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Perspectives

The current electrical revolution: portrait of a newly emerging architecture in industrialized countries*

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*This article is translated from the seminal paper originally published in 2004, in VertigO-La revue électronique en sciences de l'environnement (Dunsky, 2004). Although the corpus of references is partially outdated, the analyses and the key messages are still relevant today.

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Abstract. In the short and medium terms, the precise architecture of the industrial world's electricity system remains hazy. Yet in the long term, it seems quite clearly headed toward a new configuration, rooted in a triad of solid trends: miniaturization, decentralization and the "greening" of power generation. This text describes and explains these trends and their underlying forces, namely the combined effects of technological progress, growing environmental consciousness, the advent of a digital economy and the opening of markets to competition.

Keywords. Electricity, energy, renewable energy, greenhouse gases, decarbonization, miniaturization, environment, economy, technology

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"If you do not know where you are going, every road will get you nowhere." – attributed to Mark Twain

1 Introduction

The energetic situation industrialized countries are currently faced with is drastically different from situations experienced in the past. Technological innovations, combined with environmental concerns, the restructuring of markets and changes in the economy draw a new, surprisingly coherent picture of our energetic future. Although this evolution was predicted by a handful of American and European experts as early as in the 1980s, it is not before the mid 1990s that this transformation of the energy sector became evident to a critical mass of experts and stakeholders in the sector.

As will be described in the following sections, the current evolution has gradually taken shape over the last 20 years. It revolves around four fundamental focal areas in which changes are occurring. The keystone of the evolution of the sector is the mutual reinforcement of changes in these four areas:

– **Technology:** Production techniques are evolving away from the construction of large, remote power plants and toward the construction of small-scale units in close

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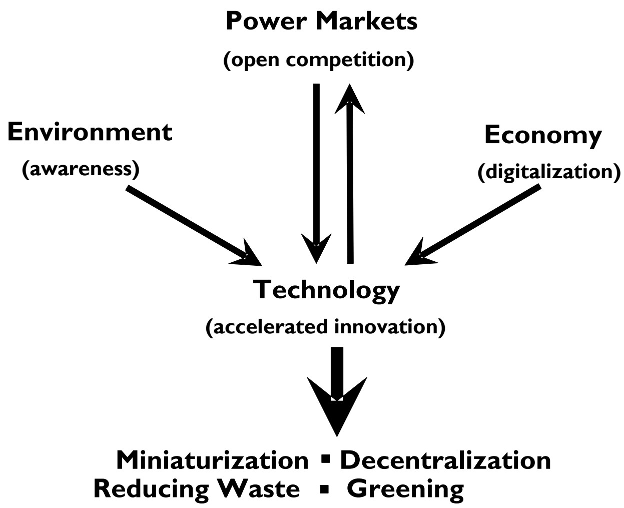

Figure 1. The major forces involved in the creation of a new architecture in the energy sector.

proximity to consumer centres, thus creating new opportunities for heat recovery and self-generation;

– **Markets:** Markets are headed toward vertical disintegration, that is, they are moving away from vertically integrated and regulated monopolistic systems and toward competition in power generation and targeted economic regulation;

– **Environment:** Our view of nature as bountiful and infinitely productive is giving way to our growing awareness of its limited capacity to sustain and meet the demands of human activity. We are becoming increasingly conscious of our excessive waste of resources and the critical need to accelerate the greening and decarbonization of economies;

– **Economy:** Industrialized countries are slowly replacing resource-based economies with knowledge-based economies, thus increasing their focus on the value added of the rapid transmission, analysis and exploitation of information.

The simultaneous presence of these different forces drives the energy sector toward a new architecture, which, when fully operational, will be better suited to reconcile environmental imperatives with the energy demand of modern societies (Fig. 1).

In this paper, we will describe the four key forces involved in the unprecedented transformation that the energy sector is undergoing.

We will also discuss the ways in which the evolution and progression of the changes taking place should or need to be accelerated, considering the environmental challenges we are faced with today. To conclude, a brief overview will be given of the risks and uncertainties looming on the horizon.

The main purpose of this text is to present a broad picture of the changes taking place in the energy sector, and, indirectly, to give a general idea of the challenges, trends and opportunities on the horizon. This overview may then provide an input into the strategic thinking process that multiple stakeholders will have to adopt and the political, regulatory, individual and business choices they will have to make in the years ahead.

2 An emerging energy architecture

The nature and extent of the transformation occurring in the energy sector can be understood by looking at the main structuring forces – individually and collectively – underlying it. Even though, the precise structure this architecture will take has not yet been established, its key elements – or global portrait – can be defined with a reasonable degree of certainty. The resulting portrait of the future will then help us to better direct and define today's strategies and policies.[1]

2.1 Technology: miniaturization and decentralization featured

Following the initial economies of scale race, the size of power generation plants began to decrease steadily. In all likelihood, this ongoing miniaturization process will be accompanied by the decentralization of power generation and an unprecedented diversification of technology and energy resources.

The technological diversity that will cater to our electricity needs is considerable. Far from there being "*a* solution" to energy-related environmental problems, a multitude of solutions will and, indeed, have already begun to be put forward (see Fig. 3).

In practice, miniaturization is already firmly rooted in the power-generation industry. An analysis carried out in the year 2000, of some 13 500 power-generation plants in service in the United States since 1920, reveals the extent of the recent reversal of historic trends in economies of scale (Dunsky, 2000).

As described in Fig. 2, the average size of American units rose steadily at an annual rate of 5.5% between the end of World War I and the end of World War II. The following decade saw the first search for economies of scales: on average, power plant size increased by 17% annually,

[1]This text will present only cases of highly industrialized economies. As to developing or transition economies, some will adopt the Western models of recent decades (large-scale central power plants supported by large transmission systems), whereas others will be able to take advantage of the current transition and leap directly (*leapfrog*) to the decentralized model. The latter presents an interesting option for areas where there are no large-scale energy infrastructures. A good example is the village-by-village rural electrification program in Africa, which was often carried out using small renewable energy systems.

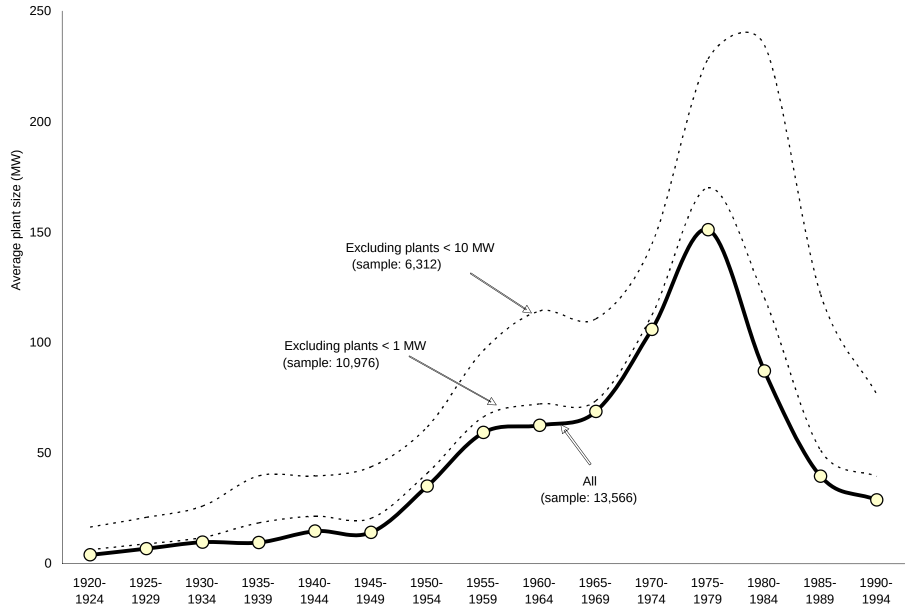

Figure 2. Miniaturization after economies of scale. Source: Dunsky (2000).

quadrupling within a ten-year time frame. Following a short period of stability, the second (and last) phase of explosive growth took place in the 1970s. The end of that decade – marked by an unprecedented appetite for large-scale nuclear, coal and hydroelectric plants – saw average unit size increase tenfold compared to that of units built 50 years earlier.

However, the 1970s were also witness to the end of this frenetic race to develop larger power-generation plants. In the decade that followed, new technological developments – mainly involving thermal power plants (gas turbines) but also renewable energy technologies (wind turbines) – combined with the sudden end of the nuclear era, resulted in a reversal of the growth trend that took place during the previous twenty-five years.[2] This reversal was so dramatic that by the mid-1990s, average plant size was at its lowest since just after World War II.

There is nothing theoretical about the reversal of economies of scale. In 1995, a cost comparison performed on all gas turbine systems available on the market (from 3 to 250 MW each) revealed that maximum net benefits were obtained from a model of only 40 MW. This analysis did not take into account the more than 200 additional economic and environmental benefits associated with small-scale technologies (Lovins et al., 2002).

Today, the advent of fuel cells, micro turbines and other small-scale systems has reinforced this marked shift.[3]

As will be discussed below, this miniaturization, and consequent decentralization, is rooted – other than in public efforts in research and development – in the opening up of markets to competition, growing environmental pressures and current economic transformations.[4]

2.2 Markets: competition will dominate

There is a strong likelihood of future electrical structures becoming an important part of the market economy.[5]

[2]As unexpected as it is ironic, a major part of these technological advances (aviation turbines and advanced materials) owe their existence to the massive investments made by the United States in military research and development efforts during the Reagan era.

[3]Dispersed energy technologies can be grouped into three categories: those acting on demand (efficient power consumption, leading-edge management practices, storage, rapid substitution, power quality, etc.), supply (solar, wind, biomass, fuel cells, micro turbines, diesel generators, etc.) and transmission (voltage regulation, controls, network storage, etc.).

[4]As the *Electric Power Research Institute* (EPRI) stated in its publication, *Perspectives on the Future* (Borbely and Kreider, 2001), the evolution of the electricity industry is expected to "[play] out in much the same way the computer industry has evolved. Large mainframe computers have given way to small, geographically dispersed desktop and laptop machines that are interconnected into fully integrated, extremely flexible networks." With the advent of micro turbines, fuel cells and other decentralized generation, storage and advanced electronic control technologies, the electricity industry is expected to undergo similar changes in the decades to come.

[5]From this point on, we will discuss only the opening of *power-generation markets*, both wholesale and retail. However, although power transmission and distribution functions may at present have the characteristics of natural monopolies, they are not entirely immune to competitive forces. Eventually, the advent of decentralized power generation sources may call into question their monopolistic status.

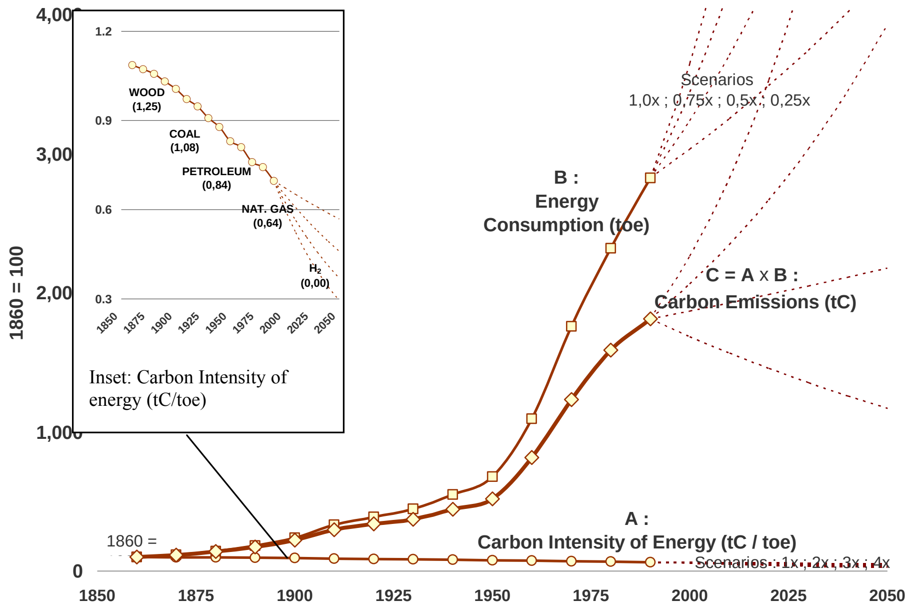

Figure 3. Relative decarbonization and absolute emissions. Sources: Grübler (1998) and Nakićenović (1997a).

In fact, the shift toward competition in power generation is much less the result of a dominant ideology than it is a result of the nature of generation technologies; economies of scale, which once could give rise to natural monopolies, are now yielding to economies of scope and assembly-line production techniques, as mentioned previously. Moreover, electrification – another objective justifying the granting of monopolies in the past – has, in practice, reached its peak in industrialized countries.

Consequently, over the last two decades, the power generation market (the wholesale market) has progressively opened up. As a result, most of the electricity generated in North American is no longer supplied by the vertically integrated monopolies of old, but rather, by independent generators such as Cinergy, Calpine, Sempra, Tractebel and others.

The opening of the power market first took place in two phases: (i) through the requirement that vertically integrated monopolies become monopsonies by calling on third-party generators through invitations to tender for long-term contracts; and (ii) through the arrival of stock exchanges in real-time and the construction of merchant plants (built entirely at the developer's risk).[6] The third and last phase of this opening – which has already been initiated – involves (iii) self-generation through decentralized units.

The last decade has also seen efforts being made to open *retail sales* to competitive forces. Despite serious setbacks – namely in California and Ontario – Western countries seem interested in pursuing this path (albeit with more skepticism than before). Although certain challenges are associated with this type of market opening, there is not much doubt about the opportunity they provide for the opening of niche markets for new products and services.

Niche Markets – which monopolies have a tendency to overlook in favour of "average" customer bases – give specialized generators the opportunity, through the use of new technologies, to offer products and services that are highly valued by a minority of customers (e.g. reliability, reduced environmental impact, etc.) in exchange for premiums offered over market prices. The opening of these markets begins a cycle of economies of scale and cost cuts that can eventually lead to technological maturity and its worldwide market acceptance.[7] In this sense, market booms – which are the *result* of technological innovations – also reinforce and accelerate the development of these same innovations.[8]

[6]This second phase has not yet been completed in Quebec, where the rate of restructuring is slower, namely because of the existence of several large-scale remote plants. This unique context, as well as the "heritage pool" concept to which it lends itself, was dealt with for the first time in (Dunsky and Raphals, 1997).

[7]According to Rogers (1992), this type of market penetration typically evolves following an S-shaped diffusion curve. This curve is characterized by a slow and difficult market entry, followed by rapid growth, and finally, by a stabilization at high levels of market penetration.

[8]The main niche markets to emerge in competitive markets are (1) green power, (2) power reliability and (3) price stability. The first two are offshoots of the forces described in the following two sections (environmental awareness and the digitalization of the economy) and lead to the development of technologies that are both green and very small-scale (that can be located in or near consumer centres). The third is a result of prices that will increasingly reflect those of stock exchanges, fluctuating at intervals of as short as five minutes. Price stability leads in part to decentralized technol-

Moreover, the development of the internet and powerful microprocessors facilitates the functioning of near-real time power exchanges.[9]

As with all the changes coming in the years ahead, this one will not take place without prevarications, errors and questioning.[10] Moreover, there is a great possibility that numerous vertically integrated companies will, out of financial or institutional interest, succeed in temporarily maintaining their dominant position through the abuse of legislative inertia. In time, however, the traditional model of vertically integrated monopolies will undoubtedly disappear (at least its most common structure.[11]

2.3 Environment: stepping up the greening and decarbonization process

Overall, there is no doubt that environmental quality – ecosystem health, species survival, air, water and soil quality and world climate – has generally deteriorated since the industrial revolution, mainly as a result of the astounding economic and demographic growth that took place during the last century.[12] Indeed, this demographic and economic pressure has led to an exponential growth in the production of goods and services which, in turn, requires energy.

Although power generation technologies have, in environmental terms, shown consistent progress as energy needs increased, the progress they have made has clearly lagged behind growth in demand.

There are two factors that help evaluate the extent of the progress that has been made and the important steps that still need to be taken: (1) the quantitative measure of the carbon intensity of the world's energy systems, and (2) the qualitative assessment of the electricity sector's environmental performance.

The decarbonization of the global energy system, shown in the inset of Fig. 3, is measured in terms of tonnes of carbon per tonnes of oil equivalent (tC/toe). The graph illustrates the progress made to date as a result of substituting primary sources of energy. Over a period of only 100 years, significant worldwide success has been achieved in replacing dominant energy sources such as wood (1.25 tC/toe) with coal (1.08 tC/toe), and then coal with petroleum (0.84 tC/toe). Moreover, over the last twenty years, the Western world has placed a clear emphasis on the use of natural gas (0.64 tC/toe). This evolution will culminate in the establishment of pure hydrogen systems (0.00 tC/toe, when obtained from renewable sources) as the main source of energy.

Figure 3 also shows a global portrait of absolute emissions. Although an average annual decrease of 0.34% in the carbon intensity of the energy sources we use might appear to be significant, the graph reveals that this average is clearly overshadowed by the more spectacular growth (approximately 2.73% annually) of the *quantity* of energy we consume. Therefore, despite the strides that have been made, carbon emissions in the planet's atmosphere have continued to increase significantly (that is, by a factor of more than 18), indeed sufficiently, according to the IPCC (2007), to alter the world's climate.

Today's challenge lies in accelerating the two trends already in motion: the energy de-intensification of the economy (through the use of more energy-efficient technology) and the decarbonization of energy sources (through the increased use of green power sources). Significant gains in the former trend were made during the 1970s, but its rate of progress of 1% per year has considerably slowed down since then (Nakićenović, 1997b). As shown in the inset of Fig. 3, the second trend, the rate of decarbonisation, is markedly too slow to offset the growth of energy demands.

The electricity sector – an increasingly more important microcosm of the world's power systems – also offers a clear picture of the progress that has been made and that remains to be made. As it did with primary energy sources, power generation has, up until now, made environmental gains at a constant yet moderate rate.

Figure 4 shows the two parallel paths the electrification of society has taken throughout history: that of "conventional" thermal energy and that of hydroelectricity. In both cases, the first century of development saw progressive but moderate environmental gains being made, as well as the more or less progressive growth of plant size.

ogy, demand management methods, and financial risk management methods.

[9]Currently, the most advanced stock exchanges allow for trading to take place at five-minute intervals. Some are expecting to further reduce this time interval.

[10]North America's deregulation movement is a case in point. Although it was off to a spectacular start (twenty-five states – three of which were the largest – as well as two of the three largest provinces, opened or announced that they were soon opening their retail markets), its enactment was called into question following the California energy crisis in 2000. Since the Fall of 2002, six states postponed their market opening deadlines, whereas California did an about turn, cancelling the opening of its retail market and establishing a state-owned monopolistic wholesale market on a temporary basis. However, California's deregulation failure is the result of a combination of well-documented fundamental errors in market opening procedures. Most analysts believe that the current lull is only temporary.

[11]Indeed, niche-market based product differentiation can take place in the absence of free retail markets. Regulators can attempt to reproduce the benefits offered by competitive markets by ensuring that monopolies under their jurisdiction offer, not one, but a panoply of rate options. Oregon state – where residential consumers remain captive but nonetheless can choose among six rate options (one standard rate, three "green" rates, and two time-differentiated rates) – is, in this respect, a good example to follow (Hélios Centre, 2002).

[12]Within a 70-year period (1930–1999), humanity added 4 billion people to the earth's population, that is, twice the population it previously took several million years to attain. (Haupt and Kane, 2000).

– Conventional thermal power plants became less polluting with the application of stack emissions control technologies and, above all, attained higher levels of combustion efficiency.[13]

– It is somewhat more difficult to assess the progress made by hydroelectric developments, given the specific nature of each project. However, significant progress was made during the last decades, namely in efforts to protect fish and wildlife habitat.

Yet, from an ecological perspective, the results produced by both thermal and hydraulic systems continued to be disappointing (although to varying degrees). In the early 1990s, however, a second phase of progress – slightly faster than the preceding one – began to emerge, which seemed to link two phenomena: the fall of economies of scale (see sub-section entitled "Technology: miniaturization and decentralization featured") and the advent of truly "green" technologies (discussed below).

This "green lane" of electrification is not only a result of the technological and economic changes mentioned previously, but also of a growing environmental consciousness that began to emerge in the 1960s and continues to take shape today with the ratification of the Kyoto Protocol.[14]

The first step on the road to new environmental technologies was that of advanced thermal power generation, which has solidly established itself over the last fifteen years through the use of combined cycle gas turbines (CCGT), a leading edge power generation technology sometimes used in cogeneration.[15]

However, the greatly anticipated second step is that of advanced "green" technologies, which now seem to be emerging.

There exist numerous sources of green energy. There are those that constitute renewable natural resources, such as wind, sun, heat from the earth, biomass, waves, tides, and to a certain extent, rivers,[16] and those that constitute the different energy-recycling techniques that involve energy obtained from industrial, agricultural and municipal waste.[17]

In all likelihood, fuel cells will become a dominant technology. Through an electrochemical (non-combustion) process, they convert hydrogen and oxygen from the air into electricity.[18] By serving as a storage medium for electrical energy, fuel cells will not only accelerate the trend toward often intermittent power sources, but also allow for any advances made to be transferred to the public and freight transportation sectors.[19]

2.4 Economy: digitalization driving growth

More than ever, Western economies depend on the transmission, analysis and development of the brainpower provided by information and human knowledge. The advent of this "digital economy" affects the energy sector in several ways.

The digitalization of the economy accelerates the development of more efficient end-use technologies, which reduces growth in demand.[20] Such an improvement of economic energy intensity is evidence of a more productive economy.

The digitalization of the economy also facilitates the transition toward a fully competitive power market through the accessibility and transparency of exchanges and through the

[13]During the first years of electrification (1882–1920), combustion efficiency doubled approximately every thirteen years, going from about 2.5% in 1882 (Pearl Street Station built by Edison) to about 20% toward 1920. However, about fifty years would pass before another doubling of efficiency was to be seen.

[14]This environmental consciousness – which gained momentum in 1962 with the publication of the bestseller "Silent Spring" by Rachel Carson – first expressed itself through environmental movements and actions taken by citizens mainly concerned with the quality of the air they were breathing and with protecting nature for the sake of nature itself (existence value). The coming into force of the Kyoto Protocol – concerned with global climate change – will, within forty years, establish it as a major international force.

[15]Although CCGTs that are not in cogeneration do not constitute progress for regions having focused on hydraulic systems, they do offer a clear advantage for those having favoured coal-fired power plants in the past. New CCGT plants are now 50% energy efficient (taking into account transmission and distribution losses), whereas in cogeneration, gas turbines or fuel cells can attain an overall energy efficiency of 75% to 90%. Their efficiency is 30 times as great as was Edison's first plant, while their size has now become comparable.

[16]Hydroelectric power differs from other renewable resources in that it has a significant non-atmospheric impact on the environment. Also, its availability is more limited, and there are more serious use conflicts associated with it. Nonetheless, certain projects can have a negligible impact and be described as "natural" (For more information on this topic, see www.lowimpacthydro.org).

[17]Methane generated from animal waste (hog manure, etc.) can be recovered for use in direct heating systems, in the production of electricity or in natural gas systems (after processing). Energy recycling techniques can also be applied to landfill sites, municipal sewage systems, and other sources of wasted energy.

[18]Hydrogen itself can be obtained from several sources: hydrocarbons (natural gas, petroleum and coal), biomass (through gasification) and water (through electrolysis, a process that uses electricity, either from new or conventional sources). www.hydrogen.org.

[19]Indeed, it is already possible to consider the potential integration between stationary energy markets (residential and commercial) and transportation markets, namely as a result of fuel cell multifunctionality. Responsible, paragovernmental authorities from the state of California have undertaken the first studies on this subject (Kempton et al., 2001).

[20]The annual growth in North America's energy needs over the last decade – a period of low prices and strong economic growth – represents only a fraction (approximately one quarter) of the growth in energy demand experienced during the 1960s and 1970s. The de-intensification of energy in the economy continues to take place, albeit at a much slower pace than it did previously.

Table 1. Value of reliability based on the average costs incurred by a power shortage. Sources: Weinberg (2001) and Rifkin (2002).

Type of business	Approximate cost ($CAN/hr)
Conventional small business	$500
Cellular communication	$65 500
Phone-based ticketing service (general)	$115 000
Airline ticket reservations (computerized system)	$144 000
Credit card transactions	$4 120 000
Transactions made by investment brokers	$10 350 000
Microchip manufacturing plants	$50 000 000

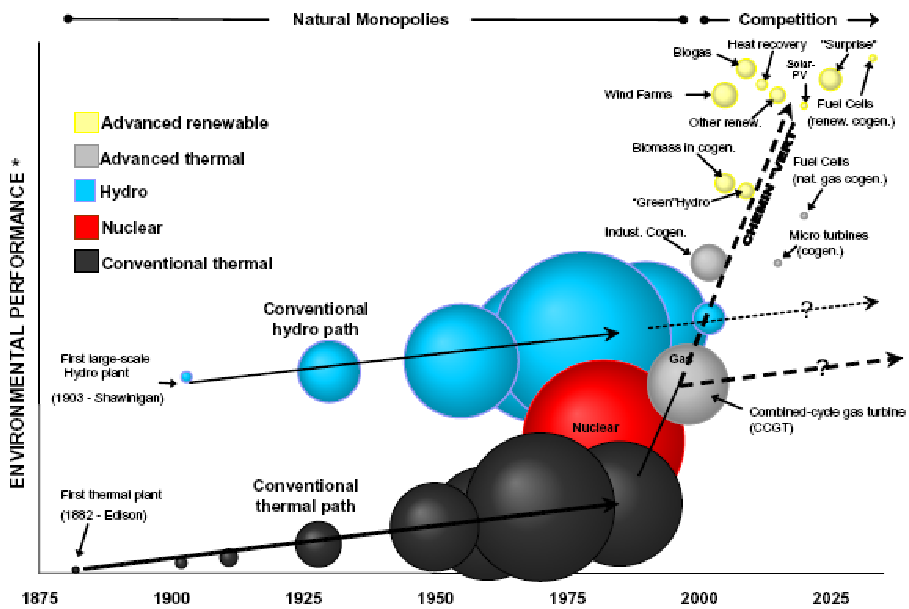

Figure 4. The greening of power generation. The circumference of the bubbles represents the relative size of leading technologies. To make them more visible, the "Solar-PV," "Micro turbines" and "Fuel Cells" bubbles have been enlarged. The bubble labelled "Biogas" refers to energy renewal (e.g. methane), which is mainly obtained from agricultural and municipal waste. The bubble labelled "Other Renew." refers to the production of energy from natural sources such as heat from the earth, waves and tides. The "Surprise" bubble refers to new technologies and innovations that may be developed in the future (e.g. nuclear fusion, thermophotovoltaic, etc.). The ecological scale is an approximation. Thermal power plants (conventional and advanced) are classified mainly according to their net combustion efficiency, which is adjusted for other ecological performance factors. Nuclear power plants – the environmental impact of which cannot be compared to that of thermal power plants – were classified according to the subjective judgement of the author. The same can be said for hydroelectric power plants, the impact of which is also largely dependent on the site.

deployment of smart meters.[21] These changes will reduce the degree of market power concentrated on a handful of generators, thus resulting in a more dynamic and robust market.[22]

[21]Smart meters facilitate two key elements of all functioning competitive markets, namely (1) marginal-cost pricing and (2) price transparency. For the first key element, smart meters allow retailers to vary their rate in real-time according to the buying-in price on the spot market, which varies hourly. This type of rate variation may prove to be of interest to certain categories of consumers, and would allow them to adjust their consumption accordingly. Price transparency allows consumers (that is, demand) to take part in the market (sell their *reductions* in power consumption on the power exchange) and have the same standing as providers. It also facilitates the potential involvement of self-generators – industrial cogenerators as well as residences equipped with solar panels – allowing them to participate on the same basis as owners of large plants. OFGEM, the British regulator of electricity and gas markets, foresees the installation of 1 to 3 million residential cogeneration systems by 2010, which poses an unprecedented challenge for the dynamic operation of networks (McCarthy, 2002).

[22]Market power is mainly to blame for the California energy crisis of 2000, which rapidly degenerated into rolling blackouts and a 1000% higher-than-average increase in wholesale prices. Since then, the American regulator, the *Federal Energy Regulatory Commission (FERC)* has come to realize – as evidenced by its recent proposals – that decentralized units are important to the functioning

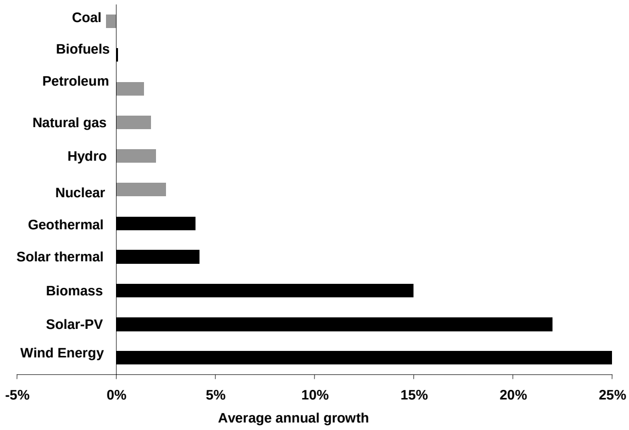

Figure 5. Growth in global sales by energy source. Source: Shell (2001).

More importantly, activities at the heart of a digital economy, (mainly electronic communication, financial transactions and the manufacture of micro and nanotechnologies) require unprecedented levels of power reliability and quality, as indicated in Table 1. For example, Hewlett Packard Company (HP) estimates that the losses incurred by a fifteen-minute power shortage in one of its microchip manufacturing plants amount to approximately $30 million US, that is, half of the annual power bill for this plant. Today, losses from power failures in the United States are estimated at $12 billion to $26 billion US per year (Rifkin, 2002). These losses highlight the scope of potential markets for less vulnerable technologies, particularly those concerning clients.

This increased need for reliability emphasizes the major weaknesses of current systems, which include plants that are not only very large but also far from consumer centres. In North America, the challenge posed by the increased need for reliability is commonly referred to as the "seven nines of reliability" problem. On average, power networks are designed to provide 99.99% reliability, whereas the new economy would possibly require 99.99999% reliability. In practice, the most advanced technologies available on the market today aim to provide "six nines of reliability" (99.9999%).

These characteristics highlight the vulnerability of these systems to natural hazards (transmission lines), physical terrorism (attacks on nuclear power plants) and economic terrorism (attacks on transmission lines or virtual sabotaging of power plant operations).[23]

The vulnerability of existing centralized models makes the need for reliability in a digital economy apparent and shifts the focus – as it does for competitive markets and environmental pressures – to decentralized power systems, which allow the businesses involved to protect themselves against problems concerning power quality and costly interruptions of power service.

As the need for reliability associated with the digitalization of the economy constitutes one of the factors in technological decentralization and miniaturization, there is strong evidence that such a fundamental change will intensify in Western economies over the next decades.[24]

3 The challenge of transition

3.1 Overview: mutually-reinforcing factors

In and of themselves, technological modifications, market "deregulation," environmental awareness and the advent of a digital economy do not account for the paradigm change taking place in the world of energy. Rather, it is the confluence of these different facets – the technological *hardware* as well as the economic and social environment in which it operates – that is calling traditional ways into question.

Indeed, local as well as global environmental concerns are creating pressure to develop greener technologies, such as decentralized units that maximize combustion efficiency through heat recovery. With the advent of the digital economy has also come an increased need for reliability, namely through the decentralization of power sources. Consequently, the technological miniaturization resulting from these forces leads to the opening of competitive electricity power markets. This opening of markets, in turn, through the opening of niche markets, facilitates the financing of innovation and the accelerated development of technologies able to meet these new economic and environmental demands.

The momentum these forces have gathered is such that it would be difficult to imagine, *in the long term*, a future very different from the one just described. The astonishing speed at which renewable energy technologies have been developing over the last decade serves as a good indicator of the opportunities that might present themselves in the future (see Fig. 5).

of competitive power markets.

[23]A few examples: *Natural hazards* – The 1998 ice storm provides the perfect example of how vulnerable extended power networks are to natural catastrophes. *Physical terrorism* – As part of the plans that would lead to the tragic events of 11 September 2001, the *Al Qaeda* network chose not only the World Trade Centre, the Pentagon and the White House but also American nuclear power plants as its primary targets. *Economic terrorism* – Richard A. Clarke, former White House cyber-security and counter-terrorism adviser, warns of the advent of an "electronic Pearl Harbour" with consequences that would be just as, if not more, disastrous.

[24]This intensification will take place inasmuch as the world economic architecture continues to evolve toward transnational free trade. Indeed, global economic integration will facilitate (not without maintaining or accentuating intra-and international inequalities) the transfer of low information intensity economic sectors to countries with the least educated labour force, and vice versa.

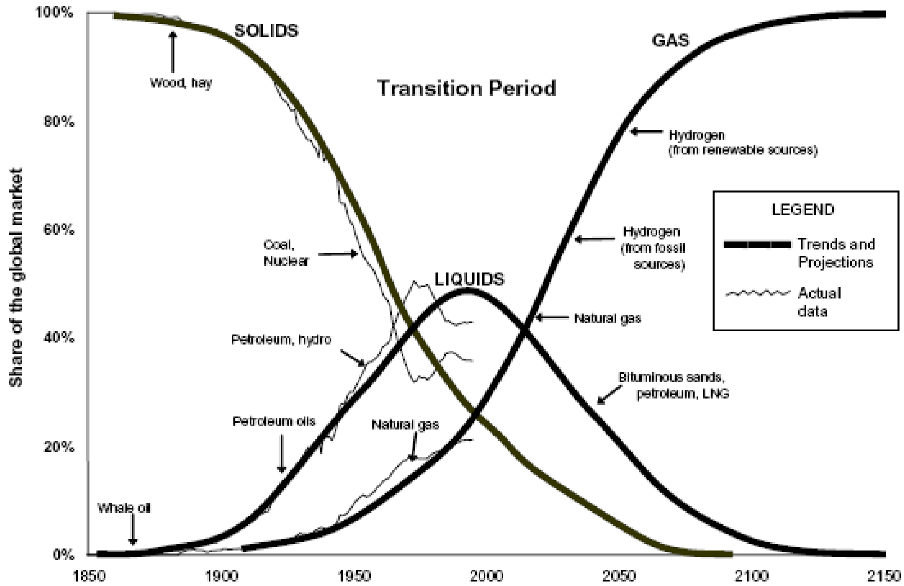

Figure 6. Energetic Transitions (1850–2150). It is proposed here that the fundamental nature of the changes that will occur depends on the phases of the sources of energy used, moving away from solids toward gas via liquids. Although the precise timeline is open for discussion there is little debate as to the strong trends that are presented. Sources: trends – Hefner (2002); raw data – Grübler (1998).

However, there are forces that may eventually come into play to impede the realization of this future.

3.2 Obstacles on the path

There are numerous short- and medium-term risks of setbacks which cannot be ignored.

On a technological level, vertically integrated monopolies might attempt to and succeed in blocking the regulatory modifications required to facilitate the decentralization of production.[25] Moreover, energy sources which at present are perceived negatively and in decline (coal, nuclear) might, through the use of new processing technologies, be seen in a different light and become preferred options.

In terms of power markets, there is a risk that the continuous opening of retail markets may be thrown off course, especially if a "second California scenario" were to occur. This would halt innovations that accompany the opening of niche markets.[26]

On the environmental front, players dominating today's energy markets (particularly those whose product is carbon-intensive) might succeed in diminishing or postponing the enforcement of environmental requirements, especially those targeting greenhouse gas (GHG) emissions.[27] Moreover, there is a risk that the implementation plans for the commitments to reduce GHG depend either on measures having benefits strictly limited to CO_2 (i.e. they do not create co-benefits, such as air quality improvement), or on measures taken at the expense of other environmental concerns (e.g. the damming of rivers). The question of co-benefits and co-costs associated with the measures taken should occupy an important place in future debates regarding the enactment of the Protocol, in Canada and elsewhere.

Finally, in economic terms, a slowdown or recession of pan-Western dimensions could drastically reduce the venture capital available for technological RDD&C, which in turn would set back the development and marketing of promising technologies.[28]

[25]Such modifications involve mainly the adoption of simplified and non-discriminatory standards intended for self-generators using green power technologies. This allows them to connect to the distribution network and obtain credit (either directly or by making the meter run backwards) for selling their production surplus to the network. These standards are not yet firmly established in most American states and in a large number of European countries.

[26]This recognition of technological innovation benefits associated with competitive markets should not be mistaken for a global appreciation of the opening of retail markets, the net effects of which are as complex as they are variable, depending on the region concerned. However, as mentioned previously, there is a possibility that regulators can reproduce these benefits within regulated monopolistic markets.

[27]In the short term, the greatest concerns are the ratification, the enactment and the attainment of the targets outlined in the first emissions reduction phase (2008–2012) of the Kyoto Protocol. In the medium term, future negotiations will determine the targets that will be set in the second reductions phase (post–2012) of the Protocol.

[28]Between 1995 and 2000, the venture capital allocated to decentralized power technologies increased by approximately 2700%, constituting a powerful impetus for the miniaturization and greening of technologies underway (Hydro-Québec, through its subsidiary HQ-Capitech, is one of the companies having invested in

4 Conclusions

In the short and medium terms, the precise architecture of the industrial world's electricity system is far from being established. However, despite potential temporary setbacks, in the long run, this architecture seems destined to take the paths of change described in this text: miniaturization, decentralization and the greening of electric power generation, all of which result from the combined effects of technological progress, environmental awareness, economic digitalization and the opening of markets.

The endurance of this trend over the long term is well illustrated in Fig. 6. According to the author of this graph, who is the president of an American natural gas drilling company, the fundamental nature of the change that will occur depends on the sources of energy used. We are moving away from the use of solid sources (e.g. wood and coal) and toward the use of gas (natural gas, hydrogen) via liquids (petroleum).

This evolution – as well as the increase in electrification accompanying it – reveals the important scientific advancements that have led to the intense dematerialization of the global economy, which has been taking place since the industrial revolution. This dematerialization – a clear indicator of increased economic productivity – not only brings hope for the environment, but also constitutes a *sine qua non* condition for long-term economic viability.

In essence, the energy sector must now rise to the challenge presented by this unprecedented transition – the next great technological, commercial and social revolution in history (Rifkin 2002). Our answer – that of governments, regulators, businesses and civil society – will determine not if, but how and when it will be complete.

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