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Abstract

There is a revival in the nuclear debate observed in the literature. Most of the emission scenarios of the Intergovernmental Panel on Climate Change (IPCC) show an important role for nuclear energy to satisfy energy demand in the long term. Moreover, several analyses have shown that nuclear technologies may represent very attractive options for greenhouse gas (GHG) emission reductions, especially in developing countries with high growth projections for energy demand. Our objective is to analyze the role of nuclear energy in long-term climate scenarios using the World-TIMES bottom-up model. World-TIMES is a global model with 15 regions that optimizes their entire energy system over a 100-year horizon (2000–2100).

We present energy and emission results for climate scenarios for two levels of CO_2 concentration (450 and 550 ppmv by 2100). We specifically analyze the penetration level of nuclear energy in these scenarios, under various sets of assumptions on technology parameters and exogenous constraints on nuclear energy development to reflect social perceptions.

We highlight the fact that nuclear technologies satisfy most of the electricity production in all scenarios. The 450 ppmv scenario imposes very stringent technological changes. Most regions experience an energy transition based on advanced oil and gas technologies and by developing hydropower at the maximum potential. Other renewable technologies could play a more important role, but need further cost reductions or new regulations to penetrate the market in substantial proportions. Carbon sequestration and endogenous demand reductions for energy services are also significantly contributing to reach environmental target.

Key Words: Nuclear energy, World-TIMES model, Climate scenarios.

Résumé

Il y a un regain d'intérêt observé dans la littérature à propos du débat nucléaire. La plupart des scénarios d'émissions du Panel intergouvernemental sur les changements climatiques (IPCC) montrent le rôle important de l'énergie nucléaire pour satisfaire le demande énergétique à long terme. D'ailleurs, plusieurs analyses ont montré que les technologies nucléaires représentent des options très attrayantes pour la réduction des émissions de gaz à effet de serre (GES), particulièrement dans les pays en développement où la croissance prévue de la consommation énergétique est très élevée. Notre objectif est d'analyser le rôle de la filière nucléaire dans les scénarios climatiques de long terme avec le modèle World-TIMES. World-TIMES est un modèle global de type 'bottom-up' qui permet d'optimiser le système énergétique de 15 régions mondiales sur un horizon de 100 ans (2000–2100).

Nous présentons les résultats d'énergie et d'émissions pour deux scénarios climatiques visant la stabilisation de la concentration de GES à 450 ppmv et à 550 ppmv en 2100. Nous analysons plus spécifiquement le niveau de pénétration de l'énergie nucléaire dans ces scénarios, selon diverses hypothèses au sujet des paramètres technologiques et contraintes exogènes sur le développement de la filière pour refléter certaines perceptions sociales.

Nous mettons en évidence le fait que les technologies nucléaires satisfont la majeure partie de la production d'électricité à long terme, et ce, dans tous les scénarios. Le scénario 450 ppmv impose des changements technologiques majeurs dans le système énergétique des régions. La plupart des régions voient donc une transition vers des technologies propres de production d'électricité à partir du pétrole et du gaz, et développant au maximum leur potentiel hydro-électrique. D'autres technologies renouvelables pourraient jouer un rôle plus important, mais des réductions de coûts importantes ou de nouvelles réglementations seraient nécessaires pour assurer la pénétration du marché dans des proportions substantielles. La séquestration du carbone et les réductions endogènes des demandes énergétiques contribuent également de manière significative à l'atteinte de la cible environnementale.

1 Introduction

According to the energy and emission scenarios of IPCC, the primary energy consumption is expected to increase by a factor varying between two and seven times by the end of the 21st century, depending on various demographic, technological and economic growth assumptions (Nakicenovic and Swart, 2000). In all projections, the world energy consumption is expected to increase, particularly in developing countries (Duffey, 2005; Fiore, 2006). Consequently, there is an important potential for fossil fuels substitution or avoidance in meeting the future energy needs of the developing countries. Moreover, an energy growth based mainly on fossil fuels is by no means assured to be feasible, at least at the current level of fossil fuel price, and if feasible would lead to considerable increases in GHG emissions.

Indeed, a major stake of the 21st century is to devise strategies to produce more energy to satisfy the global needs, while reducing GHG emissions. Several renewable energy sources contribute to GHG abatement, and they might be suitable for less developed countries as relatively low capital demanding (except large hydro power plants) and decentralized options. However, their development on a large-scale basis faces important limits of economic and technical feasibility even if effective potential reserves are well documented. Nuclear power, a capital intensive and centralized technology, is foreseen as a long term and high performance option, and might contribute to climate policies as well as to energy security, considering the risk of high volatility prices of oil and gas on international markets (Fiore, 2006). However, the development of nuclear power has also some significant limitations, such as the risk of accidents and the production and management of radioactive wastes, contributing to a generally low social acceptation.

Our objective is to analyze the role of nuclear energy in two climate scenarios of the CO_2 concentration at 450 and 550 ppmv (parts per million volume) by 2100, using the World-TIMES bottom-up model. Using a detailed technology-based model such as World-TIMES represents an interesting contribution to global climate scenario analysis. More specifically, we analyze the penetration level of nuclear energy under contrasted sets of assumptions on technology parameters and exogenous constraints on nuclear energy development to reflect some negative social perceptions of nuclear power. Section 2 presents the current picture of nuclear capacity worldwide, and the prospective for nuclear power in future energy projections. Section 3 describes the bottom-up energy model World-TIMES used to analyze the role of nuclear energy in climate scenarios. Section 4 includes energy and emission results for the base scenario (4.1), the two climate scenarios (4.2), and sensitivity analyses (4.3). The article ends with a conclusion (Section 5) on the main advantages and drawbacks of this approach, as well as future works.

2 Nuclear energy

After an increase of nuclear plant projects in the 70's and the 80's in the developed countries, the 90's were characterized by several cancelations of nuclear projects leading to a general stagnation of nuclear energy development. This trend was initiated by the electricity market deregulation, slower growth of electricity demand, negative public perception (after accidents at Three Mile Islands in 1979 and Chernobyl in 1986), and economic reforms in Russia and Eastern Europe (Omoto, 2005). Today, 441 nuclear power reactors are in operation in 31 countries around the world, and the world nuclear generating capacity represents 360 GW, generating approximately 2500 billion kWh (kilowatt-hours).This capacity is expected to increase by 2025 to about 420 GW in a reference scenario and 450 GW in a Kyoto-like scenario (EIA, 2005). In addition, most of the IPCC emission scenarios show an increasing role for nuclear energy to satisfy energy demand on the 2100 horizon (Nakicenovic and Swart, 2000).

Indeed, it is accepted overall that long-term energy and environment strategies should be characterized by a transition from fossil fuels to renewables (hydroelectricity, solar, wind, and biomass) or other non GHG-emitting energy. Nuclear technologies could contribute to the production of non GHG-emitting energy. Their main advantage is their capacity to produce large amount of energy, on an uninterrupted basis, from a small amount of primary resources. Moreover, this option relies on abundant resources, and consequently, represents a stable energy source on the long term, without large price fluctuations as for fossil fuels. Finally, considering the future economic growth and energy needs of developing countries, the development of nuclear energy is more and more considered as a valid option in a global strategy of sustainable development (Duffey, 2005; Omoto, 2005).

Nevertheless, their development still induces a legitimate debate in the public opinion. The generation of radioactive wastes and their disposal represent important shortcomings and the public perception remains negative. In addition, although the risk of accidents in nuclear fission reactors has a very low frequency of occurrence, the damages to the population are much more severe and large areas can be contaminated for hundred years by radioactivity (as much as 1000 square kilometers for the Chernobyl accident) (Kessler, 2002).

In spite of these limitations, there is a clear revival of nuclear energy in long-term projections to fill an important part of the gap between the current capacity and the future energy needs of developing countries without increasing GHG emissions. About 30 power reactors are currently being constructed in 11 countries, notably China, South Korea, Japan and Russia. The International Atomic Energy Agency has also significantly increased its projection of world nuclear generating capacity (at least 60 new plants in the next 15 years), based on specific country programs together with the changed outlook due to the Kyoto Protocol. The fastest growth would be in Asia. Many countries are investing in nuclear research and development, encouraging the current or future penetration of new nuclear technologies. For instance, the European pressurized water reactor (EPR); the Advanced CANDU reactor (ACR) in Canada; the Generation IV nuclear systems developed within an eleven-member R&D consortium, or the ITER (International Thermonuclear Experimental Reactor) project for nuclear fusion. The ITER project is one of the most important scientific collaboration currently in elaboration (Fiore, 2006).

India is a specific example of country with a high projected growth in energy demand for the next decades. In fact, India has to consider all available options to meet the future demand, "including using the known fossil reserves efficiently, looking for increasing fossil resource base, competitive import of energy, harnessing full hydro potential for generation of electricity and increasing use of non-fossil resources including nuclear and non-conventional" (Grover and Chandra, 2006). For this purpose, the Indian Department of Atomic Energy initiated a nuclear program. The objective is to increase the nuclear proportion for electricity production from 3% to about 25% and to reach 20 GW of capacity by 2020 from various types of reactors, in order to limit energy imports to the current level (about 30%), during the first half of the century (Grover and Chandra, 2006).

3 Methodology

3.1 World-TIMES model

The World-TIMES model is used to analyze the role of nuclear energy in long-term climate scenarios. TIMES (The Integrated MARKAL-EFOM System) combines all the advanced features of MARKAL (Market Allocation) models, and to a lesser extent of EFOM (Energy Flow Model Optimization) models. The equations of the initial MARKAL model appear in Fishbone and Abilock (1981) and numerous improvements of the model have been developed since then for various applications (Kanudia et al., 2005; Kanudia and Loulou, 1999; Labriet et al., 2006). Currently, MARKAL and TIMES models are used in more than 80 institutions in 50 countries for various purposes including economic analysis of climate policies. The full technical documentation of the TIMES model is available in Loulou et al. (2005).

TIMES is a linear programming model that represents the entire energy system of a country or a region. Such a system includes the extraction, transformation, distribution, end-uses, and trade of various energy forms and some materials. Each economic sector is described by means of technologies, each of which is characterized by its economic and technological parameters. End-use demands (i.e. energy services) in the base case are based on socio-economic assumptions and are specified exogenously by the user in physical units (number of houses, commercial area, industrial production, vehicle-kilometers, etc.) over a future horizon. However, contrary to traditional bottom-up models, TIMES acknowledges that demands are elastic to their own prices. This feature insures the endogenous variation of the demands in constrained runs (on emissions or concentrations), thus capturing the vast majority of the macroeconomic feedbacks on the energy system. TIMES computes a dynamic inter-temporal partial equilibrium on integrated energy markets. The objective function to maximize is the total surplus. This is equivalent to minimizing the total discounted system cost while respecting environmental and many technical constraints. This cost includes investment costs, operation and maintenance costs, plus the costs of imported fuels, minus the incomes of exported fuels, minus the residual value of technologies at the end of the horizon, plus the welfare loss due to endogenous demand reductions.

Emission reduction is brought about by technology and fuel substitutions (which lead to efficiency improvements and process changes in all sectors), by carbon sequestration (including CO_2 capture at the power plant and hydrogen plant level, storage in oil/gas fields, oceans, aquifers, etc. and sequestration by forests) and by endogenous demand reductions. The main model outputs are future investments and activities of technologies at each period. An additional output of the model is the implicit price of each energy form, material and emission, which is equal to its opportunity cost (shadow price).

The model tracks emissions of CO_2, CH_4, and N_2O from fuel combustion and processes. The climate module of the model starts from global emissions and successively computes the change in CO_2 equivalent concentrations in three reservoirs (atmosphere, upper ocean/biosphere, deep ocean), the resulting change over pre-industrial in atmospheric radiative forcing and the global mean surface temperature changes over preindustrial level in two reservoirs (atmosphere/upper ocean, deep ocean). This module is adapted from Nordhaus and Boyer (1999) climate equations, and the complete description is available in Loulou et al. (2005).

The objective function of the World-TIMES model is the sum of the system costs of the individual regions. Costs are expressed in US$ and discounted at 5% to year 2000, in all regions. The World-TIMES model is run over a 100-year horizon (2000-2100) and comprises 15 regions: United States (USA), Canada, Mexico, China, India, Japan, South Korea, Australia, Western Europe, Eastern Europe, Former Soviet Union (FSU), Africa, Central and South America, Other Developing Asia and Middle East.

3.2 Nuclear power plants

The World-TIMES model database used for the analysis includes about 1,300 technologies used for energy production and consumption This figure comprises of over 50 centralized and decentralized electricity power plants, including conventional fossil fuel plants (conventional pulverized coal, integrated gas combined cycle (IGCC), combined cycle gas turbine (CCGT), internal combustion, etc.), nuclear power plants, hydroelectricity, biomass and other renewable power plants such as geothermal, solar, wind and tidal. Biomass includes energy derived from wood, crops, biogas and waste. More specifically, the database includes five types of nuclear power plants, based on the following different types of reactors:

- Light Water Reactor (LWR): This type of second-generation reactors, represents 90% of the reactors currently in use worldwide (NEA, 2005). LWRs include Pressurized

Water Reactors (PWR) and Boiling Water Reactors (BWR). They were first developed in the USA, as well as in the FSU (OECD, 2001). This technology has been available from the first period of the model (2000). Presently, nuclear power is produced in all regions, except in the Middle East and Australia. After their useful time life, LWRs are replaced by more advanced types of reactors.

- Advanced Light Water Reactor (A-LWR): This is the advanced version of the LWR characterized, amongst other things, by lower investment and operational costs, a higher availability factor, longer lifetime, etc. This category includes third generation reactors, available in this decade (Hamacher and Sheffield, 2004). This is the most common technology available to replace the existing LWR in the short term. Indeed, A-LWRs represent 80% of the reactors currently under construction (NEA, 2005).
- Pressurized Heavy Water Reactor (PHWR): This type of reactors, less common than LWR, represents 5% of the reactors currently in use and 15% of the reactors under construction. It includes amongst others the Candu (Canada Deuterium Uranium) reactors, designed by Atomic Energy of Canada. At this time, they have been built in five countries other than Canada: Argentina, China, India, Romania, and South Korea and other reactors are under construction in India and Romania (EIA, 2006).
- High Temperature Gas-Cooled Reactor: The availability of these fourth generation reactors on the market is planned for around 2030. Developed in the UK, there are presently projects in several countries using this type of technology, such as the Pebble Bed Modular Reactor (PBMR) planned for construction in South Africa (OECD, 2001). These reactors use helium as the coolant rather than water.
- Fusion power reactors (few reactors are being studied): Nuclear fusion is currently under development through the ITER project (with a tokamak type reactor). The availability of this technology for commercial uses is planned for 2050, according to the average estimate (Fiore, 2006; Hamacher and Sheffield, 2004; Tokimatsu et al., 2003).

While the first four types of reactors are based on nuclear fission, using uranium, the last type of reactors is based on nuclear fusion, using tritium produced from lithium. The uranium reserves are modeled using a four-step supply curve, while the lithium reserves are considered unlimited. Indeed, reserves of lithium will be available for a thousand years (Fiore, 2006). The costs of fission and fusion technologies described above are based on the literature (Beckjord, 2003; NEA, 1998, 2005; OECD, 2001; Tokimatsu et al., 1998). Costs of all power plants are regionalized.

The minimal level of nuclear production is fixed exogenously at the level obtained in the IPCC B2 marker scenario, since decisions to invest in nuclear power plants in non-intervention scenarios (without a constraint on the global GHG concentration), are based on various factors other than economics. As for the renewable energies, their potentials come from the literature. The regional potentials for hydroelectricity in 2050 reflect the potentials technically exploitable as given by the World Energy Council, and their values increase between the potentials technically and theoretically exploitable in 2100.

The totals of energy and emissions for the base scenario are presented in Section 4, and the results for two climate scenarios are presented in Section 5.

4 Base case

The base year period (2000) of the model is calibrated to the IEA (International Energy Agency) statistics and balances for that year (IEA, 2000). The future energy demands are projected to the 2100 horizon using various socio-economic drivers, which are consistent with the storyline behind the B2 family of IPCC scenarios. The B2 storyline describes a world based on local solutions to sustainable development, and is characterized by a medium population growth, a relatively low economic growth and a slower, but more diverse technological change in general (Nakicenovic and Swart, 2000). Figure 1 shows the world primary energy consumption in the base scenario, as modeled by World-TIMES. The primary energy consumed at the world level increases from 418 EJ in 2000 to 998 EJ in 2100. Currently, fossil fuels satisfy most of the global energy demand (86%), with oil representing almost half of the fossil fuel consumption. The remaining demand for energy is satisfied mainly by biomass and other renewables (hydroelectricity, solar, wind and geothermal consumption (12%), while nuclear energy represents only 2% of the global primary energy (assuming a regional fossil equivalent of 3.11 on average). On the long term, fossil fuels remain the most important energy source (77%), however, with an increasing proportion of natural gas over the proportion of oil. The part of biomass and other renewables remain constant, meaning there are no economic or environmental incentives for these energy forms in a non-intervention scenario. As for nuclear energy, its proportion increases from 2% in 2000 to 13% of the global demand in 2100, and represents the energy form with the highest relative growth on the entire horizon.

As shown in Figure 2, the global CO_2 emission trajectory (only, and not of all GHG) of the base case is close to that of the B2 marker scenario of IPCC (Nakicenovic and Swart, 2000). It follows a moderate growth on the whole horizon to reach 12.8 gigatonnes of carbon (GtC) in 2100. In the first period, the emissions come mainly from the electricity sector (31%), the transportation sector (27%) and industry (18%). The emissions of the electricity sector increase gradually until 2050 and remain constant in the second half of the century, where the gradual replacement of coal power plants by oil and gas power plants in most regions and the construction of new nuclear power plants, counteract the increase in demand for electricity. In 2100, it still represents 31% of the global emissions. The increase of emissions in the transportation sector is low. Although the fuels consumed for road transportation remain mostly gasoline and diesel over the horizon, the penetration of more efficient vehicles contributes to moderate the increase in emissions (which represent only 17% of the total in 2100). Industries represent the sector where the emission growth

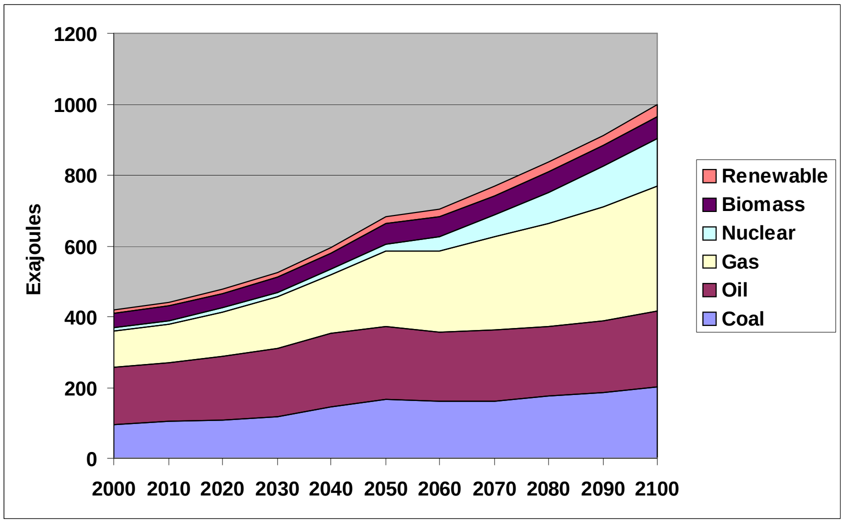

Figure 1: World primary energy consumption in the base scenario

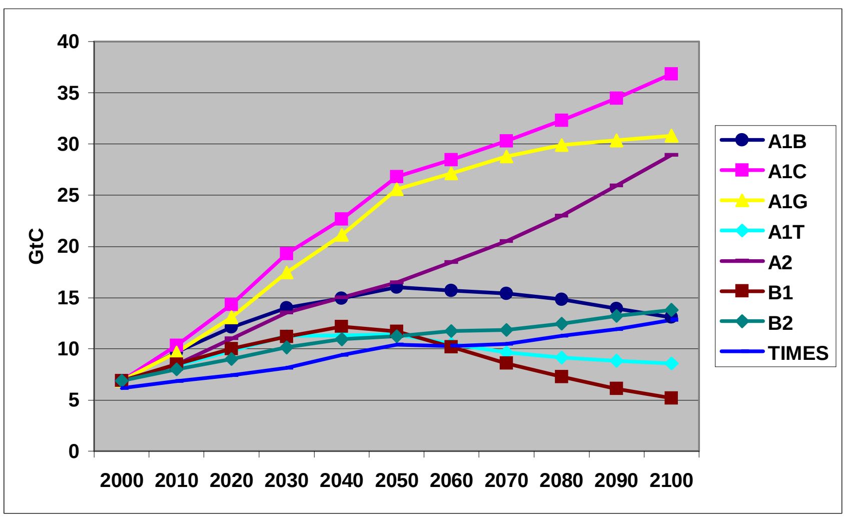

Figure 2: Comparison of global CO_2 emission trajectories

is the largest, mainly between 2020 and 2040 with an annual growth rate of approximately 2%. The industrial emissions reach 27% of the global emissions in 2100. Indeed, the energy demand growth in the industrial sector is important and there is no significant fuel switching. In other words, the fuel proportions remain more or less the same on the entire horizon.

To summarize, the base case describes a relatively moderate growth in primary energy demand, which is multiplied by a factor of 2.4 over the 100 year horizon, with emissions growing at almost the same rate (by a factor of 2.1). This indicates that the global emission intensity of the world economy would not really improved (from 13.9 MtC/EJ in 2000 to 13.0 MtC/EJ in 2100) if no environmental constraint is imposed.

5 Climate scenarios

The climate scenarios are characterized by the imposition of a constraint on the atmospheric global GHG concentration, to limit its level at 450 ppmv and at 550 ppmv by 2100 (however, only CO_2 emission results are discussed in this article). These levels were chosen because they are frequently used in energy studies (Morita, 2000); of course, they represent possible futures among many other possibilities.

In the base case, the GHG concentration reaches 584 ppmv in 2100. Consequently, the 550 ppmv scenario represents a relatively modest constraint on the CO_2 concentration level, compared to the 450 ppmv scenario, reflecting a less stringent environmental constraint, but involving higher climate adaptation costs in addition to the technological costs (only mitigation costs are included in this version of the model). In other words, any climate policy based on a higher concentration means accepting to pay for higher adaptation costs and lower mitigation costs.

5.1 Emission reductions

The World-TIMES model computes the optimal GHG emission trajectory to reach the global target in 2100 (Figure 3). Compared to the base scenario, the 550 ppmv target imposes minor reductions on the global emissions until 2040 and a 17% reduction in 2100. The 450 ppmv target imposes stringent reductions earlier: 12% in 2030, 28% in 2050 and 68% in 2100, compared to base case emissions. Over the century, the emission intensity would be only slightly improved in a 550 ppmv scenario (13.1 MtC/EJ), but significantly improved in a 450 ppmv scenario (4.9 MtC/EJ) compared to the base case.

The 550 ppmv target implies emission reductions mainly in the electricity and industry sectors, where the most cost efficient and largest opportunities of abatement exist. They experience respectively a 17% and 29% reduction in 2100. The 450 ppmv target represents a very stringent constraint, putting indeed more pressure on the various sectors. Figure 4 compares, for the base and the 450 ppmv scenarios, the emissions from the electricity sector and those from the other energy demand sectors separately. Industry represents the demand sector where the absolute reduction is the most significant, i.e. 3.2 GtC in 2100. The pressure is equally stringent on the electricity sector, which experiences a drastic reduction of 3.1 GtC in 2100 (an 80% reduction over the base case). Reductions seem far more difficult to reach in the transportation sector, with only 0.8 GtC. We analyze the

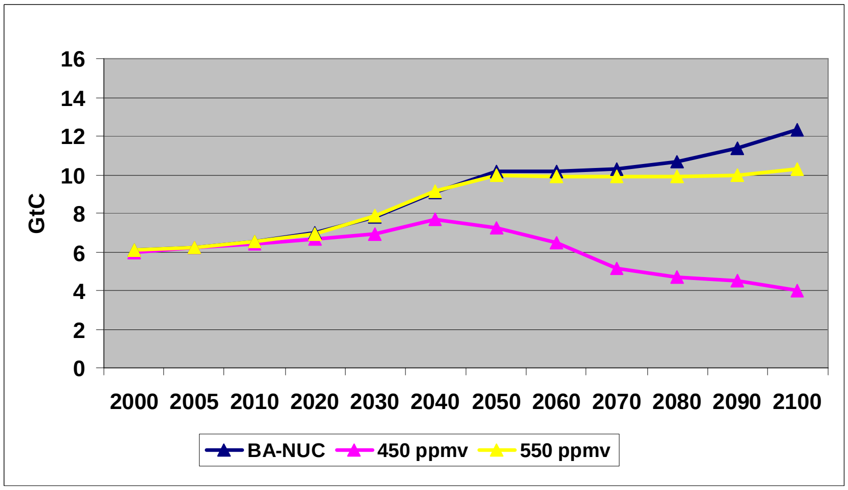

Figure 3: Global CO_2 emissions in the base and the climate scenarios

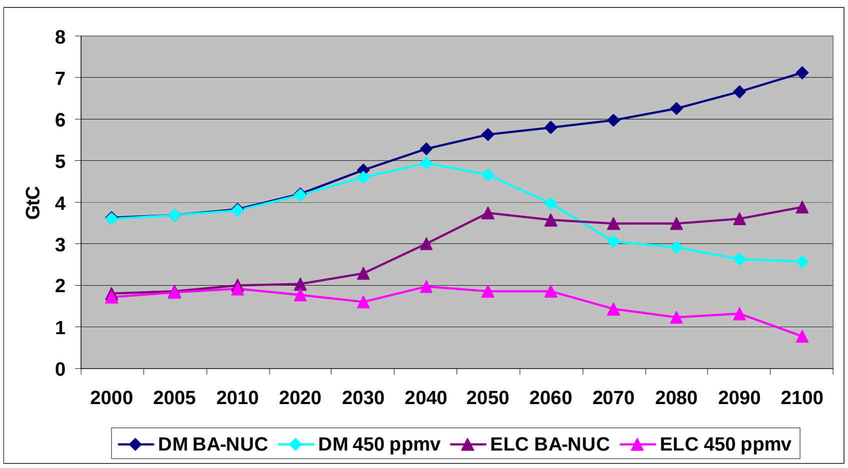

Figure 4: Emissions of the electricity and the demand sectors in the 450 ppmv scenario

emission reductions of the electricity sector in more details below, mainly for the 450 ppmv scenario.

Beforehand, it worth mentioning that emissions reductions are also due to reductions in energy demand and carbon sequestration. For example, in the 450 ppmv scenario, the demand for residential space heating is globally reduced by about 1000 PJ in 2100 compared to the base case. The sector for which the target has the most significant impact on energy demand is transportation: end-use demand for road transportation by cars is reduced by 436 billion vehicle-kilometers in 2100 (a 3% reduction from the base case), while the demand for domestic and international aviation is reduced by 23% in 2100. As for carbon sequestration, it contributes to reduce emissions by 2.0 GtC in 2100 in the 450 ppmv scenario, mainly in forests (1.4 GtC), but also in oil/gas fields, coalbed methane recovery, and deep oceans.

5.2 Electricity production

Large fuel substitutions occur in the electricity production sector. Figure 5 illustrates electricity production by energy type in 2050 for the three scenarios (the fuels are presented in the same order in the graph as in the legend). The total electricity production increases from 41 EJ in 2000 to 118 EJ (base and 550 ppmv) and 112 EJ (450 ppmv) in 2050. In the base case, the global electricity production is mainly satisfied by oil and gas plants (45%) and coal plants (25%), while nuclear and renewable plants represent respectively 18% and 12%. In the 550 ppmv scenario, fuel substitutions remain minor in 2050 and the proportion of nuclear remains at 18%. In the 450 ppmv scenario, larger changes are already occurring in 2050, where nuclear energy increases to 22% of the total electricity production. At the same time, one observes an important increase of renewable energy (mainly hydroelectricity), to the detriment of coal. Electricity production by natural gas power plants remains important since competitive CO_2 capture CCGT technologies are replacing conventional CCGT.

In 2100, the total electricity production reaches respectively 252 EJ (base case), 249 EJ (550 ppmv) and 258 EJ (450 ppmv). Although fuel substitutions are occurring later in the 550 ppmv scenario (after in 2050) than in the 450 ppmv scenario (already large in 2030), all scenarios suggest a major transition to nuclear energy in 2100, to respectively

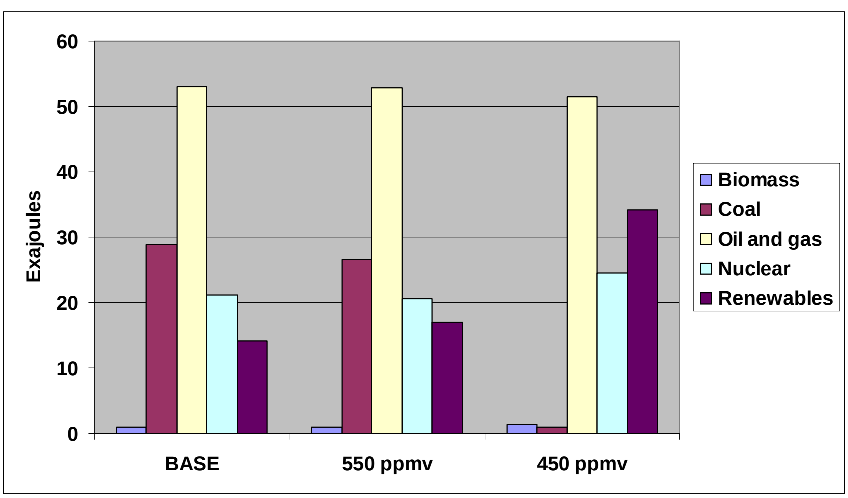

Figure 5: Electricity production by energy type in 2050

50%, 51% and 68% of the total electricity production. Renewable sources benefit also from this situation with a relative increase of 102% compared to the base case in the 450 ppmv scenario. On the other hand, fossil fuels experience a significant decrease of about 50%. Although coal increases slightly after 2060, since clean coal technologies with capture of CO_2 are available at competitive costs, even if nuclear energy is dominant and renewables have more than doubled.

5.3 Technological and regional analysis

This section details the evolution of nuclear power from a technological point of view. In the base case, the size of the nuclear market represents about 127 EJ of electricity production in 2100. The market is dominated by advanced LWRs (121 EJ in 2100), which gradually replace current LWRs, while PHWRs penetrate only in regions where such projects are already planned: Canada, China, Central-South America, Eastern Europe, India and South Korea.

Under the 450 ppmv scenario, the nuclear market size is particularly large in 2100, consisting in an annual production of approximately 175 EJ of electricity, a 20-fold increase over 100 years. This means more than 6 000 GW of new nuclear installed capacity by 2100, starting mainly from 2050 (Figure 6). Advanced LWRs will still dominate the market, but their total capacity will not increase compared to the base case (4500 GW in 2100). This stagnation in absolute value results in a significant decrease in their market share in 2100, i.e. from 95% to 69%. Even if nuclear production from PHWRs doubles compared to the base case and if these reactors penetrate the markets in the regions where projects are

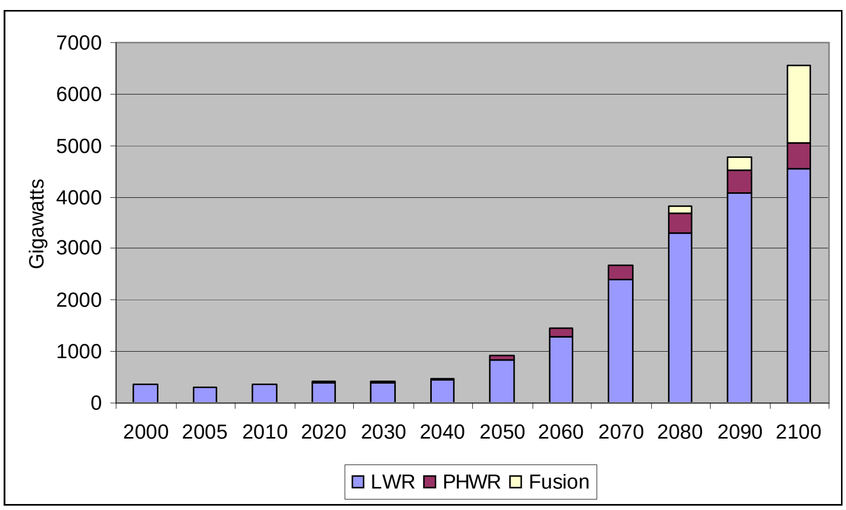

Figure 6: Evolution of the nuclear capacity under the 450 ppmv scenario

already planned, they would still be of only marginal importance on the global market in 2100, with an 8% share.

In fact, the incremental increase in nuclear capacity over the base case comes mainly from nuclear fusion; 1500 GW in 2100. Although nuclear fusion reactors are not entering the market as soon as they become available (2050), they quickly capture parts of the market, from 3.6% in 2080 to 23% in 2100. Nuclear fusions is developed mainly in the USA and Western Europe, with respectively 485 GW and 375 GW in 2100, and to a lesser extent in China, India and the FSU. In fact, nuclear fusion is expected to play an important role in transitional and developing countries, such as China, India, and South Korea, during the second half of the century (Hamacher and Sheffield, 2004). Based on the current assumptions about the techno-economic parameters of nuclear technologies, the gas-cooled reactors, available from 2030, will not penetrate the market at all.

Interesting facts regarding regional electricity production are highlighted here. First, it must be reminded that Asia and other developing regions, such as Africa and Central-South America, are areas where significant energy needs must be met by 2100. Consequently, important changes occur in the electricity sector of those regions, where production increases by a factor of 10. In developed regions, growth is approximately three-fold.

In the base case, most regions continue mainly using fossil fuels (without CO_2 capture) to fulfill electricity demand up to 2050, in extent varying from 40% to as much as 90% for the Middle East. The proportion of various energy types used for electricity production vary across regions according to the resources available:

- Coal remains important in Australia and China, while natural gas and oil are dominant in Eastern Europe, the FSU, the Middle East, Japan and Western Europe.
- In the FSU, natural gas and oil power plants represent a fast growing industry from 2020, peaking in 2080 with about 70% of the electricity demand. In the USA, the market shares of coal versus oil and natural gas are almost equal and remain constant until 2100.
- Only a few regions, where the hydroelectricity potential is high (Canada and Central-South America) or where the nuclear proportion is already high (South Korea), use fossil fuels for less than 30% of electricity production.
- Nuclear and renewable power plants start developing around 2050, indicating that those technologies become competitive to satisfy the energy demand growth, even in a non-intervention scenario.

In 2100, nuclear power represents the main energy source for electricity production in most countries, i.e. at more than 50% in nine regions, and represents almost the only energy source in South Korea. However, a few regions see their renewable potentials develop significantly, while other regions keep using fossil fuels (without CO_2 capture) in significant proportions:

- Renewables are used for more than 25% of electricity production in Canada, Central-South America, China, FSU and Western Europe.
- These regions essentially build hydroelectric dams, while Western Europe also develops its wind power industry by implementing decentralized power plants.
- In the USA, coal, oil and natural gas remain the main sources of electricity production over the whole horizon (68% in 2100).
- Similarly, natural gas remains an important source of electric power in Eastern Europe, the FSU, the Middle East, Japan and Western Europe.

In the 450 ppmv scenario, the global emission trajectory increases up to 2040 (as shown in Figure 3). Consequently, modest reductions are occurring and fossil fuels are still being used in large proportions in 2050 in many. However, in most scenarios, coal power plants are being replaced gradually by gas and oil power plants, in the first three decades of the century. Indeed, between 2030 and 2060, coal power plants are kept only in China. After this period, clean coal power plants start penetrating the market in several regions and consequently, the proportion of coal used for electricity production with CO_2 capture increases. However, in 2100, significant modifications occur in the electricity sector:

- Fossil fuel use remains very marginal overall, i.e. below 5% for nine regions. They are used significantly (around 20%) only in those regions (Australia, Eastern Europe, the Middle-East, the USA and Western Europe) investing in power plants with CO_2-capture features, mainly the Unites States (coal) ,the FSU and the Middle-East (natural gas).
- Nuclear power becomes, by far, the main energy source for all regions (51% in Australia and above 60% in the other regions), except for Canada, where renewables are used instead, for electricity production (at 63%).
- The regions where important natural gas reserves exist develop the nuclear industry to a lesser degree and later than the other regions (from 2060 or 2070).
- For some developing regions (Africa, Central-South America, Mexico, etc.), nuclear production does not increase with environmental constraints. Indeed, nuclear already accounts for a large proportion of their total electricity production in the base scenario (e.g. already 70% in AFR in 2100) and consequently, other renewables can replace fossil fuels under the constraints.
- The same regions as identified in the base case develop their renewable potentials, although in a larger proportion. For example, the development of hydroelectricity is particularly fast in China (already from 2010), reaching 12 EJ of electricity production in 2100. For the other regions, the hydropower sector expands significantly after 2040 only.
- In addition, the USA also increases the contribution of hydroelectric dams, wind and biomass power plants to their electricity production. Wind power plants are built in few more countries, such as China and India.

6 Sensitivity analysis

6.1 Alternate base case

We have modeled an alternative base case, in which the lower constraints used to calibrate nuclear production to the IPCC B2 marker scenario are reduced arbitrarily by 60%, and we analyzed the 450 ppmv scenario using this new base case assumptions. The B2 scenario already shows a level of nuclear production lower than all other IPCC marker scenarios until 2080. After this period, only the A1 family includes a maker scenario in which the nuclear production is slightly lower than in the B2 scenario. We analyze the impacts on the electricity production sector (Figure 7).

With the 60% reduction, the alternate base case shows a nuclear level production lower than all IPCC marker scenarios, reaching only 76 EJ in 2100 rather than the 127 EJ in the default base case (31% of the total electricity produced rather than 50%). This significant reduction is compensated by more oil and gas (34%), coal (19%) and reneweables (16%). Since the reference energy system relies more on fossil fuels, it emits an additionnal 2 GtC of CO_2 in 2100 and results in a higher CO_2 concentration of 602 ppmv in 2100. Applying the 450 ppmv constraint to this alternate base case illustrates very smiliar emission reduction strategies in the electricity sector. Nuclear penetrates the market almost as much as in the default 450 ppmv scenario, with only a 7% difference in 2100 (reaching 162 EJ rather than 175 EJ). In contrast, renewable electricity experiences a 17% increase compared to the default 450 ppmv scenario.

However, since the global reduction effort required to reach the 450 ppmv target is more significant in the alternate base case, the cost of the entire system is 100 billion dollars (B$) higher in the alternate 450 ppmv scenario (1295 B$ compared to 1195 B$). While the absolute emission reductions from the electricity sector totals 3.1 GtC in the default case, they reach 5.2 GtC in the alternate case.

6.2 Nuclear production and total system cost

The default 450 ppmv scenario illustrates a situation where techno-economic parameters are the main factors influencing political and business decisions in the electricity production sector. This situation assumes that society's perception of nuclear energy would be more positive in the future and/or that the remaining negative perception would not affect investment decisions in nuclear projects. In order to illustrate a situation where society's opposition would affect nuclear investment decisions, we have modeled two additional scenarios with upper constraints on nuclear production with the 450 ppmv target:

- Minimum fission only: nuclear fission production is limited at its minimum level (i.e. using former lower bounds as upper bounds) and nuclear fusion is allowed to penetrate freely. This scenario does not have a major impact on the electricity production sector since nuclear fission production does not increase in the 450 ppmv scenario compared

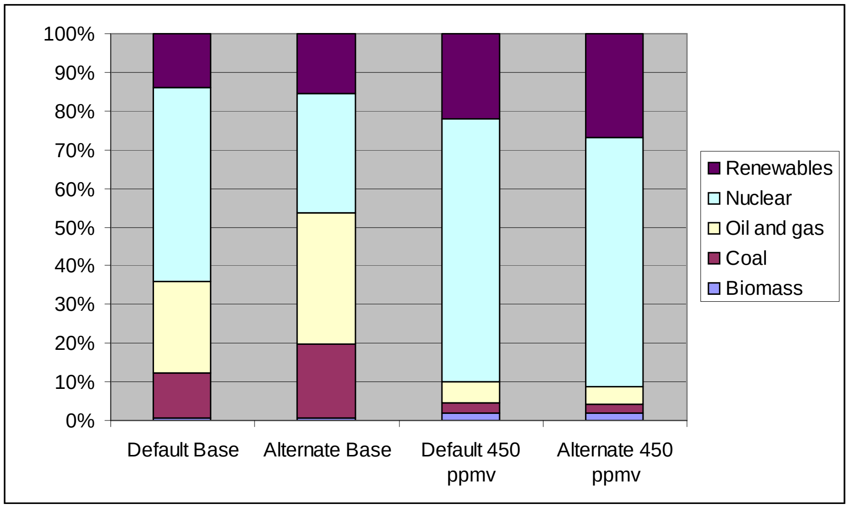

Figure 7: Electricity production by energy type in 2100 in both cases and 450 ppmv scenarios

to the base case. In this new scenario, total nuclear production is lower than in the default case (144 EJ rather than 175 EJ) and replaced by hydroelectricity and clean fossil fuel power plants. A relative small decrease occurs in nuclear fission (LWRs and PHWRs), indicating that these technologies are competitive under the 450 ppmv target. Indeed, they are not forced to penetrate by lower bounds and produce 104 EJ of electricity in 2100 (rather than 135 EJ). The difference corresponds to the amount of nuclear production, which would penetrate the market for non-economic reasons (energy security, high growth in energy consumption, etc.). The suppression of the lower bounds on the nuclear fission production reduces the total cost of the energy system by 180 B$. Nuclear fusion remains at the same level of production (around 40 EJ).

- Minimum fission and fusion: nuclear fission production is limited at a lower level (i.e. using lower bounds, which are decreased by 10% from 2050 to 40% in 2100) and nuclear fusion is not allowed to penetrate. In this scenario, the nuclear production is significantly reduced to 62 EJ in 2100 and represents only 25% of the total electricity produced (Figure 8). Clean thermal power plants, using mainly natural gas, replace a significant proportion of the electricity produced by nuclear plants. Consequently, the electricity produced by fossil fuels still accounts for 44% of the total in 2100. However, renewables penetrate the market significantly under this scenario to produce 29% of the total electricity. An additional 10 EJ comes from hydropower, which reaches the maximum potential (60 EJ), while a total of 10 EJ comes from wind, solar and geothermal power. The total cost of the energy system increase by only 59 B$ over the previous case in which neither nuclear fission nor fusion production were constrained.

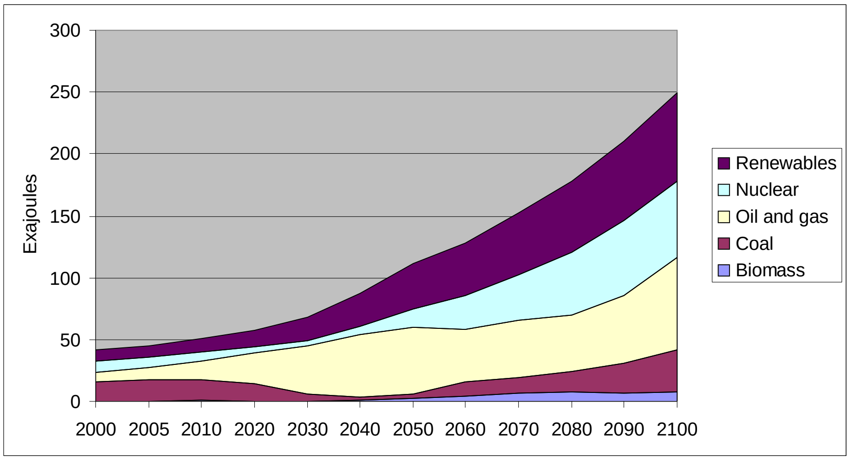

Figure 8: Electricity production by type under the 450 ppmv climate scenario

Further analysis on renewable potential and costs is necessary, in order to determine the conditions in which they could penetrate the market in a significant way. Moreover, it is important to mention that uncertainty analysis on climate policies show different conclusions about the nuclear option. While nuclear energy remains the most important energy source for electricity production in different climate scenarios, nuclear does not qualify as a robust abatement option in stochastic analysis of climate policies, i.e. it does not penetrate before the uncertainty is solved (Labriet et al., 2006). The authors show that in a context of uncertainty about the global target, any limitation of nuclear penetration does not compromise the possibilities to satisfy a 2.5^oC target at an “acceptable” cost, thanks to other forms of non-emitting electricity production (mainly wind, solar, biomass and natural gas power plants with carbon capture and storage).

Similarly, further analysis is needed on carbon capture and storage, an option with a growing role in climate scenario with nuclear constraints. Although the carbon sequestration potential estimates for the next decades are high, “the modeling of future trends in natural carbon fluxes suggests a progressive weakening of the efficiency of the natural oceanic and biospheric carbon sinks” (Jean-Baptiste and Ducroux, 2003). Consequently, carbon sequestration in natural ecosystem could be partially nullified because of some climatic feedbacks.

6.3 Investment cost of nuclear fusion reactors

We have performed a sensitivity analysis on the investment cost of nuclear fusion reactors, under the 450 ppmv limit. Indeed, the current designs of nuclear fusion reactors are not competitive in non-intervention scenarios (Tokimatsu et al., 2003). The objective of this exercise is to better understand the conditions for the penetration of this technology on the market,whose investment cost varies from 3780 US$ to 5880 US$ between the regions in the default case. We have analyzed the nuclear fusion market share under various investment cost scenarios: with increases of 10% and 20%, as well as decreases of 10% and 20%.

The analysis reveals that investment cost increases have a high impact on the market share of nuclear fusion. Indeed, even with a 10% increase, nuclear fusion penetrates only in China and India at the very end of the horizon (2100), and disappears completely from the market with a 20% increase. In this case, nuclear fusion is replaced partially by nuclear fission; the total nuclear production reaches only 131 EJ in 2100 (instead of 175 EJ). The gap is filled by coal and natural gas power plants with CO_2-capture, as well as with wind power plants. This conclusion is also observed by Hamacher et al. (2000), who indicate that nuclear fusion will only gain a large market share in Europe, over nuclear fission and coal power plants, if the capacity of fission is constrained and if stricter safety and environmental standards are applied to the electricity sector.

Oppositely, cost decreases do not affect its period of entry and market share as significantly: nuclear fusion increases its share by 17% in 2100 with a 10% cost decrease and by 32% with a 20% cost decrease. In the later case, only China invests in nuclear fusion 10 years earlier (in 2070) than in the default case. Investment cost would need to be reduced by as much as 35% for nuclear fusion reactors to become competitive with other technologies and start penetrating the market as soon as they become available in 2050. Based on techno-economic parameters only, it is unrealistic to expect nuclear fusion reactors to penetrate the market before the end of the century. However, other factors may influence investment in fusion power, such as energy security concerns.

7 Conclusion

The results of this analysis show a growing role for nuclear energy in long term climate scenarios, especially at a 450 ppmv level. However, the nuclear option takes place in a controversial context. It is a large-scale and non-emitting energy source, which can meet the growing demand in developing countries, but nuclear technologies, in their current state, show a few weaknesses. In particular, the risk of accidents and the generation of radioactive waste is a significant shortcoming, contributing to the negative social opinion of nuclear energy.

At the same time, renewable energy alone will not be sufficient to meet global energy needs in climate scenarios, especially in countries with a high socio-economic growth, unless there are significant techno-economic developments. Moreover, unless there are very significant developments in the technical and economic renewable potentials, renewables will continue to play a minor role in global electricity production during the current century, given the other available GHG options available in the model. This analysis suggests that non-hydro renewables are not competitive even in a 450 ppmv scenario. Although their costs have already started to decrease and considering that some forms of renewable energy are promising (wind power), further cost reductions or new regulations will be necessary to see renewables penetrating the market in substantial proportions. For example, the European Union requires to new member states to shut down the least safe nuclear reactors and by 2009, eight reactors have to be closed with financial support from the European Bank for Reconstruction and Development (Reiche, 2006). This condition, added to the fact that few countries in Western Europe have already decided to phase-out nuclear, might encourage development of renewable energies and eventually increase their proportion in electricity production. In addition, removing subsidies for fossil fuels and nuclear energies would be essential to make renewable energies competitive (Reiche, 2006).

However, considering the potential role of nuclear energy in a sustainable global future, many countries are investing in the research and development of nuclear technologies. In the current state of development, nuclear cannot be considered as a sustainable energy source. Nevertheless, under certain conditions, it is possible to consider nuclear energy in a sustainable framework. For example, new generations of nuclear fission reactors should improve such that large-scale contaminations by radioactivity do not occur in case of accidents. The amendment of the German Nuclear Law of 1994, already specified that the radioactivity level of new reactors must be low enough in case of accidents so that the evacuation of the nuclear plant is not required (Kessler, 2002). The European Pressurized Water Reactor (EPR) and the Pebble Bed Modular Gas-cooled Reactor (PBMR) could satisfy those conditions. Moreover, new separation techniques have been development to treat fission products and potentially improved the current waste disposal approaches (Kessler, 2002). As for nuclear fusion, those technologies would have many advantages compared to current fission technologies: the reserves needed (deuterium and lithium to produce tritium) are practically unlimited, the energy produced would be vast, it would not generate any risk of explosion and the quantity of radioactive wastes would be close to zero (Fiore, 2006; Tokimatsu et al. 2003). Developing countries with a fast growth rate, such as China and India have manifested interest in participating to the ITER collaborative program. For China, the goal is to have 10% of electricity produced from nuclear fusion by 2100 (Hamacher and Sheffield, 2004).

Finally, the development of each energy form depends on the geography, the techno-economic potentials, the social-economic situation, the political context and other factors in each country or region. For example, because of the intermittence of the wind source in France, a large scale development of the wind power industry would require additional fossil fuel power to fill the gap and this would lead to more GHG emissions (Jean-Baptiste and Ducroux, 2003). Moreover, for energy security reasons, the diversity of energy supply sources will become a major preoccupation for countries dependent on fossil fuel imports and countries with fast economic growth. Moreover, nuclear energy is expected to play a major role in the production of hydrogen to be used in the transportation sector (Duffey, 2005).

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