité de France* or EDF) and another one for gas (*Gaz de France* or GDF). GDF results from the merger of the other gas companies, excluding mixed-capital and municipal companies. In the Great Britain, the Gas Act 1948 nationalized the entire industry of town gas and divided it into a dozen of area boards under coordination of the Gas Council. In 1973, the area boards and the Gas Council merged into the public company "British Gas Company." The company was privatized and unbundled after 1986. In 1963, the Dutch State in partnership with Exxon and Shell created Gasunie, the company responsible for production and transportation of natural gas from the Groningen deposit.

The public companies will convert and modernize the network of town gas, improving the interconnection of inter-regional networks and setting transport networks for natural gas.

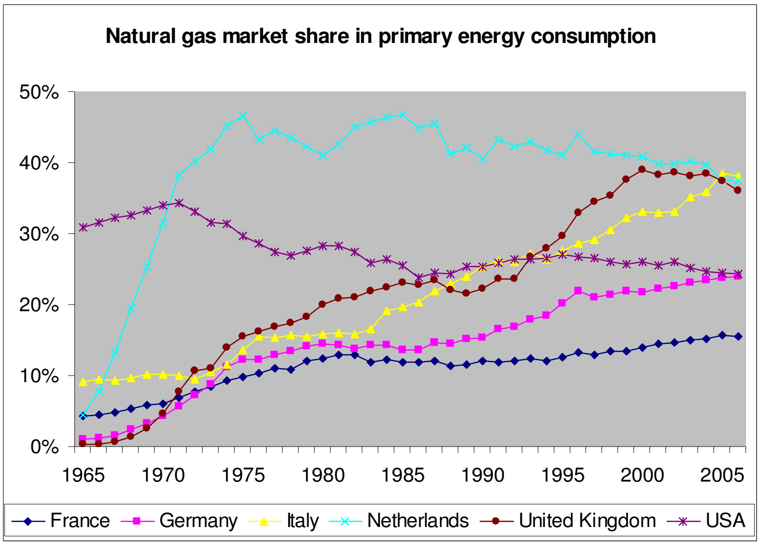
The growth of domestic gas industries in Europe after the 1960s

The natural gas industry in Europe is younger than in the United States. This industry appeared in Europe in the 1950s, that is about 30 years after the introduction of the first gas networks in the United States. The development of the natural gas in Europe benefited from: (i) the existence of the town gas infrastructure in major urban and industrial areas (e.g. Great Britain); (ii) local discoveries of natural gas; (iii) economic growth voracious in energy consumption, especially in industrialized regions as well as in high standards of living areas; and (iv) the authorities' willingness to promote the new energy.[19]

Since the deposits discoveries, the natural gas has progressed very rapidly in the energy balances of the Western Europe. (Figure 5)

[19] cf. Angelier, 1994, p.42-43.

Figure 5 Natural gas market evolution



Author's calculations from BP (2007).

In the early 1960s, the natural gas industry is taking off in Europe while in North America it is already a consolidated industry, enjoying the third of the national energy mix. In Europe, natural gas has the greatest weight in Italy by meeting about 10% of total energy consumption. France and the Netherlands stand behind Italy in terms of penetration in the energy balance, while it is almost absent in the United Kingdom and Germany.

The first stage, until 1975, is characterized by the highest growth rates in the history of the European gas industry, particularly in Germany, the United Kingdom and the Netherlands. For the latter, the share of natural gas in the energy balance raised from 5% to almost 50% between 1965 and 1975. This energy revolution on Netherlands can be explained by the discovery of the Groningen deposits in 1959. The second stage, between 1975 and 1985, is marked by the deceleration of the growth rhythm. The UK is the only country experiencing an important increase of the natural gas share in the energy balance (from 16% to 23% in 1975-1985), facilitated by a number of field discoveries in the British waters of the North Sea. The third stage, after 1985, is characterized by a new growth period, but this time at a lower rate than in the first period. The UK remains the country with the largest growth rates of the natural gas share. However, in the recent years, the growth rates have become more unstable with the arrival to maturity of some fields in the North Sea. In Italy, natural gas is also increasing its share, passing from 28% in 1995 to 38% in 2006, driven notably by the consumption of the electric power industry. In Germany, the market share of natural gas raised from 14% to 22% between 1985 and 1996, comparable to the growth during the first stage. The pattern of growth has slowed down since then and the market share grew only slightly mainly driven by residential and commercial consumption. In Netherlands, the market share of the natural gas has been declining after the late 1980s. On the contrary, the share of natural gas in France increased very slightly between 1986 and 2006 (passing from 12% to 15%).

This is due primarily to the political engagement for the nuclear in response to the oil crisis of the 1970s and 1980s.

Historically, the gas industry in Europe is more concentrated than in North America. In fact, European markets have long been characterized by a two-level organization: (i) upstream (production and imports), a bilateral oligopoly formed between producers-exporters and national gas companies from importer countries; and (ii) downstream, closed national markets dominated by the public company. In the upstream, production is traditionally concentrated in the hands of a small number of exporters, for the most public companies: Algeria (Sonatrach), Norway (Statoil), Russia (Gazprom) and the Netherlands (Gasunie). The development of the European natural gas network since the 1960s is correlated with the new import contracts. Given the heavy investment required for production and transport infrastructures, as well as the vulnerability to the opportunistic behavior as a result of the specificity of the projects, long-term contracts were signed between the consortia formed by public European companies and exporters in order to finance the long-term projects. More precisely, in order to share the "price risk" and the "market risk" between the counterparts. This institutional architecture enabled the development of stable and mature European supplies. In the downstream, the gas industry was developed in Europe in most of the cases in the framework of national public monopolies. The reasons evoked to justify the strong state intervention in the industry were mostly associated with macroeconomic goals (promoting employment and growth), security of supply and redistribution (social or geographical). In short, the two-level market structure and long-term contracts have facilitated the realization of the necessary investments in infrastructure, and thus the development of the gas industry.

The European gas markets are still characterized by the importance of national public companies. That is the case in France (GDF) and Italy (ENI). Moreover, in countries where the state is less present in the gas market (e.g. UK), the market structure is less integrated in the downstream compared to the former group. In a large number of countries, the gas distribution has been developed by regional or local authorities in the form of local distribution monopolies (e.g. in Germany, where a significant portion of the distribution is handled by the communes).[20]

The integrated structures have been challenged by the liberalization movement in the European gas market organized around two Directives, Directive 98/30 of June 1998 and Directive 2003/55 of June 2003. These guidelines have introduced in the gas industry the principles of the separation (unbundling) of competitive activities (especially in the production and trading) from the essential facility, the third-party access to networks and the pricing regulation of the activities remaining in monopoly. The goal is to create a competitive and integrated gas market in Europe, particularly between states and major suppliers (with gas-to-gas competition between different sources) that can ensure both energy security and supplies at more advantageous conditions.

[20] For a synthesis of the national gas development, see table in the annex 1.

4. Prospects for a transition to hydrogen

Both electricity and natural gas appeared to reach a point of critical mass in the market after which their respective market shares increased more rapidly. After this point, network externalities played an important role in both transitions. Natural gas could diffuse and develop quicker because of the availability of town gas infrastructure in the main urban and industrial areas and the discoveries of natural gas after the period around 1950. Electricity could diffuse and develop quicker because of the high voltage transmission and the turbine introduction around the 1920s. In both cases, they started as decentralized networks that were interconnected before forming regional networks, and then national systems. Electricity took about 60 years before reaching critical mass and diffusing widely. Town gas failed to become a national energy and it was replaced by natural gas which needs just a few decades to diffuse in Europe countries.

The diffusion of electricity beneficiated from the public recognition of the technology superiority compared to gas in lighting and other household appliances. The superiority of the electric motor under steam engine was decisive for the increasing of the electric consumption in the industry sector, which was the main driver of the electricity progression during the first half of the XXth century. The technical progresses in production and in the electric transmission give the basis for the development of the network at the national level. Technical progress was also important in the case of the natural gas. In fact, without the progress in steel industry, particularly in pipeline construction, the widespread of the natural gas network would not be possible.

The old town gas infrastructure was an important feature allowing for a rapid penetration of the natural gas in the cities. Although, an infrastructure had to be built between the producing fields recently discovered and the main consumer areas after the 1950s. That infrastructure was generally built up by the national public company in Europe. The diffusion of the electricity after the World War II was possible thanks to the infrastructure meanwhile constructed. It was possible after the industry reorganization. In fact, most countries in Europe had integrated and nationalized their electric industry after the War.

So, in both situations the government backed the establishment of the supporting infrastructure. In both cases it integrated the activities in a national company charged to develop the respective industry. A national organization under public control was created in the electric industry charged to the operational harmonization and to growing the network coverage. In the case of the natural gas, the national company was formed in order to organize the local production and to build up the infrastructures needed to serve users. Lately, the demand for natural gas increased and the European national organizations jointly created together networks for imports.

The development of energy network industries often needs huge investments and implies long delays of recuperation of the capital before the network can reach the critical mass and diffuse by the network externalities. In this context it is unlikely that private companies take the lead of the investments. The intervention of the State is therefore necessary as it was in the past for the natural gas and the electricity in Europe.

The introduction of hydrogen needs both infrastructure and technology available. The infrastructure is needed in the beginning in order to solve the “chicken-or-egg” dilemma and to reach the ‘critical mass’ after which the hydrogen diffusion is faster thanks to network externalities and scale economies. In the case of hydrogen technologies, in particular fuel cells, they are being developed by public and private entities around the world. Progresses have been recently announced particularly in terms of durability and robustness of the fuel cell. Nonetheless, the competitive level is still far from being reached and the research and development (R&D) period has been taking decades without any significant entry in the market.[21]

In the case of a radical innovation like hydrogen a highly public intervention is required at two levels: firstly, to support the pre-market stages (research and development and demonstration R&DD) in order to make hydrogen technologies competitive with conventional technologies; secondly, to support the market-entry and infrastructure investments.[22]

Conclusion

Natural gas and electricity experience in Europe as well as techno-economical analysis of the hydrogen infrastructure generally converge to the vision that infrastructure starts in densely populated areas, with a huge demand potential, in a decentralized production configuration and then evolves towards a centralized production when the demand expands. Criteria such as economical status, existing natural gas and grid power infrastructure, and hydrogen by-product availability nearby are frequently presented as preconditions for the choice of the regions where to build the early infrastructure. Even if estimated at a least-cost way, the infrastructure is estimated to cost several billions of euros. This huge amount of investment required to build the hydrogen infrastructure and the uncertainty about the demand uptake, make it unlikely that one private agent (or a group of them) can deploy and co-ordinate the necessary infrastructure to overcome the “chicken-or-egg” dilemma on their own. The same problem occurred on different occasions in the past when the state felt a strategic necessity to develop energy networks such as pipelines and power grids. There were also economical reasons for the state to build

[21] Lattin and Utgikar (2007) present the hydrogen and fuel cells’ main efforts in the United States since 1970s. They conclude that without government intervention promoting the development of the technologies and creating economic incentives for the new energy system, the transition would not be possible.

[22] Both technology development and market-entry used to be supported by private investments in the case of incremental innovations. (Bourgeois and Mima, 2003, p.11) Nevertheless, Melaina (2003) notes that automotive infrastructure in the United States was generally supported by private investment. Bouwcamp (2004) takes also the example of the wireless communication to show the market can impose the better standard and private companies can afford the investment in the infrastructure. In both cases, the infrastructure is not entirely new. In the case of the automotive infrastructure, it started from the old infrastructure for the gasoline for the oven. In the case of the wireless communication, it used phone communication technology already existent.

these networks on his own, such as scale economies, scope economies, club effects, and economic growth.

Therefore, public authorities have an important role to play during the hydrogen transition. On the one hand, they can improve the context for the introduction of hydrogen into the market by: supporting R&D; economic instruments (e.g. carbon taxes, cap and trade); command and control policies (e.g. efficiency requirements, renewable energy requirements); public education; and codes and standards for hydrogen technologies. On the other hand, historical review and network effects point out that more direct intervention of public authorities is needed during the early phases of the transition in order to reach rapidly the 'critical mass' and to release network externalities allowing for the market diffusion. This is true at the state level as well as at the local level. Local partnerships between public authorities and industry can be very important for the transition by reducing uncertainty and, therefore, accelerating equipment deployment (such as fuel cell cars), while at the same time helping to ramp up investments in the infrastructure.

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	Germany	Netherlands	France	Italy	Great Britain	United States
Country type	Importer	Producer ; Exporter	Importer (initially producer too)	Producer Importer	Producer Exporter (recently importer)	Producer Importer
Demand drivers	1° Industry 2° Power 3° Residential and commercial	1° Residential and commercial 2° Industry ; Power	I. Industry ; energy II. Residential - tertiary ; Industry	1° Industry 2° Residential and commercial 3° Power	1° Residential 2° Industry 3° Power	1° Industry 2° Residential and commercial 3° Power
Industrial structure	Integrated (transport/importation) ex.: Rurhgas Municipal distributors	Public-Private Partnership (Gasunie) Municipal distributors	Public integrated company (GDF)	Public integrated company (ENI)	I. Gas Act 1948 : *Area Boards* (12), *Gas Council* ; II. Gas Act 1972: Public integrated company (British Gas) III. Privatization and unbundling of British Gas (1980s, 1990s)	Private local distribution companies (LDC) Private transporters (pipelines)
Public intervention	Local administration Public stake in distributors	Partner Municipal distributors	State owner	State owner Municipal distributors	State owner Public regulation (since 1980s)	Public regulation (PUC ; FERC)
Development phase [23]	Transition to maturity	Maturity	Transition to maturity	Transition to maturity	Maturity	Maturity
Diffusion (number of years before reaching 10 % of the national energy mix)	15 years (1960-1974)	7 y. (1960-1967)	24 y. (1951-1975)	16 y. (1952-1968)	5 y. (1967-1972)	10 y. (1920-1930)[24]

Annex 1 Summary of natural gas development in Europe and United States

[23] According to the Estrada et al. (1995) methodology and to competition indicators such as market share, unbundling, etc., available in the French Energy Regulator's site (www.cre.fr) and the European Regulators' Group for electricity and gas' site (www.ergeg.org).
[24] Marchetti C., Nakicenovic N. (1979), « The Dynamics of Energy Systems and the Logistic Substitution Model", RR-79- 13, December, IIASA, Laxenburg.