A LOW CARBON ELECTRICITY SCENARIO

As a contribution to
the energy policy and climate change debate

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It reflects a work in progress, particularly concerning regional analyses and energy efficiency.

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Executive summary

Electricity is a major contributor to greenhouse gas emissions

The human implication in climate change is now widely acknowledged and worldwide generation of electricity is a major contributing factor: in 2002, electricity accounted for 40% of energy-related CO_2 emissions (three-fourths of all anthropogenic CO_2 emissions) and, by 2030, the figure would rise to 44% according to the International Energy Agency (IEA) reference scenario, surpassing emissions due to transport (21% in 2002, 23% in 2030 in the same scenario[1]).

These figures reflect the share of fossil-fired energy in global electricity generation: 40% for coal (with an average emission level of 1.1 tCO_2/MWh from existing plants) and 26% for gas and oil (with an average emission level of 0.6 tCO_2/MWh from gas plants and 0.8 tCO_2/MWh from oil plants), with the remaining generation coming from nuclear (16%), hydro (16%) and other renewables (2%).

By relying primarily on nuclear and hydro to generate electricity, countries like Sweden and France emit levels of energy-related CO_2 per inhabitant which are 30 to 40% below countries like Germany or Denmark, whose electricity is coal and gas-based. This shows the potential for emissions reduction through changing generation structures.

Using best available technologies on both the demand and supply sides could allow cutting electricity sector emissions by 4 in industrialised countries.

Electricity could be at the core of a strategy to attenuate global warming at acceptable economic cost if we take advantage of: the natural rate at which existing plants are replaced in industrialised countries; the need for new build to meet growing demand in developing countries and; the best technologies available today on the demand and the supply sides along with those, still in the R&D phase, which will have matured by the 2025-2040 period.

Realising cost-effective investments that make way for reduced consumption, like insulation in buildings, might allow reducing expected world energy consumption in 2050 by nearly a third, compared to its projection in "business as usual" scenarios (which see it tripling by 2050), this without hindering economic growth and while substituting electricity for other energies.

Adding to this investment effort gradual restructuring of the world's electricity generating fleet toward:

- more than one-third of renewables, primarily hydroelectricity followed by other technologies breakthroughs in electricity storage as they materialize,
- just under one-third nuclear, compatible with natural uranium resources and realised only in countries which already master this technology,
- just over one-third coal and gas, based on a long term broad rollout of CO_2 capture and storage technologies,

would make it possible to cut electricity sector emissions (in reference to 1990s levels) by two worldwide and by four in industrialised countries.

([1]) The rest of emissions derive from stationary fossil uses, whose share in the global energy mix tends to decrease. Data come from *IEA 2004*.

Enabling framework conditions for such a low carbon electricity sector scenario (LCES) pertain to public policies and their international architecture

It is essential, through multidisciplinary debates, to create the emergence of a widely shared "framework vision" of: (i) the time-frames and efforts needed to bring the different low carbon end-use and generation technologies to maturity; (ii) the outline of the business investment programmes that appear desirable from the viewpoint of climate change mitigation on the basis of these time-frames. When those technologies are examined, the issue at stake is not to decide which ones should be used or not. Being understood that all lower carbon available technologies are needed to meet global climate and security of supply challenges at acceptable cost, the issue is twofold: first to acknowledge the respective advantages and drawbacks of these technologies and identify their respective conditions for successful implementation; second, to optimise their development and create in the different regions of the world adequate deployment conditions, notably through public policies.

Such an approach suggests setting and implementing rapidly in industrialised countries public policies which *simultaneously* orient investment towards lower carbon available technologies without inducing disproportionately high electricity prices *and* support R&D so as to bring to market the next generation of carbon-free technologies as soon as possible. Here again, the tools we have should not be opposed; on the contrary, R&D support devices and economic instruments like taxes and cap & trade systems must be considered as complementary and used as such in measures packages.

Lastly, it is clear that the participation of developing countries in the shaping of global climate change policy, i.e. the reduction of their emissions in relation to their "baseline", cannot be delayed until their level of revenue per inhabitant reaches that of industrialised countries and that, as the major emitting country, the USA cannot be left aside. A global commitment scheme, with reasonable properties in terms of international equity and acceptability is thus required. It will probably have to be "multi-stage", i.e. to provide for increasing and differentiated participation of developing countries, with advanced developing countries like China possibly accepting "non binding commitments" (emission quotas entailing no penalty in case of emissions in excess but allowing to supply credits to the emission credits market in case of emissions below quotas) in a near future while lower income developing countries are kept out of the commitment scheme for much longer time. In the short run and beyond 2012 for developing countries that would remain without commitment, Clean Development Mechanisms (CDM) appear to constitute an interesting tool to enlarge the scope and decrease the cost of mitigation efforts, provided that the field of "qualified" technologies is broadened so as to include wide scale energy efficiency programs and big hydro, coal or nuclear generation projects. Somewhat redirecting development aid mechanisms towards climate change mitigation and strengthening them would also increase the chances that climate issues provide an opportunity for rather than a constraint on development.

Introduction

Human implication in climate change is now widely acknowledged, as is the need to act quickly on a global scale to mitigate this change.

A general objective at the world level is to divide total GHG emissions by two by 2050 without hindering economic development, which implies a (roughly twice) higher reduction effort from developed countries and more sober development models.

To define pathways towards such objectives, it is necessary to build scenarios that sketch possible futures for the world economy and especially for the sectors that contribute most to GHG emissions, among which is energy.

"Business as usual" scenarios of the energy sector describe the unacceptable, i.e steadily increasing GHG emissions from now to 2050. They rely on optimistic assumptions on macroeconomic growth, demography and energy prices and the unrealistic presumption that there will be no change in the existing public policies. Their function is to point out the extent of the challenge facing the world society.

"Uncoupling" scenarios, which combine pessimistic hypotheses on growth, demography and energy prices with excessively optimistic view of new public policies, result in low levels of GHG emissions that solve the climate change issue but lose sight of and even accentuate the development issue. They describe the politically unacceptable.

"Miracle technology" scenarios solve all issues thanks to a "backstop" technology –for instance hydrogen fuelled by renewables or new generation of nuclear power plant on the supply side – presently at an early stage of research but which would nevertheless be massively introduced around 2030. They are misleading since they come down to a technological bet, encourage inaction and anyhow underestimate the time required to develop and deploy this kind of complex technology.

Scenarios like the "IEA alternative scenario" (see IEA, 2004) or the "Enerdata-LEPII-EPE factor 4 scenario" elaborated for the French administration (see Enerdata-LEPII-EPE, 2005) are more consistent. They claim that not only changes in behaviour but also technological leaps are required if we want to keep climate change within acceptable limits. They advocate the use of all technological options and early action to curb the GHG emission curve. These "global alternative" scenarios have the advantage of considering all energy-related service sectors, i.e. non-electrical energy used in transport ("mobility"), fossil fuels used to provide heat ("stationary uses") and electricity supply ("electrical uses" and "fuel inputs to power generation"). However, they do not develop all the consequences that could be drawn from an in-depth analysis of the technologies involved in each sector.

We would like in this paper to apply such technology-based approach to the electricity sector. A first reason for focusing on this sector if that we have some knowledge of it. We also believe that electricity can be at the heart of a viable strategy of climate change mitigation. GHG emissions from electricity are indeed the result of choices regarding the generation fuel mix and could be zero if only carbon free technologies –which do exist- were used; emissions are high today -40% of energy-related GHG emissions- because of past fuel source choices but investment needs in the decades to come are massive and provide a real opportunity to improve energy efficiency and alter the generation mix in a way leading to dramatically reduced emissions at acceptable cost.

After documenting this assertion (section I), we will derive from the in-depth work done by "IEA alternative and "Enerdata-LEPII-EPE factor 4" scenarios' builders an investment path for the electricity sector which uses at each point of time available technologies and achieves the objective of dividing its emissions by two at the world level by 2050 (section II). Such an investment scenario, however, can only have plausibility if public policies adequately support R&D and investments. Moreover, there is a chance that it will be realised only if developing and developed countries participate in a joint effort in the near future. We try to formulate those key issues in the last part of the paper (section III).

I. Why electricity is key to meeting the climate change challenge

Electricity is a key to meeting the climate change challenge since it is a major contributing factor to GHG emissions (1) and there is a real opportunity to decarbonise the power generation fuel mix when investing massively to meet plant replacement and build needs in the decades to come (2).

1. The electricity sector: major contributor to GHG emissions

The objective of stabilising the concentration of GHG in the atmosphere at an acceptable level in a global warming perspective can be translated into an objective for global yearly GHG emissions (A). The share of electricity in those emissions appears substantial and sharply increasing in business as usual scenarios (B).

A. The meaning of long term GHG emissions objectives in the energy sector

The long-term objective of the European Union climate policy is to prevent global mean temperature from rising by more than 2°C over pre-industrial levels. To explore the implications of this target, Criqui et al. (2003) have developed two constrained global emission profiles which correspond to stabilising after 2100 the total GHG concentrations at levels of 550 and 650 ppmv (parts per million in volume) in CO_2 equivalent, for the set of six greenhouse gases covered by the Kyoto Protocol. These profiles are referred to as S550e and S650e.

As Criqui et al. (2003) say in their study for the European Commission, "using the uncertainty range estimated by the Intergovernmental Panel on Climate Change (IPCC), the S550e profile will result in a global mean temperature rise of less than 2°C for a low to median value of the climate sensitivity". The 650e "profile is less likely to meet the EU target. If the climate sensitivity is high, the EU target will not be met in either profile". In the S550e profile, "global emissions must peak as soon as 2015-2020". "For greenhouse gas emissions from energy use and industrial processes, this [S550e profile] implies that in 2025 global emission levels can still [lie] about 20% above 1990 levels" but that "in 2050 emissions have to be reduced strongly (…) compared to 1990 levels".

A target of stabilisation of GHG concentrations at 550 ppm is made equivalent to stabilising the concentration of CO_2 at 450 ppm and the concentration of the five other combined anthropogenic GHG (CH_4, N_2O…) at 100 ppm (see Criqui et al., 2003).

For energy, the 450 ppm CO_2 profile implies going down to *an annual global volume of CO_2 emissions in 2050 equal to half that of 2002 -a "factor 2" reduction-* or to 60% of its 1990 level (according to the IEA, CO_2 emissions related to energy have increased by 17.7% between 1990 and 2002, from 20 Gt[2] to 23.6 Gt).

Inasmuch as a margin for growth has to be left for developing countries, this means that the objective for industrialised countries should be more severe. Hence the *"factor 4"* idea, i.e. the

[2] Gt stands for Gigaton.

idea of *annual CO_2 emissions from industrialised countries' energy sectors in 2050 divided by 4, compared to 2002 level*.

B. CO_2 emissions from the electricity sector: substantial and rising

Global energy supply has tremendously increased over the course of one century ([3]) and accounts today for three quarters of anthropogenic CO_2 emissions (deforestation and agriculture account for the remaining). *Electricity accounts for 40% of CO_2 emissions related to energy*, more than transport does ([4]). This weight of electricity in CO_2 emissions reflects the weight of fossil fuels in world electricity generation, which is high (see table below).

Primary sources of world electricity generation
in 2002 (16,000 TWh)
and IEA 2030 reference scenario (32,000 TWh)
Source: IEA 2004

	2002	2030
Coal	40 %	39 %
Gas and oil	26 %	33 %
Nuclear	16 %	9 %
Hydro	16 %	13 %
Other renewables	2 %	6 %

The breakdown of electricity generation can of course and does vary widely among countries: the USA, Germany and China for instance are more representative of the average world mix in this respect, than France, Scandinavia or Brazil where more than 90% of electricity comes from hydro and nuclear generation. In those countries where CO2 free technologies are today the main primary source of generation, national CO_2 emissions are significantly lower than in other countries, as the table below shows.

Impact of electricity mix on CO_2 emissions: the cases of 4 countries in Europe

2000 data (*sources* EC (2003), IEA (2004 b))

		France	Germany	Sweden	Denmark
Emissions in tCO_2/inhabitant	• Total due to energy	6.3 t	10.1 t	5.5 t	9.6 t
	of which, to electricity	0.7 t	3.8 t	0.6 t	4.3 t
Structure of power generation	• Nuclear and hydro	90%	35%	93%	0%
	• Coal, gas and oil	10%	64%	6%	88%
	• Other sources*	< 1%	1%	1%	12%

(*) Notably wind-power and biomass in Denmark

The trend in the 1990s was characterised by significant economic growth, with related significant transport and electricity growth. Coal remained the prime electricity source, CCGT was the privileged way to supply new electricity demand in a context of cheap gas ("dash for gas") and other possibilities such as nuclear, renewables and energy savings were considered as much too costly compared to CCGT.

The Reference scenario of the IEA (IEA 2004) for 2010-2030 still reflects this view, despite a hypothesis of long term gas prices slightly higher than in the past:

- primary energy supply in 2030 is 60% higher than today, and despite annual energy growth, supposedly lower than in the past (below that of economic growth); developing countries account for two thirds of this growth (because of population growth and the need to dramatically enlarge access to commercial energy and electricity);

([3]) From 1900 to 2000, world population was multiplied by 4 and average energy consumption per inhabitant also by 4 (leading to an overall consumption multiplied by 16), with a higher growth trend over the last decades.

([4]) Source IEA 2004. Transport and stationary energy uses account respectively for 20% and 40% of CO_2 emissions related to energy. Electricity includes cogeneration and heat networks.

- electricity generation in 2030 is twice the present level, and the breakdown remains similar to the present one (see table above, third column).

As a logical result, given the persisting dominant role of fossil fuel, CO_2 emissions from electricity double from now to 2030 in the IEA Reference scenario.

2. A real opportunity to reduce GHG emissions in the electricity sector

The opportunity is real since the investment required to meet demand in developed as well as developing countries is massive (A), and efficient energy saving and low carbon generation technologies are already available today (B).

A. Massive investment needs over the next two decades

The regional overcapacities observed in the 1990s are part of the past. The need for new investments is massive in the electricity sector in the next two decades, not only to sustain growth in developing countries but also to renew existing facilities in developed countries. The IEA study (2003) points to this importance of investment.

In spite of substantial increase of global energy efficiency (+1.5% per year), the study's global projections are considerable: $10 trillion of investment worldwide (60% of total energy investment and about 4% of world Gross Fixed Capital Formation), of which 55% for networks and 45% for generation.

In physical capacities, the study provides the following figures:

Source : IEA 2003 Figures in GW	World	India	China	EU-15	USA-Canada
Installed generation capacity (end of 2000)	3500	111	322	584	942
Capacity to build by 2030 (include renewal)	4700	272	800	650	830

- Over 50% of needs are accounted for by growth in developing nations such as India and China (for China, this involves putting on stream the equivalent of the entire French electricity generation capacity, approximately 100 GW, every 3 to 4 years);
- Significant investments will nevertheless also be needed in developed countries: more than 2000 GW in OECD. The situation in Europe and the US is no longer characterised by overcapacity as was the case in the first years of the new millennium. Despite slower growth of demand in Europe, most existing plants (more than two-thirds of thermal plants) will need to be replaced between now and 2030: according to the IEA, the 650 GW of new capacity will include 330 GW for replacement of existing power plants.

Finally, it should be understood that with the move towards energy savings, desirable for a number of reasons, particularly with respect to reducing CO_2 emissions, there is likely to be a technological shift toward electrical processes. This will require investments at customers' premises comparable to the total investment required for power plants and networks.

B. Available low carbon technologies and promising innovation prospects

Before reviewing [(ii),(iii)] and summarising [(iv)] the state of technologies on the demand and supply sides, it is important to recall the specific dynamics of the electricity sector [(i)].

(i) The dynamics of the electricity sector

The electricity sector has strong specificities:

- It is capital-intensive: investments in supply are 2-3 times the annual turnover of the sector; the remark is similar for demand side when comparing the investment cost of "electricity terminals" to the annual cost of electricity consumption;
- Assets have a long lifetime: 30-60 years for power plants, around 100 years for housing, 15 years for end-uses in average;
- As far as they concern complex technologies, innovation lead-times are pretty long: 30-40 years are expected for the technological breakthrough required for having competitive photovoltaic 3rd generation, nuclear 4th generation, carbon sequestration and electricity storage (and probably more for new energy systems like that of hydrogen).

These specificities have major consequences in terms of the time-frame of the different decisions to be made:

- The industrial deployment of the above new technologies cannot reasonably be expected before 2040-2050;
- Electricity demand and supply in 2015-2030 must mainly rely on the choice of current best available technologies, which is a major challenge, whether in countries such as China and India with the building of a lot of new plants, or in Europe and the USA with the renewal of existing plants;
- Leeway up to 2010 is limited to using more extensively low or zero emission existing plants.

(ii) Technologies for energy efficiency improvements and energy savings ([5])

There has been a lot of innovations in more efficient energy technologies in the past: domestic appliances like clothes washers, dishwashers, TVs or refrigerators use much less electricity for the same use than thirty years ago; the production of one ton of primary aluminium (a technology invented in 1886!) uses one-third less electricity now than in the fifties.

These technological changes were partly "natural", i.e resulted from the competitive pressure which led industrial companies using energy for their processes and appliance manufacturers to cost-reducing innovations, and partly due to public policies using a variety of instruments (standards, labelling, taxation,…). The level of efficiency improvements actually observed was and still is well below estimates of cost-effective potential. This is due to barriers to investing, among which are consumer lack of information, inaccurate estimates of cost and benefit estimates notably neglecting consumer "snap back" to previous consumption levels for a higher comfort level, restrictions on entries into efficiency markets and lack of competent equipment suppliers and installers.

([5]) Energy efficiency defined from a technological point of view is a part of global energy efficiency, which "encompasses all changes that result in decreasing the amount of energy used to produce one unit of economic activity (e.g. the energy used per unit of GDP or value added) or to meet the energy requirements for a given level of comfort". Let us just recall that electricity prices reflecting costs are a prerequisite for global energy efficiency (as soon as customers are well-off enough), and this is not only a formal clause, as examples in several countries still show.

What is relatively new is that there are now government policies aiming at accelerating this natural trend. These policies are widespread in Europe and Japan and, maybe to a lesser extent, in North America. They are gradually implemented in many emerging countries, which also benefit from the diffusion on their markets of energy efficient appliances or industrial processes initially conceived for developed countries markets, but manufactured for a large part in these emerging countries (e.g. compact fluorescent lamps -CFL).

Moreover, these policies are no longer limited to specific topics (e.g. building codes for new houses in cold climates) but are systematic. For instance there are now, in many industrialized countries, programmes aimed at strongly reducing energy consumption in all existing buildings, and in several emerging countries building codes aimed at limiting electricity consumption for air conditioning. These policies involve a lot of applied scientific research. They draw from the substantial experience acquired: they take into account the shortcomings of experimental energy efficiency policies implemented (principally in the U.S) during the eighties. However, they have only started addressing the multiple barriers to investing identified so far.

Hoping that these difficulties will be overcome, informed forecasting bodies like the IEA, the WEC or the European Commission believe that energy efficiency will play a much larger role in the coming decades than in the past, even taking into account the fact that global energy efficiency will lead, in some sectors, to more substitutions of fossil fuels by electricity (e.g. heat pumps for space heating or plug-in hybrid vehicles).

One point is quite important, however, when looking forward: in several examples, more energy efficiency means more electricity consumption, not less: induction heating, both for industrial purposes and for cooking at home, is far more efficient than the use of -say- natural gas; heat pumps for space heating replace very advantageously oil-fired central heating, hybrid vehicles (which, in a not so distant future, will be reloaded on the grid) are more efficient than ordinary vehicles …If electricity generation is largely CO_2 free, there are huge quantities of CO_2 to be saved through such substitutions.

(iii) Technologies for power generation

We will consider the different power generation options –i.e. natural gas, coal, nuclear, hydro an other renewables- and will observe that they provide altogether interesting opportunities and are all needed, but also that the timetables for them to reach maturity are quite different.

Natural gas

Gas has taken a significant share in global electricity generation (18% share in 2002) over the last years while its price was "low" (2-3 $/MBtu) and infrastructure was there. It is the cleanest fossil fuel and gas-fired generation is dominated by the Combined Cycle Gas Turbine (CCGT) technology, which is mature. However, it no more appears as the "miracle technology" that caused a dash for gas in developed countries when electricity markets were liberalised for several reasons. The need to make heavy investment in infrastructure (pipelines, LNG terminals…) to be able to exploit existing reserves makes gas more costly: gas prices are today at 7-8 $ per MBtu; they are expected to be around 5.5-6 $/MBtu in the long run ([6]), which corresponds to a cost of more than 50 $ per MWh for CCGTs, i.e. more than the full cost of nuclear or coal with zero CO_2 price. Reserves depletion could be rapid (30 to 40 years of present consumption of proven reserves in conventional gas) and security of supply concerns would rise substantially if annual world gas consumption went 2.6 times higher than today in 2030, as in the IEA alternative scenario. Lastly, CO_2 emissions from new CGCTs are lower than those from new coal plants but are not negligible (0.4 t CO_2/MWh instead of 0.8 ton), until technologies with carbon capture and storage become mature.

([6]) IEA 2005

Coal

Coal is the most used fuel in electricity generation (39% share) and global resources would allow for electricity generation at least twice higher than today for more than a century. Almost all existing coal-fired generating plants use the conventional Pulverised Coal (PC) technology, which is mature, and the "advanced" available technologies (supercritical PC especially) presently used in plants built in some industrialised countries and also some emerging countries like China or India have satisfying performance in terms of economics and local pollution, and they display a significant improvement in terms of GHG emissions compared to the average of existing plants in the world (0.8 ton of CO_2/MWh instead of 1.1 ton, i.e. a 30% reduction of emissions). Effective access to these technologies in developing countries where the local coal resource is abundant would be very helpful in the fight against climate change. Boosting research & development to make available cheaper carbon capture technologies as quickly as possible (i.e. in a few decades) and solving storage issues are absolute necessities in a longer term perspective (countries endowed with a lot of coal will be willing to use it, whatever CO_2 emissions ultimately are). According to industry estimates, implementing carbon capture & storage (CCS) technologies in the near future would drive the full cost of a coal plant from 40 to 70-90 $/MWh, which corresponds to a cost of 50-80 $ per ton of CO_2 avoided. R&D ambitions are to divide this extra-cost by 2, which would mean a cost for the ton of avoided CO_2 at 25-40 $. Potential storage sites have to be tested and, to a certain extent, a new infrastructure (capture, transport and storage) will have to be tested and deployed at wide scale. To sum-up, CCS technologies could be available at industrial stage and at a price twice lower than today by 2030 in the world in general and possibly before in the USA, China or European countries like Germany or Poland.

Nuclear

After a strong growth in the 70's and the 80's, the share of nuclear power has remained stagnant at 16%. Prospects for uranium resources are such -14.4 million tons ([7])- that they would allow building and operating around four times the number of plants currently in use (4x360 GW, i.e.1440 GW) by 2050. Water-cooled" Generation II" reactors are either light water reactors (LWR) or heavy water reactors (HWR) like the Canadian CANDU. LWR technologies (either PWR or BWR, the most commonly used technologies) have proved to be mature and safe CO_2-free technologies in OECD countries with some successful experiences in economic terms (France, Belgium, Scandinavian countries notably). Generation III LWR technologies (EPR, AP1000, ESBWR…), which include many improvements concerning mainly safety, are economic and ready for use: they could be developed soon in some European countries, China, and also in the USA; the US industrial players failed to build economic plants during the previous investment wave because of fragmented industry and inadequate regulation, but they have a substantial LWR experience and have taken the necessary step to become ready. According to international studies, the economic performance of future new plants appears relatively favourable compared to coal and gas plants with moderate or high gas price, without even including carbon externalities in the cost of fossil fuel technologies. Bringing nuclear installed capacity to 1440 GW in 45 years would require the same amount of investment (including plant renewal), i.e. building 32 GW per year; this seems attainable (when France realised its construction programme in the eighties, it built 5 GW per year during 10 years). Nuclear can thus constitute a substantial part of the investment in power generation in countries that master the technology in the decades to come if, however, some conditions are met. Lessons from experience tell us that key success factors are a credible safety authority, clear and coherent license design process and site authorisation by regulatory authorities, and industrial organisation allowing for standardisation and the associated economics of scale. Stakeholder participation in structuring choices is also key, in particular with regard to legitimate concerns about waste management and the safety and security of installations.

[7] According to OECD-NEA-IAEA (2003), these 14.4 million tons would allow 270 years of present annual use of uranium in nuclear plants, i.e. more than 60 years of annual use of uranium in a nuclear fleet 4 times higher than today (270/4=67.5), this without any fuel reprocessing.

Four "Generation IV" technology designs over six are "fast breeder" technologies, which use non only the small fraction of fissile U-235 (less than 1% of the natural uranium) but also the non-fissile U-238; one over six uses Thorium, whose reserves would be of the same order of magnitude as uranium. Fast breeders could come in line by 2035-2050 and the uranium resource lifetime be extended by up to a factor of 50 by using them.

Hydropower

Hydropower contributes for some 90% to world's renewable electricity generation ([8]). Although hydro capacity is expected to increase by 60% from now to 2030, hydro generation share would be less than today 16% figure by that date according to IEA forecasts. Yet, at least two thirds of the hydro economic potential remains unused, especially in developing countries[9]. Plant lifecycle GHG emissions are negligible in the majority of cases except under certain circumstances in tropical areas. Development prospects of hydro are thus quite encouraging in developing countries, provided that two points are kept in mind: the development of large hydropower is almost always as part of a large water management scheme (sometimes running across several countries) which requires collaboration between stakeholders; biodiversity must be preserved and population movements properly managed. Good governance is key in these matters but, following national or international available guidelines, it should be possible to develop large schemes with mitigated and acceptable environmental impacts, and even benefits in terms of development for local populations.

Other renewables (wind power, biomass, geothermal power, photovoltaic…)

Renewables other than hydro generate around 2% of world electricity, two thirds of which come from biomass and waste, geothermal and wind representing most of the remainder[10]. The IEA extrapolates recent growth rates to project a share of generation of 6% in 2030 in its business as usual scenario. Beyond their diversity, other renewables represent a vast potential, a small fraction of which only, however, is accessible with today technologies. Recent trends favouring their development are ongoing and will be pursued. Windpower and biomass are not far from maturity (50 $/MWh for the biggest wind farms in the best sites and 70 $/MWh in favourable sites, for instance). If solar thermal technologies are ready for use in many circumstances, photovoltaic technologies are much farther than windpower from maturity, which is reflected in costs (more than 200 $/MWh in the very best sites, and more than 400 $ in favourable sites[11]). The IEA acknowledges in its alternative scenario that vigorous public policies (as those conducted for instance in Europe through feed-in tariffs, auctions, or "green certificates") could drive the share of these other renewables to 10% in 2030.

What mainly limits the use of windpower and solar energy is land use and intermittency. A breakthrough in electricity storage would change the picture dramatically. It is not expected in the next decade but should be actively supported.

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[8] IEA 2005

[9] WCD1, IJH&D, WEC 2004 b, WEC 1995

[10] IEA 2005

[11] Photovoltaic panels nevertheless offer interesting low power off-grid potential.

(iv) Summing up technological prospects

The table below provides a summary of the power generation technologies that are available for investment in the short term (2005-2015) and of those which could be available in the medium run (2015-2030) and the long run (from 2040). It provides estimates of their costs at each period in euros (€), under assumptions regarding the price of CO_2 :

	Period	Technology	Description	€/MWh
	2005-2015 with no or low CO2 price (0-5 €/MWh)	nuclear	generation 3: EPR, AP1000, ABWR, VVER	35-45
		coal	pulverised "clean" coal (PC, desulphurised)	40-50
		gas	CCGT (gas price: 4.5-6 $/Mbtu; thermal efficiency: 55%)	45-55
		hydro	large hydro; no standard : costs depend on sites and acceptability	25-50
		wind	land wind, including 5-10 € intermittence extra cost	50-80
	2015-2030 with higher CO2 price (30 €/tCO2)	coal	PC and IGCC, with CO2 cost included	60-70
		gas	CCGT (gas price: 4.5-6 $/Mbtu; thermal efficiency: 60%, CO2 cost included)	55-65
		wind	offshore, with 20-30 € extra cost compared with land	70-100
		biomass	cost for dedicated generation	site specific
large uncertainties	2030-2040 ?	coal	IGCC or PC with CO2 capture-storage (if geological storage is feasible & acceptable)	55-65 ?
	beyond 2040	PV	photovoltaic: 3rd generation technolo-gies; competitive in summer peak period?	< 100 ?
		nuclear	generation 4	40-60?
		others	electricity storage?	?

* simplified estimates of levelised costs with discount rates and labour costs homogeneous to conditions of high or middle income countries (see for instance OECD-NEA-IEA 2005)

All in all, when considering both the available technologies and the opportunities provided by future investment needs and the "natural" pace of decommissioning of old power plants, it is our conviction that opportunities exist in developing as well as industrialized countries to start a course of significant reduction of CO_2 emissions in the electricity sector within the next decades. Hydro could be used twice more and nuclear twice to three times more than in business as usual scenarios; renewables could take a share of 10% in the world generation mix; gas could be used moderately although increasingly and left to developing countries, as long as CO_2 capture is not mastered. As the future of coal clearly hangs on the success of carbon capture and storage, this technology could and should be the subject matter of voluntarist R&D and in-time-deployment strategies. At the same time, we are convinced that each available technology has success conditions specific enough to induce different use rates in the different regions of the world. What we will do in the next section is to draw a global potential picture of the future electricity sector if lower carbon available technologies are used at best.

II. A low carbon scenario for the electricity sector

IEA 2004 and Poles 2004 reference ("business as usual") scenarios studied in IEA 2004 and Enerdata-Lepii-EPE 2005 ([12]), are considered as not sustainable. IEA reference scenario, which ends in 2030, uses so much hydrocarbon resources and allows for such a rise in CO_2 emissions on this horizon that unacceptable ruptures would be necessary in the 2030-2050 decades to attain the long term GHG emissions reduction objective. In Poles 2004 reference scenario, the high level of world electricity consumption in 2050 (four times the present level) is associated with a high level of fossil fuel generation. Thus GHG emissions from the energy sector in 2050 nearly reach an unacceptable level of 60 $GtCO_2$/year (2.5 times the level emitted in 2002), half of it coming from power generation.

Our work draws from two scenarios that present similarities : the alternative scenario of the IEA World Energy Outlook 2004 [hereafter "IEA alternative"], which also ends in 2030 and includes substantial efforts in energy savings on the demand side and in the development of renewables other than hydropower, and the "alternative scenario" in Enerdata-Lepii-EPE (2005) ["hereafter Poles factor4"] which covers the period 2002-2050 and defines a path for the energy sector leading to world GHG emissions divided by 4 in industrialised countries by 2050. "LCES" (for Low Carbon Electricity Sector) will designate our scenario for the period 2002-2050. As a short cut, we will follow the IEA convention that assimilates industrialized countries to OECD countries, and developing countries to the world excluding the OECD countries and transition economies.

To be short, LCES has been mainly built on a global basis with the purpose of obtaining progressively the desired global CO_2 emission profile, at acceptable cost since using decidedly available technologies when they are mature. Then, we have realised breakdowns of projected energy savings and of projected sources of generation among broad regions, in a way that is consistent with the geographical diversity of electricity levels of consumption and the geographical diversity of energy mix potentials.

Being understood that they are linked in any scenario building, we will present first the evolution of electricity consumption (A), then that of electricity supply (B) in the LCES scenario.

A. Electricity consumption [13]

Macroeconomic and population growths in LCES are standard and identical to those in IEA alternative and Poles 2004 scenarios (i). The decoupling between energy consumption growth and economic growth is a common assumption, and energy efficiency improvements objectives are reasonably ambitious in all three scenarios (ii). Electricity consumption is almost multiplied by two in 50 years, but with a stabilisation from 2030 in OECD countries (iii).

([12]) Strictly speaking, these scenario are not "business as usual" inasmuch as they take some recently adopted public policies and measure into account.

([13]) As will be mentioned in the tables, electricity consumption means here "gross" consumption and includes final consumption, network losses, CHP and district heating consumption. It is homogeneous with the level of electricity supply that generation must meet.

(i) Standard macroeconomic and population growth assumptions

Assumptions on macroeconomic growth are the same as in "reference" scenarios:

GDP world average yearly growth	IEA reference	Poles reference		IEA altern.	Poles factor 4		LCES	
	2002-30	2002-30	2030-50	2002-30	2002-30	2030-50	2002-30	2030-50
	3,2%	3,1%	2,1%	3,2%	3,1%	2,1%	3,1%	2,1%

The current medium scenario of UN 2004 for population growth, used commonly by IEA Alternative, Poles factor 4 and LCES, projects a world population of 9.1 billion inhabitants in 2050 (more than in WEC drivers):

UN 2004 medium scenario: population in million inhabitants and average yearly growth

	World	OECD	Developing countries
2002	6200	1150	5860
2050	9080	1250	7540
AYG	0.8%	0.2%	0.5%

(ii) Decoupling between energy consumption growth and macroeconomic growth

Primary energy and electricity consumption growths are completely decoupled from macroeconomic growth in all three scenarios, which is quite a change as compared to the past trends, both recent and less recent ([14]):

World average yearly growth (%/year) **in:**	IEA reference	Poles reference		IEA altern.	Pole factor 4		LCES	
	2002-30	2002-30	2030-50	2002-30	2002-30	2030-50	2002-30	2030-50
GDP	3,2%	3,1%	2,1%	3,2%	3,1%	2,1%	3,1%	2,1%
Primary energy	1,7%	1,9%	1,4%	1,3%	0,5%	0,0%		
Electricity consumption	**2,4%**	**2,8%**	**2,3%**	**1,9%**	**1,6%**	**1,3%**	**1,8%**	**0,9%**

The decoupling is particularly manifest for industrial countries. It is less stringent in developing countries. The pace of uncoupling in industrial countries is less rapid in LCES than in Poles before 2030 (we rely more on existing technologies).

Electricity yearly growth	IEA reference	Poles reference	IEA altern.	Pole factor 4		LCES	
	2002-30	2002-30	2002-30	2002-30	2030-50	2002-30	2030-50
OECD	1,4%	1,6%	0,9%	0,3%	0,2%	0,7%	0,0%
Rest of the world	3,6%	4,0%	3,1%	3,1%	1,3%	3,0%	1,0%

Projections regarding average electricity consumption per capita in all scenarios show stabilisation of the ratio in OECD countries and a notable growth in developing countries:

Average electricity consumption * in kWh per capita: current situation and LCES for 2050

	World	OCDE	Developing Countries
2002	2600	8500	800
2050	3500	9600	2400

* includes final consumption, network losses, CHP and district heating consumption

(iii) Rising role for electricity

Electricity growth is higher than primary energy (used for all energy services) growth *(see table above)*. In other words, the importance of electricity as an energy carrier increases over time.

([14]) These scenario might also be contrasted with WEC perspectives ("WEC drivers", 2004), that reverses the factors of causality and assumes that constraints on energy growth imply lower demographic and economic growths.

In developing countries, electricity is first a vector of economic development. In every country, electricity is a vector for energy and environmental efficiency and thus substitutes for other energy services (primarily fossil fuel stationary uses but also transport). Assumptions of energy efficiency improvements and energy savings are ambitious everywhere, in terms of public policy quality and consumer behavioural changes.

More precisely, LCES goes beyond the IEA Alternative scenario as far as electricity efficiency is concerned, but also supposes significant substitutions of fossil fuels by electricity. The result is close to IEA Alternative in terms of TWh (see table hereafter), but LCES includes a bonus in terms of CO_2 emissions reduction because of a different electricity generation mix (LCES CO_2 emissions in 2030 are 15% lower than in IEA Alternative, see §B below) .

Characteristics of electricity world consumption * in LCES scenario in 2030, compared with IEA alternative

	2002 16,070 TWh	IEA 2030 27,700 TWh	LCES 2030 26,600 TWh
coal	39%	31%	30%
oil	7%	3%	3%
gas	19%	28%	19%
nuclear	16%	12%	20%
hydro	16%	15%	17%
other renew.	2%	9%	10%

* includes final electricity consumption, network losses, cogeneration & district heating. It is thus comparable to IEA data (electricity generation).

More precisely, period by period, the picture looks like that:

- In 2050, the level of electricity demand in LCES is supposed to be similar to the one in Poles 2004: within 50 years, electricity consumption is thus nearly multiplied by two, from 16,000 TWh in 2002 to 32,000 TWh in 2050 (in "business as usual" scenarios, this "factor two" is usually reached around 2030) ([15]). In our scenario, a factor two at the world level includes a complete stabilisation of demand in OECD countries after 2030 (see the next table).
- In 2030, the IEA alternative and the Poles 2004 scenarios are relatively close: 27,650 TWh in IEA and 25,650 TWh in Poles. LCES adopts an intermediate hypothesis (26,600 TWh), assuming that we could be a little more ambitious than the IEA in terms of public policy energy efficiency and demand savings, but not as much as Poles given the time constraints mentioned in section 2.B.

B. Electricity supply

We will first explain in general terms how the generation mix is supposed to evolve in the scenario (i). We will then describe the path of each technology (ii).

([15]) Technically, all the values given here in TWh are the values of yearly power generation, used to supply final demand and network losses. We also follow the convention of IEA that includes cogeneration and district heating.

(i) A gradually decarbonised generation mix

Shares of the generation sources in LCES

Technology	2002 *	2030	2050
Coal **	39%	30%	23%
oil	7%	3%	0%
Gas **	19%	19%	11%
Nuclear	16%	20%	31%
Hydro	16%	17%	24%
Renewable (other)	2%	10%	11%
Total	100%	100%	100%

* IEA figures ** partly with CO_2 capture and storage in 2050

In LCES, worldwide CO_2 emissions of the electricity sector are divided by a factor of two in the long run: in 2050, the level of emissions is 61-62% of 1990 level, and 42% of 2002 level. For OECD countries, this means a level that is less than one-fourth the existing emissions. We proceed towards this objective through the progressive and balanced deployment of all available CO_2-free technologies according to their degree of maturity to keep costs acceptable (hydro, nuclear and other renewables by 2030 ([16]); coal with CO_2 capture and storage beyond 2030), at regional annual investment paces that never exceed the sum of regional demand growth and natural decommissioning of existing plants to ensure that decisions are cost-effective. The development of renewables other than hydropower in the 2010-2030 period is supposed to be ambitious: given their economic performance, compared with other primary sources, renewables are assumed to benefit from financial subsidies, paid by public authorities or by electricity consumers through different mechanisms; subsidies are substantial at the beginning but decreasing over time; the use of these other renewables is limited by intermittency insofar as there is no breakthrough in electricity storage. Oil is progressively but completely removed from the sector, while the growth of gas use is limited (its share in electricity generation is still 19% -i.e. what it is today- in 2030, and falls down to 11% in 2050). The share of coal in the generation mix remains substantial in 2050 (23%) but is partly associated with CO_2 capture and storage then: we assume that from 2030, CCS technology is mature worldwide; the volume of CO_2 supposed to be stored appears reasonable (see figures in (ii)).

Worldwide generation in TWh : comparison of scenarios

	2002		**2030**										**2050**			
	IEA		IEA ref.		Poles ref.		IEA altern.		Poles fact.4		LCES		Poles fact.4		LCES	
Coal	6240	**39%**	12090	38%	11810	34%	8700	31%	4940	19%	8100	**30%**	950	3%	7400	**23%**
Fuel oil	1180	**7%**	1180	4%	960	3%	940	3%	370	1%	900	**3%**	50	0%	0	**0%**
Gas	3070	**19%**	9330	29%	11700	33%	7850	28%	6330	25%	5100	**19%**	4540	14%	3400	**11%**
Nuclear	2650	**16%**	2930	9%	4660	13%	3330	12%	6660	26%	5300	**20%**	18390	56%	10000	**31%**
Hydro	2610	**16%**	4250	13%	5840	17%	4270	15%	7140	28%	4600	**17%**	8990	27%	7600	**24%**
Renew. (other)	320	**2%**	1880	6%			2570	9%			2600	**10%**			3600	**11%**
Total	16070	**100%**	31660	100%	34970	100%	27650	100%	25430	100%	26600	**100%**	32920	100%	32000	**100%**

Compared to IEA alternative, which deals only with the 2002-2030 period, LCES:

([16]) Strictly speaking, these technologies are not fully CO_2 free in a full life-cycle analysis (e.g. net initial emissions from large dams in tropical areas). But taking them into account has insignificant impact on our global results. We also suppose that our scenario avoids specific locations and circumstances in some tropical areas that would lead to significant emissions from large dams.

(i) assumes a much slower growth of gas-fired generation, taking into account higher gas prices;

(ii) adopts a slightly slower growth pace for coal, as the result of high growth in developing countries and less renewal of decommissioned coal plants by coal plants in OECD countries than in IEA alternative;

(iii) is more ambitious in terms of hydropower growth;

(iv) is similar for other renewables, because IEA alternative is already ambitious, and

(v) adopts a much higher pace of growth for nuclear, though still slower than the pace of gas growth in the IEA alternative.

These evolutions are compatible with the pace of plant decommissioning in OECD countries in IEA projections (nearly two thirds of coal plants and a third of gas plants, assuming expected lifetimes of 30-40 years). The renewal of coal and gas plants with the same fuel source is partial and is realised with available technologies by 2020 and with technologies including CCS after 2020: as a result, in 2030, CCS technology has been applied to a 10 to 20% of the fossil-fueled plants in operation in 2002 in the USA and in Europe. Concerning nuclear power, the assumption in LCES is that nearly 40% of existing plants worldwide are decommissioned between 2002 and 2030, and the remaining between 2030 and 2050.

Compared to Poles factor 4, LCES presents four significant differences:

(i) the change of the energy mix from 2002 to 2030 is more limited in order to not exceed the natural decommissioning pace of existing plants (coal for the major part);

(ii) from 2002 to 2030, clean coal with carbon capture and storage (CCS) is not yet considered as an economic technology the geological feasibility of which has been checked and which can be massively developed in the world using the adequate infrastructure; in LCES view, its development on a wide scale would only begin in the USA and possibly in countries like China or Poland after 2020;

(iii) the recourse to nuclear power is more limited in LCES: in 2030 because we do not overtake the natural pace of the changing energy mix (see our first argument), in 2050 because we are cautious about the economics of generation IV reactors and their performance regarding the reduction of the volume of long-lived nuclear waste; as a consequence of more coal being used in the 2030-2050 period, CCS is deployed later than in Poles factor 4 but on a larger scale;

(iv) the recourse to hydropower is higher in LCES in 2030 and 2050 than in Poles factor 4 (this is clear, even though the public data of the Poles 2004 groups hydropower and other renewables), because we take the economic potential of hydropower in developing countries more into account.

(ii) Fossil fuel use and CO_2 emissions

With the progressive but complete removal of oil from the electricity sector, LCES uses the same hypothesis as the IEA alternative and Poles factor 4 scenarios. Of course, diesel units would still be used in isolated areas. But at our global level of analysis, this can be considered as insignificant.

Concerning coal and gas, and beside our comparison of the three scenarios, we can add the following remarks concerning LCES:

- while our aim is a progressive global reduction of coal and gas use in the electricity sector, coal still remains important in countries with abundant -but not unlimited- local resources such as the USA, China and India; as a result,
- gas is considered as a stable competitive technology for half-baseload and peak-load uses and thus in our scenario contributes to 10% of generation in OECD countries as well as in developing countries; the cumulated use of gas resources by the electricity sector from 2002

to 2050 in our scenario is less than 58,000 billion m^3 ([17]), that is less than one third of the world's proven conventional reserves (180,000 billion m^3, according to BP 2005);

- for coal, as for gas, technologies that include carbon capture and storage (CCS) are supposed to be massively developed for use only after 2030, with some earlier industrial development in the USA and a few developing countries in the 20s and a progressive increase worldwide from 2030 to 2050. In 2050, more than half of existing fossil fuel plants in OECD and more than a third of existing fossil fuel plants in developing countries are supposed to use technologies with CCS.

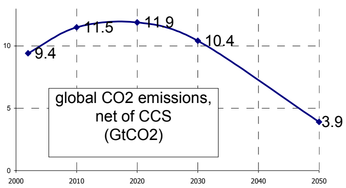
As mentioned before, the pace of reduction of fossil fuel generation and increased development of CCS technology is achieved with no acceleration of the pace of decommissioning of existing fossil fuel plants compared to IEA assumptions.

Concerning CO_2 emissions, worldwide average specific emissions in 2030 are 0.90 tCO_2/MWh for existing coal plants and 0.66 tCO_2/MWh for existing gas plants in IEA alternative. LCES has the same hypothesis in 2030. In 2050, after the complete removal in the 2030-2050 period of the last fossil plants built before 1990, global "gross" specific emissions (CO_2 generated without taking into account the part that is capture in CCS) are supposed to average 0.75 tCO_2/MWh for coal plants, and 0.4 tCO_2/MWh for gas plants.

When taking CCS into account, our scenario provides the following trajectory for worldwide CO_2 emissions in the electricity sector, with a final level in 2050 that is 61-62% the 1990 level, and 42% the 2002 level.

LCES scenario: global CO_2 emissions from the electricity sector

GtCO2		2002	2010	2020	2030	2050
CO2 emissions without capture	coal	6.6	8.0	8.2	7.5	5.6
	oil	0.9	0.9	0.8	0.7	0.0
	gas	1.9	2.5	2.9	2.6	1.4
	total	9.4	11.5	11.9	10.7	6.9
CO2 capture-storage		0	0	0	0.3	3
Effective CO2 emissions, net of CCS		9.4	11.5	11.9	10.4	3.9



The total amount of CO_2 stored by 2050 in LCES is around 30 $GtCO_2$, i.e a third of the amount accumulated in Poles factor 4 (90 $GtCO_2$). This difference is consistent with the fact that, in LCES, Carbon Capture and Storage (CCS) is developed massively 20 years later than in Poles factor 4.

A sensible geographic breakdown of CO_2 emissions and CCS in 2050 is given below:

	world	OECD	non OECD	
coal	5550	1200	4350	<== CO2 that would have been emitted without use of CO2 capture technology
gas	1360	560	800	
CCS	3000	1000	2000	<== volume and part of CO2 that is captured and stored through the using of CCS technology
	43%	57%	39%	
TOTAL	3910	760	3150	<== CO2 emissions, net from CCS

([17]) Figure to be taken as an upper bound, as it assumes that cumulated generation in TWh requires gas fuel for plants with an average efficiency of 38%.

In this breakdown, the major part of fossil fuel plants in industrialised countries integrates a CCS technology. In the developing world, we suppose that less than 40% of fossil plants integrate such a technology, developed only with plants built after 2030.

The regional emission levels in 2030 and 2050 are compared to 1990 emission levels in the table hereafter. When looking at 2050 and 1990 levels, we see that emissions are nearly divided by a factor of 5 in OECD countries, while their level increases by 10% in non OECD countries (a figure which can aggregate both drastic reductions in economies in transition and a doubling of emissions in major developing countries).

Additional CO2 emissions relatively to 1990 levels

	world	OECD	Non OECD
IEA 2030	+101%	+30%	+190%
LCES 2030	+71%	+8%	+148%
LCES 2050	-39%	-78%	10%

As a result, we observe a relative convergence of emissions per capita across the two different regions.

(iii) Nuclear power

In LCES, world nuclear generation is at twice its 2002 level in 2030 (in IEA alternative, capacity installed in 2030 is only 26% higher than in 2002), and at nearly four times the 2002 level in 2050.

This development of nuclear is significant but possible: at the world level, it means respectively 20% and 31% shares of electricity generation in 2030 and 2050 against 16% in 2002, i.e. building around 1440 GW in 45 years, or 32 GW per year in average worldwide. Moreover, in LCES nuclear power is only developed in regions that do already use it today (OECD countries, China, India, Russia).

As regards natural resource usage, prospects for conventional Uranium (14.4 million tons according to the IAEA), this leaves room for letting existing nuclear plants run the course of their life and developing fourth generation technologies beyond 2040 [18]. Thus in LCES, fourth generation technologies can progressively come on line as they mature, with no resource constraint bearing on the technologies available and used during the period (third generation).

(iv) Hydropower and other renewables

In our scenario, hydropower generation reaches 7,600 TWh in 2050, which does not fully stretch the economic potential that has been estimated over the last years. Our geographical distribution is consistent with the assessment of regional potentials, in particular in China, India, Latin America and Africa.

As regards other renewables, our scenario retains the same assumptions as in IEA alternative in 2030, which gives 2,600 TWh at the world level. This mostly comprises wind-power and biomass, and to a lesser extent geothermal. For 2050, our scenario adopts a 3,600 TWh generation from other renewables: combined with hydropower, this gives a total of 11,200 TWh, higher than in Poles factor 4 (9,000 TWh). This assumes that we know how to develop hydro projects taking into

[18] As already mentioned page11, the authoritative source OECD-NEA-IAEA (2003) indicates that these 14.4 million tons (known and undiscovered conventional sources) would allow 270 years of present annual use of uranium in nuclear plants, i.e. more than 60 years of annual use of uranium in a nuclear fleet 4 times higher than today (270/4=67.5), this without any fuel reprocessing.

account biodiversity and are prudent as regards breakthrough on electricity storage or new photovoltaic technologies.

All in all, the LCES scenario has interesting properties. It defines an investment and change path which would allow meeting long term GHG emissions objectives at the world level with a reasonable burden sharing between industrialised and developing countries. It supposes the use of decarbonising power generation technologies "in time", i.e. when they can do it at reasonable cost, and then a full use of their potential. It proposes acting immediately, rather than delaying action and betting on future technological disruptive innovations.

As we try to deploy low carbon technologies (CCS notably) at the right moment, and because hydro and nuclear technologies are fairly competitive even with no CO_2 price, the total cost per MWh for satisfying demand needs should not be higher in LCES than in business as usual scenarios.

However, the industrial picture drawn by LCES, especially with significant recourse to energy efficiency, hydro, nuclear, and CCS, is clearly more capitalistic than the "gas-coal picture" of business as usual scenarios; and a substantial part of the required investment takes place in developing countries. To gain plausibility, LCES supposes being in place public policies and elements of international cooperation that do not fully exist. We will tackle this series of key issues in the last part of the paper.

III. Enabling framework conditions for a low carbon electricity sector

Enabling conditions pertain to the content of national public policies (1) and their international architecture (2).

1. Public policy issues

We have started in this paper an analysis that aimed at assessing the state of maturity of the different low carbon and carbon-free technologies and the time and effort required to bring to maturity those which are more or less far from this development stage. On the basis of the preliminary results of this analysis, we have built an "adapted" investment path, i.e. a world investment program that would allow for the stabilisation of the sector's emissions at a satisfactory level at reasonable cost. This work brings to light the need for wider debate (A) and public policies in industrialised countries in line with technological diagnoses (B).

A. Need for general and wide debate

Before public policies can be defined and tailored to regional specificities, there is a need to debate upon the topics we have approached, namely to share facts and assumptions on:

- the constraints bearing on the development of low carbon generation technologies in terms of natural resources, industrial complexities and acceptability issues, and the means that could be used to optimise this development,

- the time-frames and efforts needed to bring the different generations of these low carbon technologies to maturity, and

- the outline of the business investment programmes that appear desirable from the viewpoint of climate change mitigation on the basis of the previous analyses, this with the purpose of building a widely shared "framework" vision (i.e. at the right level of detail) on those two topics.

Such debate is difficult to conduct because it is multidisciplinary[19] and because there has not been enough multidisciplinary work yet. We hope ours to be a useful stone on this path.

B. Public policies consistent with technological diagnoses and providing visibility

The state of the different electrical technologies, i.e. the analysis of their advantages, drawbacks and success conditions, suggests the need for conducting simultaneously in industrialised countries two categories of public policy (i). The required incentive investment framework is multiform, dynamic and provides visibility (ii).

(i) Need for simultaneous investment orientation and R&D support public policies

Energy-efficiency-improving technologies, CO_2-emission-reducing coal generation technologies and carbon-free generation technologies are at different "absolute" stages of development and different levels of control and deployment in the various world regions. We have, first, technologies within this decarbonising family, which are at "competitive stage" (building insulation and associated energy efficiency technologies; supercritical coal plants with increased efficiency, thereby reducing the amount of GHG emitted per unit of electricity generated; Generation 3 nuclear technologies; hydropower). They are used or about to be used for investment purposes in OECD countries but are little or not deployed in the developing world. Other renewables like windpower are at a pre-competitive stage. Carbon capture and storage technologies do exist but are not expected to be really in the market before the 2020's. Advanced electricity storage, third generation photovoltaic solar or Generation IV nuclear technologies look promising but still need lasting R&D efforts and will require in a later phase the building of industrial prototypes[20].

Consequently, the public policies that are required to give credibility to the virtuous electricity scenario we have sketched clearly belong to two categories:

- From now to 2030, we must implement public policies and rules encouraging actors to invest in energy savings and low CO_2 emission power generation technologies that are "in the market" or close to be, to an extent corresponding to the natural renewal of old power plants, i.e with no resort to accelerated decommissioning; within this framework, the barriers to achieving the substantial energy savings required in the low carbon scenario (multiplicity of actors, high transaction costs and rebound effects) deserve a specific treatment

- R&D organisation and support policies must be set up today, which keep all options open, with the purpose of bringing to market as soon as possible, in the 2030-2050 period, the most promising low carbon technologies.

If well designed, these policies should generate only moderate additional costs. Yet, as in the IEA alternative scenario, they will require high capital needs and thus great financing on both supply and demand sides. This may raise obstacles for developing countries, and thus raise the issue of

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([19]) Thinking and statements on energy and climate change are still fairly compartmentalised. Technology experts deal in depth with their technology; economists work on market design and structure; policy makers pick up scattered elements to build public policies which can bring results contrary to ultimate objectives although they use the right instruments, since they are designed to serving short term needs.

([20]) The French President, J. Chirac, recently expressed the wish to build a nuclear prototype of generation 4 to be put on line on 2020. If the experience were realised and proved to be a success, the prospects for putting on line reactors in series could follow, but reasonably not before 2035-2040.

articulating development and climate policy. We come back to this point after elaborating on the investment orientation policies themselves.

(ii) Differentiated and dynamic incentive investment framework providing visibility

As seen above, the technologies that need to be provided with incentives in industrialised countries break down into three categories: cost-effective end-use energy efficiency technologies, pre-competitive renewable generation technologies and ready lower-carbon fossil-fuel and carbon-free generation technologies.

Generally speaking, policies regarding cost-effective end-use energy efficiency technologies in industrialised countries should address the barriers to investing which hinder their deployment and include regulations restricting entries into energy efficiency markets, investors not fully receiving benefits generated, local equipment suppliers lacking the competences needed to correctly install and adjust the best equipment, and the lack of information, expertise and finance available to customers. To induce an early and massive deployment of carbon free renewable technologies like windpower, which are not yet competitive, it seems reasonable to use mass-subsidy schemes (purchase obligation with feed-in tariffs for energy suppliers, auctions or "green certificates"). To promote ready lower-carbon fossil-fuel and carbon-free generation technologies, industrialised countries can bring in taxes that increase with GHG emissions per unit of electricity generated. More direct action consists of introducing a cap and trade system (CTS), i.e. of setting emissions targets for the generation mix breaking down into emission allowances for emitters (caps) and allowing those emitters either to realise their reduction objectives through investment or to buy allowances on the allowance market (trade).

The issue at stake when one designs a CTS is that this system really orients long-life (from 15 to 60 years) investments in the right direction. To provide the right incentives, a CTS must provide long term visibility and address adequately the key issues of plant decommissioning, new investment projects and random price fluctuations in the allowance market. Providing the industry with long term visibility means first policy makers expressing clearly a will to conduct long-lasting and consistent over time GHG emission policies. Regarding the rule apparatus itself, we can derive from the US experience in organising SO_2 and NO_x markets some key features of a satisfactory system:

- rules governing the allowance market provide decades of visibility on global emission reduction objectives and emission allowance allocation among plants (30 years in the SO_2 market);
- allocations of emissions allowances to existing plants are not linked to future decisions about decommissioning them (they are given for a normative lifecycle);
- new plant projects buy allowances on the market or through auctions organised by public authorities;
- a "safety valve" (a ceiling price for allowances, and also a "price floor" if necessary) may be useful, to reduce the excessive impact of uncertainties due to random factors[21] and facilitate the convergence of expectations.

The European experimental "Emission Trading System" (ETS) shows that the devil is in the details of rule design and is … eager to create counter-incentives. The ETS sets CO_2 emission quotas for the electricity and CO_2-intensive industries and is in place for successive periods of respectively three years and five years; definition of national allowance (or permit) allocations has been left to the member states. Free allocation of CO_2 permits to new projects up to their expected emission

(21) In California, public authorities had to resort to a safety valve in response to the NOx market failure in the summer of 2000 (for a discussion of the case of California, see Bouttes, Leban, Trochet 2001). The original idea of a safety valve can be found in Weitzman (1974), and has more recently been favoured in Pizer (1999), Ellerman, Joskow, Harrison (2003), the US National Commission on Energy Policy (2004) and Cournède & Gastaldo (2002).

level in some countries and the anticipation by many players that their allocations for the next period could be based on their present emissions (because of the absence of long-term rules of the game) fall down to incentives to develop CO_2 high emitting technologies. What is wrong here is the principle of periodic rule renegotiation. On the contrary, the electricity sectors of some countries have received barely sufficient allocations not taking into account the volatility of emissions according climatic or technical hazards; as a result, electricity companies in these countries must buy allowances on the market; Since, on this short horizon, the only leeway to save CO_2 lies in substituting generation from existing gas-fired plants with generation from existing coal-fired plants and substitution volumes are limited by interconnection capacities, prices of allowances (i.e. of avoided CO_2) for the two years to come have climbed to 25-30 € per ton, which drives electricity prices to heights and could endanger the competitiveness of electro-intensive producers for almost no environmental benefit ([22]). Beyond the proper rules of the game detailed above, what could be missing here is a "safety valve", i.e. a ceiling for CO_2 price ([23]).

When a good design is in place, the issue at stake in running the cap and trade system is to articulate action to mitigate climate change, development and competitiveness. The emission target levels for each period of time are to be fixed having in mind the objective pursued in terms of cumulated emissions over time, effective reduction possibilities and the timetable of technology maturation. This target setting is crucial since it conditions the trajectory of the price of CO_2 and thus the technological choices regarding new plants. If targets (i.e. emission reduction objectives) for a given period must be "ambitious enough", i.e. such that they oblige players to achieve effective reductions (the long term objectives of emissions reduction in industrialised countries amount to a 3% average decrease yearly), they should not be "too ambitious", in order not to drive energy prices up for a small environmental benefit or/and push into the generating mix certain low carbon technologies "too early", i.e. before they are mature for wide deployment. We have seen that setting ambitious objectives in Europe for the 4 to 5 years to come (which is the time required to build a plant) would be harmful. Costs of reducing emissions would be increased without environmental benefit since what matters is only the final level of cumulated emissions. In addition, as the cap and trade system is far from being working worldwide, the very high resulting electricity prices would harm European companies, especially the electro-intensive industrial sectors confronted with international competition and, at the end of the day, we could observe CO_2 "leakage" (relocation of production to escape quotas and costless emissions at the new production place. On the contrary, it is reasonable to set ambitious targets the next ten to twenty years (all the more as the USA and China have chance to participate on this horizon) Having in mind that gas plants are today outclassed in terms of cost by advanced coal, nuclear and/or hydro technologies (depending on the country concerned) and that CO_2 capture and storage could be mature for mass development, with an average implicit cost of €30 per ton ([24]) when compared with a standard coal plant by 2025-2030, we might come up with a "right" price for CO_2 well below €10 per ton today and increasing progressively up to €25-30 per ton by 2020-2025 [25] .

([22]) As it can be seen, the energy context has dramatically changed since the 1990's. At that time, gas prices were low, overcapacity was prevalent in some European countries and we were not yet thinking in terms of stringent CO_2 objectives for 2050. In such a context, substituting existing gas for existing coal resulted in a CO_2 price of under €10 per ton. In long run perspective, building CCGTs instead of coal plants would have been preferable. This perspective is no longer relevant.

([23]) For more details concerning the pertinence of a safety valve, see Bouttes 2005.

([24]) As we have said, estimates of the cost of CCS range today from $ 50 to $ 80 per ton of CO_2, but we hope that, with R&D, we will be able to bring these figures down to $25-40/t$CO_2$ by 2020-2030.

([25]) This mid-term CO_2 price of 30€ per ton is low, compared to the figures currently used in the transport sector (over 100 €/ton of CO_2). The CO_2 abatement costs in this sector are ten times or more higher than what we think as necessary in the electricity sector because they are assessed in the framework of public policies mainly acting on energy prices to change mobility behaviours (which is a way to recognise that acting on the sources of mobility and bringing to maturity low carbon transport technologies are long-term tasks). This is not a point in favour of working with a single CO_2 price for the two sectors, i.e. of

Of course, the idea behind this assessment is not to publish a table of future emission targets and CO_2 prices for the 30 years to come. It is to set up some kind of "revolving strategic plan", qualitative in the far future and giving some quantitative indications in the three to ten next years, and based on a thorough discussion regarding technologies and CO_2 objectives. Wrong signals must be avoided at any time, as they are likely to jeopardise the credibility of the system. In parallel, we need a mechanism to induce investment in developing countries that uses the best available clean technologies. This brings us to our last point about the desirable international cooperation architecture.

2. International architecture for national public policies

Our low carbon electricity sector (LCES) scenario is consistent with a "S550" world emission profile, i.e. with the stabilisation of the GHG concentration in the atmosphere at an acceptable level (550 ppm). In this scenario, the yearly CO_2 emissions due to electricity decline from 2020 worldwide. Compared to 1990 levels, they are divided by 4 in OECD countries, including the USA, while they increase by around one third in advanced developing countries like China and India. 50% of the required investment is realised in developing countries using the best available power generation technologies. In other words, the scenario assumes the participation of the USA and is compatible with substantial growth in developing countries, provided that their investment in generation is adequate in volume and content. This scenario requires R&D public policies involving a substantial amount of international cooperation and investment frameworks that incite to use lower carbon technologies with the right timeframe both in OECD and non OECD countries. Those national investment frameworks clearly need to take place in international policy architecture. We will recall the work done in this matter of international governance (A) and the specificities of the situations of the USA (B) and China (C) before throwing in some ideas about the future (D).

A. Today international policy architecture

The United Nations Framework Convention on Climate Change (UNFCCC), signed by 189 countries, reflects worldwide consciousness of climate change risks and has put up the right worldwide objective: "stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". Its governing body, the Conference of the Parties (COP) has decided that only developed countries would have the obligation to reduce their emissions. Binding quantified emission targets have been accepted only by industrialised countries, excluding the USA and Australia and for a short time period (until 2012) within the Kyoto protocol. There are also multiple partnerships in R&D and governmental dialogues outside official negotiations on climate change (G8 meetings for instance) which deal with climate change issues.

Given the outlook for the changes on emission trajectories required to meet long term GHG objectives, the distribution of global CO2 emissions in the 10 to 20 years from now and the time-frame of clean technologies development, we clearly need a long term commitment scheme which includes all major emitting countries and thus takes into account the situations of the USA and advanced developing countries like China.

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implementing an across-the-board emission trading system, as long as the relevant public policies for the transport sector are not in place.

B. The case of the USA

The USA is the biggest emitting country. In 1995-2000, there was not wide public support for strong climate policy since climate change was not yet perceived as a major issue. The emission reduction objectives proposed in the Kyoto framework appeared too costly and likely to create a rent for countries like Russia, Ukraine and Kazakhstan[26]. The US Administration and the Congress explained that it was preferable to focus on R&D in hydrogen and CO_2 capture and storage and turn to reducing emissions when those technologies were mature.

Perspectives have somewhat changed since then. Following IPCC third assessment report in 2001, climate change is now considered as a real issue. The Energy Bill enacted on August 2005 provides incentives to investing in CO_2 free and lower carbon technologies. The federal government still refuses to get into any system with binding timetable of emission reductions but has accepted at the December 2005 COP in Montreal to discuss the topic under UNFCCC. Moreover, a lot of initiatives are being taken within the country: the North Eastern States have adopted quantitative objectives of emission reduction; the Mc Cain-Lieberman bill proposal contained an emission reduction profile and was near to obtaining a majority of votes; the Chicago Board Exchange has created a CO_2 exchange on the basis of companies' voluntary reduction commitments; some power generators who own a lot of coal plants are deploying a strategy of control of their emissions in order to anticipate possible future claims for drastic reductions and litigations making them responsible for environmental damages. The position of the USA at the federal level should thus evolve in the next ten years and R&D policies should be less opposed to economic instruments.

Three points must be kept in mind, however, by anyone who wants to get the country into an international commitment system: the USA has the biggest coal reserves in the world (around 200 years at present rate of use) and a geology probably favourable to carbon storage; the prominent role of private transport over long distances reflects the American way of life; the country will never enter into arrangements that might penalize its competitiveness with respect to China and other regions.

C. The case of China

Economic development is the key priority. The government wishes to go fast but is conscious of the challenges that will have to be met: according to the objectives expounded by the leaders of China in 2002 ([27]), China would become a "well-off society" by the year 2020, when the country's GDP is quadrupled from that of 2000; while the proportion of urban population goes up considerably, the widening gap between industry and agriculture, between urban and rural areas and between regions would have been reversed; the massive demographic transition would become a major challenge by 2020-2030; pollution is seen as a mounting one as of now.

Proven national gas reserves are fairly moderate: 1676 bcm (billion cubic meters), equal to less than 52 years of production from 2002, according to WEC 2004 b. Distance aside, national coal resources are extensive but not unlimited: the ratio of proven recoverable reserves (114 500

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[26] These countries had "hot air", i.e. benefited from emission quotas higher than their actual emissions, because they had experienced an economic depression since 1990, the reference year. The USA would have had to consider buying allowances from them.

([27]) Source: the 16th Congress of the Communist Party of China, 2002.

million tonnes) to 2002 production (1,393 million tonnes) is 82 years[28]; if annual generation were to be multiplied by two[29], the ratio would be less than 50 years.

In consideration of these stakes, China is eager as of today to use coal and gas in the most efficient manner, i.e. to adopt the best available fossil fuel technologies and to rely on the economic potential of energy efficiency improvements, nuclear power, hydroelectricity, and other renewables [30]. It seems to be willing to reconcile development and climate change mitigation as early as possible.

To achieve this, China will require significant technology transfers and foreign direct investment, having in mind that the country has a high domestic savings rate.

D. Desirable features for a climate policy international architecture

It is clear that the participation of developing countries in the shaping of global climate change policy cannot be delayed until their level of revenue per inhabitant reaches that of industrialised countries: in order to reach ambitious GHG concentration goals (550 ppm in CO_2 equivalent for instance), the developing countries must reduce emissions in relation to their "baseline" before reaching OECD countries' GDP/inhabitant or CO_2/inhabitant ratios[31]. As the major emitting country, the USA cannot be left aside. We need them in a global commitment scheme as soon as possible.

A variety of schemes has been studied in recent years[32]. Reasonable properties in terms of international equity and acceptability for a commitment scheme are it to be "multi-stage" and to provide for some convergence of per capita emissions in the long run. Regarding developing countries, typical multi-stage schemes provide for: no commitment in stage1, emission limitation targets in stage 2 and absolute emission reduction targets in stage 3. Defining the thresholds used for the transitions from one stage to another is a key issue, as is the degree of convergence of per capita emissions in the different regions aimed at on the long term horizon (2050 or 2100). For advanced developed countries like China, it could make sense in stage 1 to consider "non binding commitments" instead of no commitment, i.e. emission quotas that those countries could exceed without penalties but would be incited not to exceed since they are allowed to sell emission permits in case their emissions are below quota.

In the short run and beyond 2012 for developing countries that will remain without commitment, Clean Development Mechanisms (CDM) constitutes an interesting tool to enlarge the scope and decrease the cost of mitigation efforts. Implementation of CDM to date, however, has been limited: electricity projects are small scale, administrative and development costs are high, and there has been effective exclusion of some of the most efficient technologies in terms of both development and limitation of CO_2 emissions. It would be useful to broaden the field of "qualified" technologies, i.e. to include technologies such as energy efficiency programs and large hydro, nuclear and carbon capture & storage projects.

([28]) This is a lower bound. The figure does not include estimated additional amount in place and estimated additional reserves recoverable. These data are not available for China in WEC 2004.

([29]) IEA alternative forecast for 2030 is 2,960 TWh in 2030, versus 1293 TWh in 2002

([30]) Because of local pollution and local scarcity (three quarters of proven recoverable reserves of coal are in the north and north-east-west according to WEC 2004 b), new coal generation plants and large hydro dams need to be built in areas farther from the eastern, urban area of China, and require the development of the transmission grid (Source: comments by Zheng Baosen, Executive Vice-President, State Grid Corporation of China, on 18-19 October 2005 in Moscow, IP Energy Strategy Meeting of the World Economic Forum).

[31] One-third of the world's population does not yet have access to electricity.

[32] See for instance, Lepii-EPE et al. (2004) or Ghersi, Hourcade et Criqui (2003).

More generally, development aid mechanisms must be somewhat redirected towards climate change mitigation and strengthened, in order to ensure that climate issues provide an opportunity for rather than a constraint on development. This means combining financing from international institutions with foreign direct investment and domestic investment in large scale projects realised within robust cooperative frameworks. This means, too, implementing technology transfer programs (regarding demand and supply) that reduce CO_2 emissions in developing countries, with compensation of host countries for the cost of emission reduction.

If it seems technologically feasible, our low carbon electricity scenario clearly needs the national incentive public policies we have gone through and the elements of international cooperation just mentioned to be in place.

Concluding remarks

The first aim of this paper was to start an analysis of CO_2 free or low CO_2 emitting technologies, making a real distinction between the technologies that are already available for major investment decisions and the technologies that still require R&D efforts and technological breakthroughs to make them economically viable and available as soon as possible. Based on this analysis and taking into account "natural" investment opportunities over the next decades, we have built a "factor 4" scenario for the electricity sector in which increasingly ambitious CO_2 emission targets are met in the next 20-30-40 years, without unnecessary and costly reduction target in the next 5 to 10 years.

We have also sketched the enabling framework conditions for such a scenario, namely: on the one hand national public policies in industrialised countries which organise and support the R&D necessary to bring clean technologies to market as soon as possible and provide electricity companies with the right incentive to invest in lower carbon available technologies without inducing disproportionately high electricity prices; on the other hand elements of international policy architecture which encourage North-South technology transfers and realisations of emission reducing investment projects in developing countries, so as to attract at best and soonest their participation.

We will have reached our goal if, so doing, we have defined paths for future in-depth research. As a follow-up to this paper, we are conducting further analyses on energy efficiency and regional scenarios.

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