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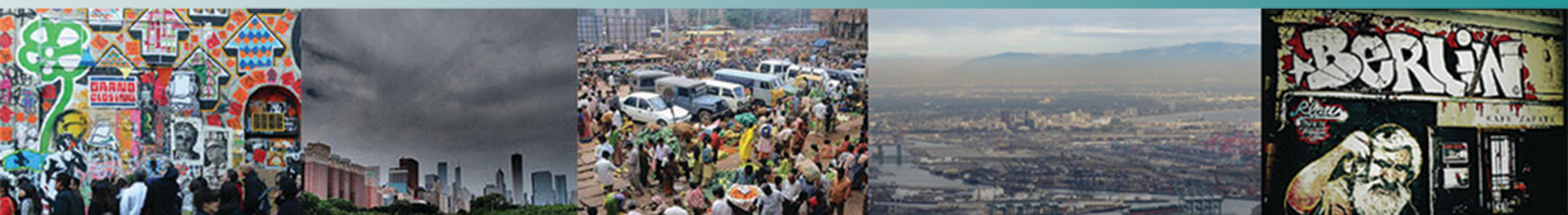

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Energy transition and the futures of the electricity sector

par Christophe Defeuilley

Abstract – In this paper, we try to understand the impact that the energy transition may have on the electricity sector's organisational model. For the last century or so, the electricity sector has been built and developed around a centralised and standardised model, primarily designed to supply cheap electricity and to feed rising demand. This model, and the actors that embody it, are now having to accommodate to new dynamics driven by the energy transition (development of renewables, promotion of energy efficiency). These new dynamics can variously be interpreted. They can be alternatively seen as factors of (temporary) de-optimisation, as incremental changes or as the first steps in a paradigm shift. What trajectories of change the electricity sector may follow? In order to give some insights related to this issue, we look back at the way the centralised model was constructed, before setting out how, and to what extent, that model is being disrupted by the changes currently underway, and then to explore the different factors – political, institutional, technical – which could influence the trajectory of change in the electricity sector and the scale of the transformations it may undergo.

Introduction

Energy transition is a shift from one energy system to another. It is not the first time in history that such a transition has occurred, but the one in which developed countries are currently engaged is undoubtedly different in nature. It is not a matter, as in the past, of replacing one source of energy with another, more efficient or less expensive, or of changing the ways whereby energy systems are designed and organised (Fouquet, Pearson, 2012). This time, the transition is different in nature because it is the primary goal assigned to the energy sector that is changing. Since the industrial revolution, the function of energy was to drive economic growth (by providing abundant, low-cost, and reliable sources of energy). It is now called upon to serve another purpose: to promote the emergence of a "low carbon economy", which in turn will be able to give a response to climate change (Stern, 2007). In this respect, the electricity sector is placed at the forefront. In many countries, electricity is responsible for a large proportion of $C0_2$ emissions and all the scenarios consider that, in a long-term perspective, the marginal abatements costs are cheaper in the power sector than in any other parts of economic activity. Therefore, the $C0_2$ reduction burden will be essentially supported by the electricity system. In the "low carbon economy roadmap 2050", the European Commission define a set of goals to drastically reduce the $C0_2$ emissions of the European countries for 2050: an overall reduction of 80% (related to 1990 level), with a fall for the power sector estimated between 93% and 99% (EC, 2011). As far as electricity is concerned, the emphasis is placed on two main mechanisms: promote energy efficiency (to reduce energy consumption) and develop renewable and (partially) decentralised energy (to replace centralised fossil-fuel thermal plants)[1]. This move towards a low carbon electricity sector broadens: national legislation in Europe (Germany, France, England), as well as national, regional or local initiatives elsewhere (California or New York in the US), translate these orientations into tangible policies and measures. This is a major shift. For the last century or so, the electricity sector has been built and developed around a centralised and standardised generic model, primarily designed to supply cheap electricity and to feed rising demand. This generic model has been variously applied and implemented, depending on national institutional settings (existence of a federal state, roles and competencies given to local authorities) and historical episodes (creation of large public monopolies after WW2 in a lot of European countries to ensure huge investment requirements, PUHCA passed in the USA in 1935 to facilitate state regulation of electric utilities and to dismantle holding companies). These national specific aspects matter and explain how (and to which extend) this centralised and standardised model has been carried out. These national features are also of primary importance to understand how the future of electric industry will be reconfigured by the energy transition.

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[1] Even if, for the time-being, technologies which could permit to benefit of a reliable, resilient and affordable electric system without the use of any flexible thermal generation unit are not available at reasonable costs.

This model, and the actors that embody it, are now having to accommodate to new dynamics driven by the energy transition. And they have to take into account the impacts of new policy measures on the functioning of electricity markets: gloomy residual demand, depressed wholesale prices, difficulties to cover supply total costs, costly networks adaptation to decentralised renewables, etc. (IEA, 2016; Robinson, 2015). These new dynamics, and the impacts they currently have on the functioning of electricity markets, can variously be interpreted. They can be alternatively seen as factors of (temporary) de-optimisation, as incremental changes or as the first steps in a paradigm shift.

In this paper, we will try to understand the impact that the energy transition may have on the future of the electricity sector. What technical and organisational trajectories of change may it follow? In order to give some insights related to this issue, we believe that it would be useful to look back at the way the centralised model was constructed, before setting out how, and to what extent, that model is being disrupted by the changes currently underway, and then to explore the different factors – political, institutional, technical – which could influence the trajectory of change in the electricity sector and the scale of the transformations it may undergo. The dynamics of transformation of any economic activity is not only a matter of technology and innovation *per se*. Technological transformation can hardly be seen in a strictly "functionalist" way. The emergence and ascendency of a particular type of technology cannot only be explained by its supposed intrinsic superiority (Granovetter, 1985; Callon, 1998) or by the fact that profit-seeking agents will allocate resources to explore and develop yet unexploited scientific and technological opportunities in a market-driven way (Freeman, 1974; Dosi, 1988). The orientation, the pace and the trajectory of technological changes are also related to social, political and institutional factors. In particular, institutional factors (laws, rules, norms of conduct) create the condition of exchange, shape the frontiers of markets, stabilize competitive arrangements and have an impact on transaction costs (North, 1994; Williamson, 1996). They tend to orientate the efforts made by economic actors to seek new technological opportunities, to innovate and to introduce new products and production processes. The dynamic transformation of markets, the innovative efforts are therefore influenced by these institutional factors, which are themselves the by-products of political and social forces (coalition of actors, political regime, national economic and industrial interests). In such a context, it is not a surprise if technological change is frequently associated with irreversibility, path-dependency, lock-in, "accident of history", self-reinforcing benefits or spill over effects (David, 1997). All these phenomenon, largely analysed in the literature, can take shape because technical change may be influenced by economic actors and by the institutional context in which they take their decisions.

The electric system is far from being an exception. Since its inception, the electricity system has been structured and influenced, not only by "autonomous" or "market-driven" technical change, but also by a coalition of actors, representing various interests, who acted to create institutional forms (negotiated with public authorities), shaping the boundaries of industry, firms and markets (Granovetter, McGuire, 1998)[2]. Therefore, they contributed to orientate and to impulse a dynamic of technical change (towards the expansion of large-scale centralised plants and interconnected networks), which was well adapted to those institutional forms and, in the long run, has created self-reinforcing, irreversibility, effects. They were strong enough to sustain the development of the electric industry for more than a century.

Early days: foundation and expansion of the centralised, growth-oriented, model

It is generally considered that the first commercial use of electricity dates back to September 1882, when Thomas Edison fired up the Pearl Street power station in New-York (Hughes, 1979, p. 139). In the years that followed, reflecting decisions that were equally the outcome of entrepreneurial goals and expectations, political choices and technical innovations, the electricity sector was gradually organised around three main principles: the preference for standardized and centralised means of production, the development of interconnected transmission and distribution systems capable of operating across large territorial scales, the assignment of a monopoly to companies that combined production, transmission and distribution. These principles came in the ascendancy between the late 19th century and the years preceding the First World War, and moulded the developmental trajectory of the electricity sector in the long run. As historians, economists and sociologists have shown (Hirsh, 1989; Hughes, 1979, 1983; Hausman and Neufeld, 1984, 2002, Hausman, 2004; Granovetter and McGuire, 1998; McGuire 1989, 1990; Yakubovich *et al.*, 2005, Nye, 1990), this trajectory was not the outcome of pure "technical determinism", acting alone, through the impetus of a series of innovations (progress in long-distance transmission, increase in the size of power generation units, improved efficiency) that shaped the sector. Its ascendancy did not emerge without opposition, debate and controversy, but arose from decisions – industrial and commercial, collective or individual – supported and encouraged by favourable regulation. It is a "social construct". On the basis of a series of decisions (largely taken before 1930), a powerful and efficient techno-economic complex was gradually forged, closely articulated with the public policy objectives then in force.

In order to understand the foundations on which the electricity sector familiar to us today was built, let us take a brief look back at its early history, during the formative years of the power industry (1890-1930), first in the USA, then in the European countries (Hughes, 1983). Again, we are well aware that each country may have institutional or historical features that let to translate the generic model into specific structures and to organize its electric industry idiosyncratically, maximising (or not)

[2] "No machine is an abstract force moving through history. Rather, every new technology is a social construction and the terms of its adoption are culturally determined" (Nye, 1990, p. 381).

possible economies of scale. Nevertheless, in this section, we will concentrate on the American situation, firstly because it preceded developments in Europe in many institutional and technological respects, and secondly because it went on to have a considerable influence on the rest of the world, as a template of the generic centralized model.

In the 1890s, the electricity sector was still in its infancy, lacking precise contours, clear demand to be met, and widely shared technical solutions. There were no clear divisions between suppliers of equipment (bulbs, then engines), customers, producers and distributors of electricity. These categories, so familiar to us, did not yet exist and would take time to emerge. A battle was raging between the adherents of direct current (headed by Thomas Edison) and of alternating current (supported by the banker J.P. Morgan). So-called "centralised" production units, developed by the first electricity companies and capable of supplying a few dozen or even a few hundred customers, coexisted with more scattered methods of production, run by customers (individuals, warehouses, factories, shops, tramway companies), in cooperatives and farms, or owned by municipalities. Some of these "isolated" plants were coordinated in larger distribution systems serving small geographic areas. Their importance should not be underestimated. "Isolated" systems chronologically appeared before "centralised" systems, and for at least three decades (1885-1915) they generated more electricity than their rivals. Even in 1915, they generated more than half of electricity in the USA and were the only form of electric service available in much rural areas until 1930. These "isolated" systems, sometimes combining electricity and heat production, were essentially run by municipalities (on a non-for-profit basis) and by industrialists producing for their own needs and selling the surplus electricity to nearby users with the right consumption profile (Granovetter, McGuire, 1998, p. 160). As for rates, they varied greatly both in amount and in the method of calculation, set largely on a case-by-case basis: flat, progressive, two-part, by usage, monthly or annual lump sum – all of these were tried (Eisenmenger, 1921).

In the USA, under the influence of Samuel Insull and the coalition of interests that formed around him (the so-called "Insull circle"), the landscape would gradually clear and the scales tip towards the centralised solution, greatly helped by the "triumph" of alternating current over direct current in the early 1890s. In 1892, Samuel Insull, Thomas Edison's former private secretary, left General Electric (founded shortly before) to head an electricity company in Chicago. He exercised a great deal of influence over the two industry associations (Association of Edison Illuminating Companies and National Electric Light Association), both created in 1885, which gathered and promoted, sometimes in a conflictual way, the interests of investor-owned companies (equipment firms as well as operating utilities)[3]. These associations

[3] The Association of Edison Illuminating Companies (AIEC) was founded by Samuel Insull in reaction to the creation of the National Electric Light Association (NELA). The "Insull circle" will took a dominant position in NELA only in 1897 and will kept it for the next thirty years (Granovetter, McGuire, 1998, p. 158).

were forums in which common positions were reached and negotiated with the public authorities. They produced the implicit or explicit standards that would subsequently spread to all the stakeholders in the electricity sector.[4] It can be stated that the discussions held within these two associations in the years 1890-1910, among various items, culminated in two main orientations. First, a consensus emerged around the need to lobby the authorities in order to stabilize the competition field and to avoid destructive struggle among investor-owned utilities (IOU) and between IOU, municipal companies and "isolated" systems, which led to price wars, cutting wires and bankruptcies in the last decade of the 19th century (McGuire, 1989, p. 186)[5]. In 1898, Insull fruitfully advocated for a regulation of the electric supply industry by state governments. This position was supported by the powerful National Civic Federation, an organization which had closed links with public authorities. Regulation through state public commission was first implemented in 1907 (New-York and Wisconsin) and then has largely spread in the decade beginning 1910, when most of the American States pursued initiatives of this nature (Stigler, Friedland, 1962, p. 5). The Wisconsin law served as a model for much of electric regulation that passed after 1907.

This state regulation was intended to have, and will have, very favourable impacts on the investor-owned utilities. State public commissions granted exclusive licences, for an indefinite period, and territorial monopolies to the companies. They protected electric companies' revenue flows by allowing them "reasonable" rates enabling capital accumulation (through cost-of-service regulation). Electric companies could also grow and expand their activities by gaining new customers (not yet connected to the grid), develop their asset bases and engage themselves in new streams of investments. Investor-owned companies, while expanding their activities beyond municipal boundaries, were able to sell electricity to a larger customer base and to benefit from economies of scale. This allowed them to lessen their costs, to raise their profits and to reinvest in more efficient, bigger, generation facilities and to expand their networks. By enabling investor-owned companies to serve large territories and by giving them a monopoly status, state public commissions paved the way of their future successes. Within this protected institutional framework, the electric companies were then able to plan, to finance and to build a coherent and robust technical system. Interconnected networks and centralized generation units, jointly designed and operated, give rise to economies of scale, economies of scope and strong coordination effects (aggregation of diverse load-profiles, optimization of the generation capacity required to meet demand and to insure security of supply). All this helped to reinforce the position of the electricity companies, gave them prospects for development and consolidation, and thus accelerated their growth, in particular by

[4] "Insull became a spokesman for the utility industry, and his company was a pacesetter both in technological and business policy" (Hughes, 1979, p. 141).

[5] In Chicago, at the end of the 19th century, there were 29 competing, non-exclusive, electrical franchises (including three covering the entire city) (McGuire, 1989, p. 186).

facilitating their access to capital and loans (Hausman, Neufeld, 2002; Hausman, 2004). It is noteworthy that the period from 1907 (date of creation of the first state regulatory commission) saw a general move of consolidation of investor-owned companies and a sharp decline of municipal ownership (Bureau of the Census, 1915, p. 111; Kitchens, Jaworski, 2015, p. 4). 'Isolated" systems, because they were limited to municipal boundaries or because their activities were restricted or even banned by state public commissions, lost the regulation battle[6].

The second task of the trade associations was to set a common tariff strategy for the whole industry, which would make it possible to sustain electricity company investment, to expand demand and to establish uniform practices. The diverse approaches then taken, briefly listed above, were gradually eliminated, and it was the two-part pricing structure, with its fixed and variable components, that won the day.[7] However, two forms of two-part pricing remained in contention: one in which the variable component would be the same for every customer (more precisely for each category of customer with the same consumption profile), and one in which each customer would be billed for the variable component not only on the basis of their global consumption, but also on the basis of the time of consumption (so-called "time-of-use" pricing). This second option, extensively debated in the 1890s and which would have offered the advantage of reflecting the costs associated with each customer's actual consumption, was ruled out in favour of the first. The reasons for this decision appear to have been twofold: first, to prevent a proliferation of rate structures (Faulhaber, Baumol, 1888, p. 588), and second, to avoid penalising the customers who were driving consumption (those who used electricity for lighting) by making them pay higher prices during evening peak times (Yakubovich *et al.,* 2005, p. 599).

It should be noted that the two-part rate structure, which subsequently spread in one form or another across most of Europe, stimulated the analysis and conceptualisation of the different cost categories applicable to electricity generation (fixed costs, variable costs, investment costs, operating costs, marginal costs). In the 1890s, engineers considered that the variable component of rates should reflect the variable costs ("running costs") associated with consumption (Clark, 1914, p. 476). These variable costs, essentially the cost of fuel in the case of thermal power generation,

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[6] " […] as state regulation represents a triumph of the unified operation idea as opposed to the geographical sub-division idea, it makes municipalization logically and practically more difficult" (Wilcox, 1914, p. 82).

[7] The electricity producers needed to cover peak production costs and achieve returns on their investment. The power stations, then essentially used to satisfy demand for lighting, did not produce the same quantity of electricity every hour of the year and were sized to meet maximum demand, which was very occasional (a few hours a day during winter). How could fixed costs be covered when plants rarely operated at maximum capacity? The solution, suggested in 1892 by the English engineer John Hopkinson, was as follows: construct a two-part tariff, one fixed and calculated on the basis of each customer's maximum demand (for power), the other variable, proportional to the customer's consumption (of energy) (Hausman, Neufeld, 1984, p. 117).

were not yet described as marginal costs, although the resemblance is striking.[8] It was not until the advances in marginalist theory and its practical applications to the electricity sector, a few decades later (1930-1950), that the connection was made. From this period onward, the principles of pricing – previously based essentially on intuition – were clearly stated and better understood in all their dimensions (Nelson, 1963).

Electricity pricing, as it emerged in the USA at the end of the 19th century, supported the "growth strategy" pursued by the electricity companies. This rate structure helped to increase demand by transferring to the final customers the benefits of the technical improvements that the sector experienced (growing unit size of power stations, rising outputs, grids with the capacity to transmit and distribute more and more electricity over greater and greater distances). These technical improvements were able to spread thanks to the existence of a favourable regulatory framework that stimulated the electricity companies to invest (stability of context, rates covering the long-term marginal costs, investments based on demand forecasts, risks mainly borne by the customers) and to adopt new, more efficient, technologies (Rose, Joskow, 1990). This regulatory framework also provided outlets for equipment manufacturers, which continued to bring new generations of innovative equipment to the market. The R&D efforts of the equipment manufacturers (in particular General Electric and Westinghouse), their decision to incorporate teams involved in fundamental research, the direction they took in their technological choices, were guided by the needs expressed by the users – the electric companies – and by the new markets that they could begin to foresee for their products.[9] These manufacturers therefore focused on improving the performance of steam turbines (first installed in 1902 in the USA), electrical motors and transformers, and worked on long-distance electricity transmission (Hughes, 1983, p. 165).

This mechanism, which would give rise to the centralised and interconnected system, began to emerge at the end of the 19th century (Insull, 1914, p.31), and really took off after World War I in the USA (slightly later for the European countries), before subsequently becoming ubiquitous. The industrial model can be summed up as follows (in its completed form): structured around investor-owned companies equipped with standardised and centralised production units, linked together by interconnected grids, the electricity sector – through economies of scale, economies of scope, coordination and learning effects – triggered a process of diminishing unit costs that benefited customers, thereby driving the development of electricity demand and a

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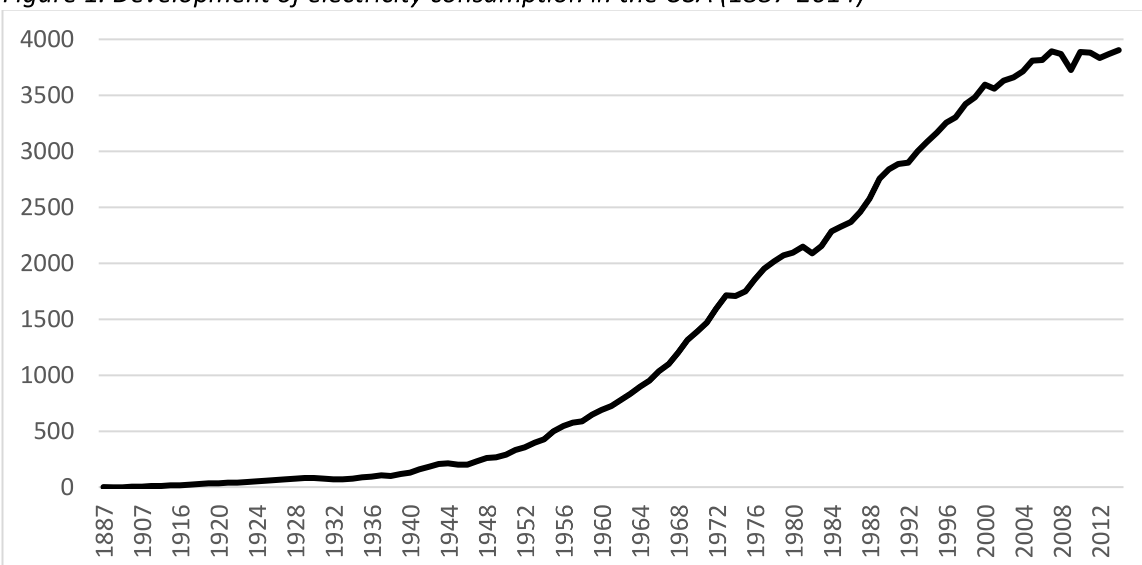
[8] From a theoretical viewpoint, marginal cost is defined as the cost occasioned by the production of an additional unit of a good or service. Under the principle of Pareto equilibrium, which seeks to describe a situation of optimum resource allocation, any producer subject to pure and perfect competition will set the selling price of their good or service at its marginal costs.

[9] In particular, with the widening industrial uses of electricity, and the demand for large-scale electricity generation equipment to supply energy to big plants.

widening of power uses (sometimes to the detriment of other, competing energy sources) (Christensen, Greene, 1976). This dynamic of growth, which justified the investments made by electric companies and the adoption of new technologies, supported overall economic development and provided a starting point for public policies of industrialisation, service universalisation and territorial solidarity. A very impressive virtuous circle of falling real prices and increasing demand began, which enabled the electricity sector to pursue large-scale development (see fig. 1, fig. 2 and Ross, 1973). In the process – and this is the downside of this long period of development – electricity generation plants, often substantial users of fossil fuels (oil, coal, natural gas), proceeded to emit large quantities of greenhouse gases and thereby to contribute heavily to climate change in most developed countries.

Figure 1. Development of electricity consumption in the USA (1887-2014)



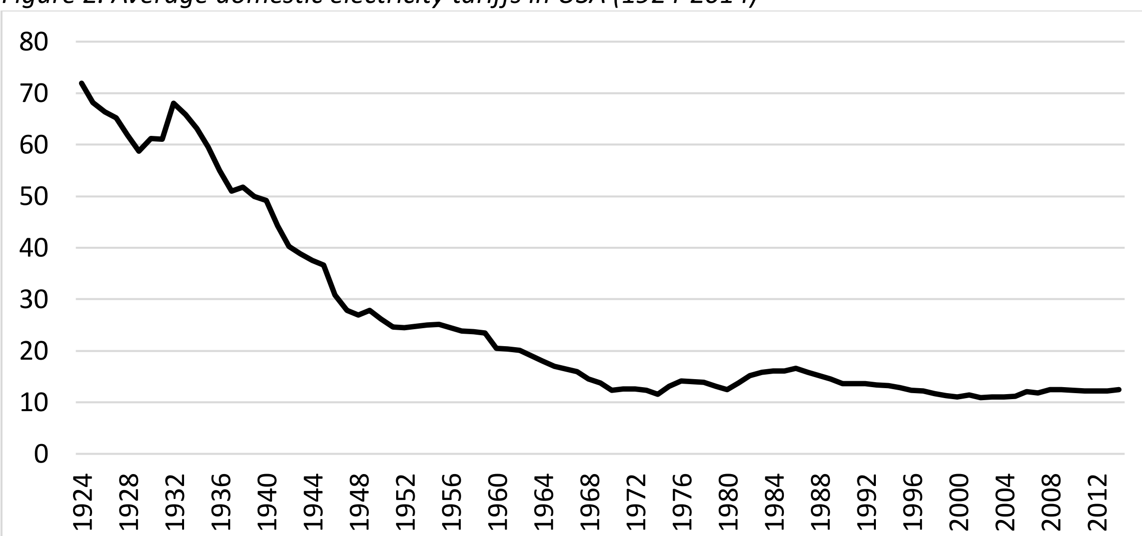
In TWh. Consumption for final users (residential, commercial, industrial). Sources: Electrical World, vol. 80, n°11, 1923, p. 546 (for 1887-1921); US Bureau of the Census (1960), Historical statistics of the United States, colonial times to 1957, Washington (for 1922-1948); US Energy Information Administration (for 1949-2014): www.eia.gov/electricity/data.cfm

In this respect, the policies of deregulation started in the 1990s in the USA and in Europe carried no significant change. While they have affected the power companies' monopoly by introducing competition into electricity generation and customer supply, they have brought about no noteworthy "systemic" transformation, nor in their model of organisation nor in their technological choices. There has been no challenge to the centralised and interconnected model: most of the companies remain vertically integrated and rely on centralised means of production to serve cohorts of customers who, overall, remain very loyal to them (Thomas, 2003; Defeuilley, 2009)[10]. The only

[10] Although some network activities have moved outside their remit. When this is not the case, they are subject to unbundling rules, set to guarantee non-discriminatory access by third parties to the network.

major change was the massive adoption of combined cycle gas turbine (CCGT) technology, whose unit size (and capital cost) is slightly smaller than the other centralized generation technologies and fit well to the new institutional, riskier environment faced by electric utilities (Watson, 2004). But, contrary to initial expectations (and apart from CCGT adoption), the result of liberalisation has been to accentuate industrial concentration around the former monopolies, in both generation and supply. Obviously, most of the organizational environment of the electric companies has changed. Decentralized markets mechanisms have replaced centralized administrative instruments (prices instead of rates), incumbent generators have to compete with new entrants on the wholesale markets, the regulation principles of transmission operators (TSOs and DSOs) have been completely renewed, retail markets have been fully-opened in Europe and in some States in the USA, market places have emerged, market prices are supposed to lead to optimal decentralized investment decisions and to convey all the appropriate, available information, etc. (Joskow, 1996; Green, 1995; Borenstein, Bushnell, 2015).

Figure 2. Average domestic electricity tariffs in USA (1924-2014)



In cents / kWh (all taxes included). All values are expressed in $2014, using Consumer Price Index (CPI) as inflation index. Sources : Federal Power Commission (1940, 1959), Typical electric bills (for 1924-1959) ; US Energy Information Administration http://www.eia.gov/electricity/data.cfm (for 1960-2014). Historical Consumer Price Index for All Urban Consumers (CPI-U): U. S. city average, all items. Source: Bureau of Labor Statistics, US Department of Labor (http://www.bls.gov/cpi/#tables).

But despite these structural changes of the organisational and institutional environment driven by deregulation policies, the dynamics of the electric industry remained basically the same. Electric utilities have been still engaged in a "dynamic of growth", even if, in this deregulated context, the risks they borne are more important as demand and prices' variations are more uncertain (and as rates, formerly set by public authorities or state commissions, don't play anymore their role of safeguard against risks). They tend to manage their (price and quantity) risks by exploiting a diversified portfolio of large-scale/low costs generation assets, by serving large and diversified portfolios of loads (through national of regional interconnected networks) and by taking advantage of their size and their risk profile to lessen their capital costs (Chao, Oren, Wilson, 2008). Centralisation, interconnection and size are still the main pillars of the electric industry, even after the deregulation takes place.

Energy transition: public policies, technical change and selection environment

Conditions have changed. Since the late 1990s, reflecting a fast-developing trend, many countries have been introducing strategies (of varying ambition) to combat climate change and to lessen CO_2 emissions. In the electricity sector, these strategies have been embodied in two main types of mechanisms: first, incentive mechanisms for renewable energy; second, instruments (incentives, norms, legislations) to promote energy efficiency and manage consumption trends, with the aim of slowing or even permanently reversing them. These initiatives form the basis of the so-called "energy transition" laws adopted in England (2009), Germany (2011), and in France (2015), and are behind different regional or local efforts in the USA (California, New York). These initiatives, which gain impetus in a growing number of countries and regions, can be considered as a major shift for the electricity sector. First, because the electricity sector is the most concerned one by the energy transition (goals set to reduce $C0_2$ emissions heavily burdened on electricity). Second because energy transition may imply a complete re-examination of the organisation and the designs of electricity markets and institutions. With the energy transition, public authorities regain a central role in the design and the orientation of the electricity sector. They set new instruments, define new long-term goals and trajectories and have a direct or indirect impact on the competitive field, the current and future revenues of the electric companies, their technological and investments' choices. This policy shaft has also an impact on the expectations and the strategic orientations taken by the equipment manufacturers. Light-hand, "market oriented" regulation need to get along with more stringent public policies, promoting new goals assigned to the power sector and giving it a new dynamic. And these new public policies are designed and deployed at various geographical scales, depending on each national institutional framework and on pre-existing industrial structure and organization. Decentralized features of renewable technologies and energy efficiency policies may imply or at least promote the development of public policies driven by public local authorities.

Varying in form from one country to another, policy instruments and measures regarding renewables and consumption seek to strengthen and accelerate tendencies that are already underway. The renewable energy sectors (essentially onshore wind and photovoltaic) were born, in their modern form, in the 1970s, and began to take shape in the 1980s, even if they remained for a long-time only "niche" technologies. In the same decade, consumption trends began to change. In developed countries, development rates slowed significantly, affected by a fall in average rates of economic growth, a shift in the relative strength of the different business sectors (services up, industry down) and a degree of saturation in traditional electric uses.

In Europe and in the USA, measures to support renewable energy began to take full effect between 2005 and 2010. In the USA, many states have been active in adopting legislation and policy measures aiming to foster the development of renewable energy resources (State Renewable Portfolio Standards, voluntary renewable energy standard or target, net-metering for solar PV systems). In Europe, feed-in tariffs allowed economic agents that invested in wind or solar equipment to rely on guaranteed prices throughout the lifespan of facilities[11]. The purchase price was set at a level and for a term that guaranteed the absorption of costs and a positive return on investment. These proved to be highly effective measures, firstly in incentivising investment, and secondly in stimulating upstream development and innovation by equipment manufacturers. The result of all this has been a sharp and rapid reduction in costs (Nemet, 2006). The cost of photovoltaic (PV) crystalline silicon modules fell by a factor of 100 between the early 1970s and 2015, from $50/W to around 0,5$/W (Mayer, 2015). Globally, a PV installation is starting to become viable without any support mechanism in countries or regions with high irradiation levels (southern Spain, southern Italy, Greece, southern US States as New Mexico, California, Arizona, Nevada, Texas). Using LCOE (Levelized Cost Of Electricity) as a benchmark, a number of studies show that PV installations (residential or commercial, rooftop or ground-mounted) will be competitive in the near future with more traditional thermal generation units (though this does not mean that the two types of supply are interchangeable or provide the same services) (EIA, 2015). In the wind power sector, the cost trend is similar, although the downward slope is less steep, with onshore wind power costs falling fivefold between 1980 and 2010 (NREL, 2012). At present, in windy areas, onshore wind farms can compete – at full cost – with centralised electricity generation units. Current PV and wind energy forecasts report that the downward trend in prices is not going to significantly slow down at least until 2030 (Kost*,* 2013; PV Technology Platform, 2015; NREL, 2015).

There is real momentum, reflected an ever-growing presence of renewables in the energy mix, both in Europe and elsewhere in the world, driven by falling costs. From a very low starting point, renewables (excluding hydro.) are progressing rapidly: they accounted for 13.4% of Europe's electricity gross production in 2015 (EU-28), though with wide variations from one country to another. In the US, progress has been slower, but remains significant: renewables (excluding hydro.) accounted for around 8% of annual production in 2016, as compared with 2.3% in 2006 (with also significant variations amongst the states, some of them, like Maine, Vermont, California, Iowa, Kansas, California, experienced between 20% and 40% of renewables – excluding

[11] They are now progressively replaced by other types of mechanisms which favor the integration of renewables in electricity markets (market premium, contracts for difference, auctions) and allow a better control of their dynamics of growth (and therefore their impact on wholesale prices).

hydro. - in the electricity generation mix)[12]. The orientation of technical change, the nature of selection environments between technologies is changing rapidly. A set of technological systems, involving innovation, development and diffusion of renewables technologies, sustained by a variety of networks of players (manufacturers, utilities, suppliers, academics), is taking shape (Nelson, 1993). They are supported by various mechanisms (RPS, feed-in-tariffs, contracts for difference, market premiums, auctions) and by public policies orientations (share of renewables to be attained). They also benefit from an evolution of the perceptions of the actors (what is desirable, what is possible to achieve), orientating their current and future decisions (Jacobsson, Bergek, 2004). Renewables also benefit from a favourable selection environment. The uncertainty surrounding the evolution of the electricity sector, the difficulties faced by electric companies to cover their fixed costs with market prices (see below), prompt a lot of players to invest primarily in renewables energy technologies.

The second major component of the energy transition is the need for control over consumption. The highly ambitious target for cuts in greenhouse gas emissions and a low carbon economy cannot be achieved exclusively through the development of renewables. Total levels of energy production must also be reduced, a goal that demands action on consumption levels. Different measures have been implemented, together or separately: energy-saving certificates, the application of standards to electrical consumer goods, labelling and information, subsidies for improving the heat efficiency of existing buildings and thermal efficiency regulations for new constructions. They would seem to be starting to have an impact on consumption, although this is difficult to isolate from other, more macroeconomic factors. Nevertheless, these energy efficiency measures may have a structural, long-term, impacts of consumption levels. As for renewables, energy efficiency programmes and standards may contribute to structure a stream of activities and to orientate innovation efforts around new buildings, new materials, advanced-energy saving technologies, IT devices and smart-home applications.

Although the energy transition is only in its infancy, it is already beginning to have significant impacts on the electricity sector as a whole. First of all, it is stimulating the expansion of new electricity generation technologies, organised and structured around renewables. This trend is accompanied by the development of new activities focusing on demand and consumption management, driven by actors from different horizons: equipment manufacturers, companies in the digital sphere, start-ups, etc. This array of new activities (in both generation and demand-side management) has the twofold particularity of introducing diversity and decentralisation into the electric power industry. It is therefore a new avenue of development. It resonates in certain national and local political circles: national authorities see it as a lever for achieving public policy goals related to climate change and are receptive to the creation of new

[12] Sources: Eurostat for Europe, and the US Energy Information Administration for the USA.

business sectors with the potential to generate jobs and new stream of economic activities. Local authorities (and in particular municipalities) are backing initiatives that favour a re-territorialisation of energy responsibilities and restore their legitimacy in the planning, and indeed the management, of future local energy systems. Renewables, demand-side management solutions, use of local energy resources (e.g. by combining heat and power, by using biomass, waste-to-energy solutions, geothermal energy, etc.): delivering local energy solutions is gaining impetus and is sometimes considered as a prime way to move towards a low carbon electricity sector. If they overcome some serious technical and economic limitations which still impede their expansion, local energy systems could become (again) a real alternative to large-scale, centralized and interconnected systems.

Energy transition is therefore potentially disrupting the fundamentals of the electricity system as we know it. And energy transition has also a more immediate impact on its functioning. The emergence of subsidised renewables, produced at a marginal cost that is close to zero, the long-term break in the upward trend in demand, associated with more cyclical phenomenon's as depressed gas and oil prices (and CO_2 prices in Europe) and over-investment in power generation capacities lead to lower electricity market prices. The adequate mechanism of setting prices on the basis of marginal costs, which – with an appropriate production stock – makes it possible to cover variable costs and to obtain a return on investment, no longer works. Wholesale prices, in rapid decline over the last few years, are not sufficient to achieve returns on investment for thermal generation. This situation, which can be described as a phenomenon of de-optimisation, cannot be endogenously corrected solely by the producers themselves (for example by deciding to close certain non-viable power plants and to delay investment in the hope of reducing the production stock to an appropriate level), because it depends on a set of exogenous factors, partially associated with public policy decisions (the rate of progress of renewables, the implementation of capacity mechanisms). In consequence, doubting the viability of their involvement in centralised production, some electricity companies are taking measures to disengage, either totally or partially. This situation throws the entire sector into disarray (Keay, 2016) and calls for a re-design of the institutional and regulatory framework of the electricity sector in the perspective of energy transition (IEA, 2016). This re-design of regulatory rules could be extended to the network activities, and more specifically to distribution networks, which could be strongly impacted by the development of renewables[13]. And who, in return, are essential facilities to envisage a massive and cost-effective penetration of renewables in the electricity system (at least without competitive storage technologies).

Energy transition may be analysed as a "reconfiguration" process. It consists of a socio-technical change, involving substitution of mainstream technologies and

[13] See, in this area, the "Reforming the Energy Vision" initiative of the State of New York and MIT (2016).

transformation of associated and aligned public policies, social practices, structures and industrial organisations and networks of actors (Geels, 2002, 2007). This process may take time to be accomplished, because the pre-existing socio-technical configuration, organised around a generic centralized and standardized model, is characterized by its stability and its strong internal consistency (alignment of activities). This model has been implemented and supported by large incumbent utilities, delivering products and services through a body of complementarity and highly capital-intensive assets, networks and infrastructures. It has exhibited large externalities, strong inertia and long-lasting lock-in effects. These characteristics, whose magnitude differs from one country to another, will play their roles in the reconfiguration process associated with the energy transition. Therefore, the scale and the timing of change (trajectories, temporal dynamics) of each national energy transition may largely rely on two type of factors. The first is related to the pre-existing industrial structure, organisational and technological choices. The larger socio-technological system, driven by a centralized national decision-making process, generating more inertia and resistance, may be slower to evolve (Grubler, 2012, p. 12). The second is related to each national institutional framework and public policy. Ambitious decarbonisation targets, appropriate measures and regulatory instruments, stability and persistency of public policies, introduction or reinforcement of decentralized levels of decision-making: all these elements will have an impact on the scale and the temporal dynamics of energy transition in each country (Sovacool, 2016).

The future of the electricity system: trajectories of change

A ferment of new activities, driven by favourable expectations, on the one hand; a weakening of the existing system, on the other hand: a new landscape is emerging. Energy transition, as a "reconfiguration process", will have an impact on the current organisational model of the electricity sector. But what form will it take and what will be its scale and magnitude? Amongst others, three possible trajectories of change can be envisaged, depending on pre-existing (industrial and organisational) structure and on public policy.

1/ Temporary de-optimisation. Under this scenario, the transition will have few structural impacts, as governments decide to readjust the mechanisms of support for renewable energy (drastic reduction, even withdrawal), to reward capacity and not to pursue public policies of demand-side management. The centralised model would recover its relevance and regulatory mechanisms (market-based or not) would lead to a re-optimisation of the production mix and to an appropriate framework for supporting network development. This would mean public authorities entirely or partially abandoning the public policy objectives they have set (maybe because of their inability to choose between contradictory and partially conflicting goals). At the same time, it would require the industrial and institutional actors backing the development of new decentralised solutions to abandon their efforts, either through lack of resources, or because of their inability to develop technical objects, system architectures and standards capable of meeting needs and providing a credible alternative – both technical and economic – to the centralised system. Finally, it would require the electricity companies to "re-enchant" the centralised model by embarking on a cycle of efficiency improvements and cost reductions sufficient to give existing solutions a new start and/or to ensure that new solutions (renewables) will have the features of centralized generation units (see below). For the time being, renewables are developed either in a decentralised way (PV roof installation, isolated wind turbines) by final customers (households, businesses, offices and commercial buildings, municipalities) to cover a part of their electricity consumption; or in more centralized way (ground-mounted PV, large-scale onshore or offshore wind facilities) by investor-owned utilities like any "centralized" generation units. The pace of expansion of those different renewables systems, the scale at which renewables will be deployed, the degree of standardization of renewable solutions: all these topics will probably be at the centre of the stage and will have a structural impact of the future of the power industry.

2/ Incremental changes. In this second scenario, the new decentralised renewables generation facilities, combined with demand-side management solutions, driven by ambitious and decentralized public policy objectives, develop extensively and give rise to genuine local energy systems, which prove effective and meet the needs of customers. These systems find their place alongside the centralised model, in a coherent hybridisation of the local and the national. This assumes that, on the one hand, the costs of the decentralised systems continue to fall and a significant part of renewables are generated locally (by individual customers, commercial enterprises or municipalities) and not in the frame of large/centralized projects supported and financed by electric companies[14]. On the other hand, changes are made to the sector's organisational rules to ensure that the two systems can coexist. In this scenario, it is probable that the imprint of existing national institutional frameworks will remain strong. Local energy systems could find support and real opportunities for deployment in countries where there already exists a "strong local public" sector, organised around local authorities that possess extensive scope for action and decision-making powers on energy matters, as is the case, for example, in a number of northern European countries (Lorrain, 2005). In these countries, hybridisation could lead towards local solutions, as it might in a number of emerging countries where the centralised system has so far only been partially deployed. In other contexts, where institutional systems are more centralised, or where regulatory rules are less encouraging, local solutions could find less scope for development.

[14] The share of centralized vs. decentralized renewables will highly depend on the kind of support mechanisms that will be designed and the level of subsidies associated with them. It will also depend on the rules, restrictions and standards applied on self-consumption/self-generation, including the charges self-consumers will have to pay for covering the network costs.

3/ A paradigm shift. In this third scenario, the centralised model is marginalised, as local systems undergo massive and widespread development. The adoption of decentralized technological solutions is hastened by very ambitious decarbonisation goals and by policy mechanisms and decision-making which favour local systems and local actors. Centralised solutions will survive simply to maintain sufficient security of supply to handle the intermittent nature of renewable energy (itself largely attenuated by the growing sophistication of demand management mechanisms and by backup from other local energy sources). This scenario would require a very sharp acceleration in the pace and scale of the technical improvements still needed in numerous domains, to make local energy solutions viable, robust and economically attractive. Which would first require strong commitments from the actors concerned, and then the capacity to organise in order to create standards and norms that would make it possible to rationalise and industrialise what can be seen as a disparate set of architectures and systems that are not always mutually complementary. Finally, this scenario would need to be accompanied by the development of a new market design and profoundly remodelled forms of regulation (including support mechanisms favouring decentralized renewables and self-consumption/self-generation solutions).

Concluding remarks

The future remains wide open. At this stage, it is not possible to determine with certainty what scenario will prevail and what trajectory of change the electricity sector will follow. Nonetheless, in the light of what took place in the years 1890-1930 (which, as we have seen, determined the sector's organisational model for around a century), we can make the following observations. The current energy transition has reopened a set of debates about the organisation of the sector which were considered closed for good (centralisation versus decentralisation, standardisation versus differentiation), and placed the actors in a situation of uncertainty about the future comparable with that experienced by the pioneers of electricity. This indeterminacy, coupled with the now widespread consensus that the current situation of the market is unsustainable, spotlights the idea that the electricity sector, its organisation and its modes of regulation, is in a "reconfiguration process". Far from any "technological determinism", past experience shows that it is institutional and political factors, entrepreneurial decision-making, coalitions of interest, which largely shaped the sector's trajectory. They created the conditions for the centralised and standardised model to succeed and spread. Although the context, the stakeholders, the forms of interaction with public authorities (governments, regulators), the forums in which discussion and decision-making take place, have changed, the logic at work remains the same. One may venture to argue that the trajectory of change in the electricity sector (scale, temporal dynamics) will probably be linked with the capacity of a coalition of actors to propose a stable model (or its lineaments) for tomorrow's electricity sector, a vision of the future, founded on a coherent set of elements (technologies, regulatory rules, policies and measures, pricing methods, type of goods and services supplied to customers), which is capable of meeting both public policy objectives and the requirements and aspirations of consumers. There are several competing models, and the future will decide which will prevail and what path it will follow, but everything leads us to believe that, as happened for the centralised model, the result will above all be a "social construct". And this "social construct" may be very different from one country to another, depending on pre-existing (industrial, organisational and technological) choices and on persistency, coherency and ambitiousness of national and local public policies.

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References

Borenstein, S., Bushnell, J., 2015. The U.S. electricity industry after 20 years of restructuring. NBER working paper n°21113, NBER, Cambridge

Bureau of the Census, 1915. Central electric light and power stations and street and electric railways 1912, Department of Commerce, Washington

Callon, M., 1998. Introduction. The embeddeness of economic markets in economics, in: Callon, M. (Ed.), The law of markets. Blackwell, London, pp. 1-57

Chao, H.P., Oren, S., Wilson, R., 2008. Reevaluation of Vertical Integration and Unbundling in Restructured Electricity Markets, in: Sioshansi, F. (Ed.), Competitive Electricity Markets: Design, Implementation, and Performance. Elsevier, p. 27-64

Christensen, L., Greene, W., 1976. Economies of scale in the US electric power generation. Journal of Political Economy, 84 (4), 655-676

Clark, M., 1914. Rates for public utilities. American Economic Review, 1 (3), 473-487

David, P., 1997. Path-dependence and the quest for historical economics: one more chorus of the ballad of QWERTY, discussion paper in economic and social history n°20, University of Oxford, Oxford

Defeuilley, C., 2009. Retail competition in electricity markets. Energy Policy, 37 (2), 377-386

De Martini, P., Kristov, L.,2015. Distribution systems in a high distributed energy resources future, Berkeley Lab, Berkeley

Dosi, G, 1988. Sources, procedures and microeconomic effects of innovation. Journal of Economic Literature, 26 (3), 1120-1171

EC, 2011. A Roadmap for moving to a competitive low carbon economy in 2050, Brussels, European Commission

EIA, 2015. Levelized cost and levelized avoided cost of new generation resources in the Annual Energy Outlook 2015, U.S. Energy Information Administration, Washington

Eisenmenger, H., 1921. Central station rates in theory and practice, Drake & Co Publishers, Chicago

Faulhaber, G., Baumol, W., 1988. Economists as innovators: practical products of theoretical research, Journal of Economic Literature, 26 (2), 577-600

Freeman, C., 1974. The economics of industrial innovation, London, Penguin

Fouquet, R., Pearson, P., 2012. Past and prospective energy transitions: insights from history, Energy Policy, 50 (Special Issue on Past and Prospective Energy Transitions), 1-7

Geels, F., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and case-study, Research Policy, 31 (8-9), 1257-1274

Geels, F., Schot, J., 2007. Typology of sociotechnical transition pathways, Research Policy, 37 (3), 399-417

Granovetter, M., 1985. Economic action and social structure: The problem of embeddedness, American Journal of Sociology, 91, 481-510.

Granovetter, M., McGuire, P., 1998. The making of an industry: electricity in the United States, in: Callon, M. (Ed.). The law of markets. Blackwell, London, p. 147-173

Green, R., 2005. Electricity and markets, Oxford Review of Economic Policy, 21 (1), 67-87

Hausman, W., 2004. Webs of influence and control: personal and financial networks in the formative years of the US electric power industry, Annales historiques de l'électricité, 2, 53-67

Hausman, W., Neufled, J., 1984. Time-of-day pricing in the US electric power industry at the turn of the century, The RAND Journal of Economics, 15 (1), 116-126

Hausman, W., Neufled, J., 2002. The market for capital and the origins of State regulation of electric utilities in the United States, Journal of Economic History, 62 (3), 1050-1073

Hirsh, R., 1989. Technology and transformation in the American electric utility industry, Cambridge University Press, New-York

Hughes, T., 1979. The electrification of America: the system builders, Technology and Culture, 20 (1), 124-161

Hughes, T., 1983. Networks of power. Electrification in western society 1880-1930, The John Hopkins University Press, Baltimore

IEA, 2016. Re-powering markets. Market design and regulation during the transition to low-carbon power systems, International Energy Agency, Paris

Insull, S., 1915. Central-station electric service. Its commercial development and economic significance, Chicago

Jacobsson, S., Bergek, A., 2004. Transforming the energy sector: the evolution of technological systems in renewable energy technology, Industrial and Corporate Change, 13 (5), 815-849

Joskow, P., 1996. Introducing competition into regulated network industries: from hierarchies to markets in electricity, Industrial and Corporate Change, 5 (2), 341-382

Keay, M., 2016. Electricity markets are broken – can they be fixed, Oxford Institute for Energy Studies, Oxford

Kost, C., 2013. Levelized costs of electricity renewable energy technologies, Fraunhofer Institute for Solar Energy Systems, Freiburg

Kitchens, C., Jarowski, T., 2015. Ownership, technology, and the provision of residential electricity, American Economic Association Annual Conference, Boston

Lorrain, D., 2005. Urban capitalisms: European models in competition, International Journal of Urban and Regional Research*,* 29 (2), 231-267

Mayer, J., 2015. Current and future costs of photovoltaics, Fraunhofer Institute for Solar Energy Systems, Freiburg

McGuire, P., 1989. Instrumental class power and the origin of class-based state regulation in the U.S. electric utility industry, Critical Sociology, 16 (2), 181-203

McGuire, P., 1990. Money and power: financiers and the electric manufacturing industry, 1878-1896", Social Science Quarterly, 71 (3), 510-530

MIT, 2016. Utility of the future, MIT Energy Initiative, Cambridge (MA)

Nelson, J., 1963. Practical applications of marginal cost pricing in the public utility field, American Economic Review, 53 (2), 474-481

Nelson, R., 1993 (Ed.). National innovation systems: A comparative study, Oxford University Press, Oxford

Nemet, G., 2006. Beyond the learning curve: factors influencing cost reductions in photovoltaics, Energy Policy, 34 (17), 3218-3232

North, D., 1994. Economic performance through time, American Economic Review, 84 (3), 359-368

NREL, 2012. The past and future cost of wind energy, National Renewable Energy Laboratory, Boulder

NREL, 2015. 2013 cost of wind energy review, National Renewable Energy Laboratory, Boulder

Nye, D., 1990. Electrifying America: social meanings of a new technology, MIT Press, Cambridge

PV Technology Plateform, 2015. PV LCOE in Europe 2014-2030, European PV Technology Platform Steering Committee, Bruxels

Robinson, D., 2015. The scissors effect: how structural trends and government intervention are damaging major European electricity companies and affecting consumers, Oxford Institute for Energy Studies paper n°14, Oxford University, Oxford

Rose, N., Joskow, P., 1990. The diffusion of new technologies: evidence from the electric utility industry, RAND Journal of Economics, 21 (3), 354-373

Ross, C., 1973. Energy as a social force, Annals of the American Academy of Political and Social Science, 405, 47-53

Sovacool, B., 2016. How long will it take ? Conceptualizing the temporal dynamics of energy transitions, Energy Research & Social Science, 13, 202-215

Stern, N., 2007. The economics of climate change: the Stern review, Cambridge University Press, Cambridge

Stigler, G., Friedland, C., 1962. What can regulators regulate? The case of electricity, Journal of Law & Economics, 5 (1), 1-16

Thomas, S., 2003). The seven brothers, Energy Policy, 31 (5), 393-403

Watson, J., 2004. Selection environments, flexibility and the success of gas turbine, Research Policy, 33 (8), 1065-1080

Wilcox, D., 1914. Effects of State regulation upon the municipal ownership movement, Annals of the American Academy of Political and Social Science, 53, 71-84

Williamson, O., 1996. The mecanisms of governance, Oxford University Press, Oxford

Yakubovich, V., Granovetter, M., McGuire, P., 2005. Electric charges: the social construction of rate systems, Theory and Society, 34, 579-612