The Potential for a Nuclear Renaissance: The Development of Nuclear Power Under Climate Change Mitigation Policies

by
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Abstract

Anthropogenic emissions of greenhouse gases are very likely to have already changed the Earth's climate, and will continue to change it for centuries if no action is taken. Nuclear power, a nearly carbon-free source of electricity, could contribute significantly to climate change mitigation by replacing conventional fossil-fueled electricity generation technologies. To examine the potential role of nuclear power, an advanced nuclear technology representing Generation III reactors is introduced into the Emissions Predictions and Policy Analysis economic model, which projects greenhouse gas and other air pollutant emissions as well as climate policy costs. The model is then used to study how the cost and availability of nuclear power affect the economy and the environment at the global scale.

A literature review shows that estimates of nuclear power costs vary widely, because of differences in both calculation methods and cost parameters. Based on a sensitivity analysis, the most important parameters are the discount rate, the overnight cost, the capacity factor and the economic lifetime. The methodological differences affect not only the absolute power costs, but also the relative costs among electricity generation technologies. Acknowledging this uncertainty, a levelized cost model leads to bus-bar cost scenarios ranging from \$35/MWh to \$60/MWh.

Cap-and-trade climate policies strengthen the development of nuclear power in the high nuclear cost scenarios. In low-cost cases, nuclear power grows significantly even without climate policies, which have little further influence on the market share of nuclear power. Lower costs of nuclear power decrease the costs of climate policies: the consumption NPV loss due to a 550ppm climate policy is reduced by 36% if nuclear costs are reduced from the highest to the lowest scenario. Nuclear power development at the largest scale projected would involve the depletion of currently known conventional and phosphate uranium deposits.

Environmental benefits of the development of competitive nuclear power include a reduction in greenhouse gas emissions, even if no climate policy is implemented. For example, CO_2 emissions decrease by 32% in 2050 in the lowest nuclear cost scenario. Conventional pollutant emissions are also reduced: NO_x and SO_2 emissions decrease by 14% and 24% in 2050.

The economic value of the political decision to keep the nuclear option open is evaluated to range between \$1,300 billion and \$17,600 billion, in terms of consumption NPV loss, depending on the climate policy regime. These benefits should eventually be weighed against the proliferation, waste and safety issues associated with further development of nuclear power.

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I. Introduction

Anthropogenic emissions of greenhouse gases are very likely to have already changed the Earth's climate, and will continue to change it for centuries if no action is undertaken. Nuclear power, a nearly carbon-free source of energy, could contribute significantly to climate change mitigation by replacing conventional fossil-fueled electricity generation technologies, which account for a large share of current greenhouse gas emissions. Climate change mitigation policies could therefore induce a "nuclear renaissance," while the development of competitive nuclear power could reduce the costs of emissions reductions.

The issues of climate change and nuclear power development are actually intertwined along three main dimensions: the economics, the environment, and the politics. Accordingly, this thesis has at the three following objectives:

1. Determine whether the economic incentives of climate policies could foster a nuclear renaissance, and whether a development of nuclear power could lower the costs of climate policies,
2. Assess the environmental benefits of a potential development of nuclear power, especially with regard to climate change,
3. Evaluate the economic value of the political decision to keep the nuclear option open.

These goals require the implementation of future nuclear technologies within an economic model, which in turn requires determining the cost of these nuclear technologies. Accordingly, Chapter 2 assesses the cost of power generated through Generation III fission nuclear technologies. Chapter 3 describes the economic model used here, the Emissions Prediction and Policy Analysis modes (EPPA). Chapter 4 assesses the economic interactions between climate policies and the development of nuclear power. Chapter 5 analyzes the impact of a development of nuclear power on two key environmental concerns, the emissions of greenhouse gases and pollution. Finally, Chapter 6 determines the value of keeping the nuclear option open.

The following introduction presents the issues of climate change and nuclear power development in greater detail. Section 1 first addresses the climate change concern, as well as the main policies that could be used to mitigate emissions of greenhouse gases. Section 2 next presents nuclear power technologies, which could generate carbon-free electricity, and discusses their main advantages and disadvantages with regard to other power technologies. Section 3 then defines the focus of the thesis as well as the framework of analysis.

1. Climate Change and Emission Reduction Policies

A scientific consensus has emerged over the last two decades regarding human-induced climate change. In 1988, the World Meteorological Organization and the United Nations Environmental Program established the Intergovernmental Panel on Climate Change (IPCC), which gathers hundreds of experts from all regions of the world, to assess the state of the scientific knowledge on climate change. The IPCC released its Fourth Assessment Report in 2007, and concluded in its summary for policymakers that "warming is now unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global sea level" (IPCC, 2007a). As to whether climate change is human-induced or the result of natural variations, the IPCC states that "most of the observed increase in globally averaged temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations."

More precisely, eleven of the twelve warmest years since 1850 have occurred in the last twelve years, and the global mean surface temperature has increased by 0.74˚C in the last hundred years. The average temperature in the Arctic has increased twice as fast as the global mean over the last hundred years, and the Arctic ice sheet extent has decreased by 2.7% per decade since 1978. Increases have also been observed in the frequency of heavy precipitation events, in the length and intensity of droughts, and in the frequency of heat waves. These observed changes are likely or very likely due to increases in the atmospheric concentration of greenhouse gases, according to the IPCC. The concentration of carbon dioxide, the most important anthropogenic greenhouse gas, has increased from 280 ppm before industrialization to 379ppm in 2005, primarily because of fossil fuel use and land-use changes. Regarding the projections about the future, a range of IPCC emission scenarios predicts a warming of about 0.2˚C per decade for the next two decades. Finally, the global temperature change between 2000 and 2100 is expected to range from 0.6˚C, if all emissions are kept to their 2000 level, to 4.0˚C or more depending on emissions and uncertainties in the climate response to greenhouse gases (IPCC, 2007a).

Acknowledging that the global surface temperature is very likely to increase in the next decades and centuries because of anthropogenic emissions of greenhouse gases, one should next determine whether this temperature change will have significant impacts. The IPCC Third Assessment Report concludes that “projected climate change will have beneficial and adverse effects on both environmental and socio economic systems, but the larger the changes and rate of change in climate, the more the adverse effects predominate” (IPCC, 2001). More precisely, climate change is expected to increase the threats to human health, alter the ecological productivity and biodiversity, exacerbate water shortages in many water-scarce areas, and have economic impacts. The sign and extent of this economic impact, in terms of GDP, is very difficult to assess. According to the IPCC, the impact on the GDP would be negative in many developing countries regardless of the temperature change magnitude, and would be negative in developed countries beyond a few degrees of warming. Conversely, the effects are expected to be “mixed for developed countries for up to a few degrees warming.” The impacts of climate change are therefore difficult to quantify, especially in economic terms, but most experts would agree that they are significant enough to justify taking measures.

If the impacts of climate change are deemed significant, two options are then available: adaptation to climate change consequences, or mitigation of greenhouse gas emissions. For example, one could argue that it might be less costly to build dikes and to let coastal populations move, than to reduce the emissions of greenhouse gases. The costs of adaptation to climate change impacts should thus be compared to the costs of mitigating the emissions of greenhouse gases, in order to determine whether the benefits of climate change mitigation policies are worth their costs. There are, however, many issues raised in making monetary estimates of benefits of climate mitigation, thus some recommend that the "benefits" calculation should involve public discussion and involvement given a description of some physical indicators of the risks of climate change (Jacoby, 2004). More generally, these cost-benefit analyses are more difficult to carry out than the mere assessment of the economic cost of climate change, and involve much uncertainty.

Assuming that one decides to reduce greenhouse gas emissions, one must then choose among several types of policies. Governments can for instance take command-and-control measures by setting precise standards, or by regulating the use of specific technologies. However, these options are usually not cost effective since they impose economic burdens on agents regardless of their mitigation costs. Another solution is to use a price scheme, such as imposing a tax on greenhouse gas emissions. This method leads to a uniform marginal cost of emissions abatement across technologies and across economic agents, and is therefore regarded as more efficient. It is, however, difficult to predict the emission reduction that a given tax will trigger. A third possibility is to use a market solution, the so-called "cap-and-trade" scheme. In this system, the government defines an overall emission reduction target by issuing emission permits. Economic agents then trade these permits, so that eventually the agents who actually implement abatement measures are those who have the lowest emission abatement cost. This solution is therefore economically efficient, and triggers predictable emission reductions defined by the policy caps. It is however difficult to assess the cost of the policy, because one needs to assess the price at which the permit market will clear. Compared to tax policies, cap-and-trade systems therefore lead to more predictable benefits, but less predictable costs. This thesis focuses on cap-and-trade schemes, which account for most of the current policy momentum: the cap-and-trade system was envisioned as part of the Kyoto Protocol, has been implemented in a test phase in the EU (see Buchner et al., 2006), and is the subject of several US Congressional proposals (Paltsev et al., 2007).

These different climate policies create incentives to take the climate change externality into account. Economic agents must next choose specific mitigation options, depending on their relative costs and characteristics. In the case of the electricity sector, only a few avenues to reduce greenhouse gas emissions are available:

- decrease electricity consumption,
- increase the efficiency of electricity use and generation,
- increase the share of renewable energies,
- implement carbon capture and sequestration in fossil-fueled power plants,
- switch power plant fuels (for example, replace coal power with gas power),
- increase the use of nuclear fission reactors (and possibly fusion at a later date).

The main objective of this thesis is to assess the last option, namely the deployment of advanced nuclear fission reactors.

2. Nuclear Power

This part introduces nuclear power, and determines in Section a the specific nuclear technologies on which to base the forthcoming economic analysis. Section b also analyzes the advantages and disadvantages that should be considered when assessing the prospects of a deployment of advanced nuclear technologies.

a. Nuclear Power Technologies

Nuclear power includes distinct technologies, in two different fields: nuclear fission and fusion. Nuclear fission consists in breaking nuclei of high mass numbers (such as uranium or plutonium) into smaller nuclei. Conversely, nuclear fusion corresponds to the process of gathering nuclei of low mass numbers (such as hydrogen) into heavier nuclei. Both these processes release considerable amounts of energy with regard to the fuel mass that is involved. Fission power, which has existed for half a century, is a relatively mature technology, as compared to fusion power, which currently consumes more energy than the plants actually produce. Nuclear fusion power is still at the research stage, which implies that neither the commercial deployment schedule nor the cost assessments can be anticipated. I will therefore focus on the case of nuclear fission reactors only.

Nuclear fission power itself gathers several methods of electricity generation, which can be distinguished through the key concept of fuel cycle. Broadly speaking, three main types of fuel cycles exist: once-through, reprocessing and breeder. In all fuel cycles, the nuclear ore is first extracted, which gives a mix of two uranium isotopes, U-235 (about 0.7%) and U-238 (99.3%). In the once-through and reprocessing fuel cycles with light water reactors, this ore first needs to be enriched in U-235, is next transformed into nuclear fuel, which is then irradiated to produce energy. This last stage results not only in the generation of electricity, but also in the production of radioactive waste. In the once-through fuel cycle, this waste is stored in surface pools to allow cooling, and is finally disposed of in long-term geologic repositories. Conversely, reprocessing consists in separating the useful nuclear materials (such as plutonium) from the actual waste within the irradiated fuel. This method decreases both the nuclear ore requirements and the amount of waste that needs to be disposed of. In the future, it could also reduce the longevity and activity of the waste through a partitioning and transmutation process. In the breeder fuel cycle, fast reactors produce more fuel than they actually consume by directly transforming the fertile U-238 into nuclear fuel (fissile plutonium). This means that for the most part, fast breeder reactors do not require the enrichment stage described above. Besides, many more nuclear isotopes can undergo fission, which implies that fast reactors can burn some of what would be considered waste in the other fuel cycles, in order to produce more electricity. The breeder fuel cycle therefore produces less waste and consumes less nuclear ore than the first two, and is considered by many as the nuclear fission technology of the future.

These three fuel cycles do not come at the same cost. Although a controversial topic, most of the current research concludes that the once-through fuel cycle is, and should remain in the near future, much less expensive than the other two solutions (see for example MIT, 2003). Consequently, if a significant deployment of nuclear technologies is to occur, once-through fuel cycles should be predominant, at least in the near future. I will therefore hereafter rely exclusively on once-through technologies to assess the potential for a deployment of advanced nuclear technologies.

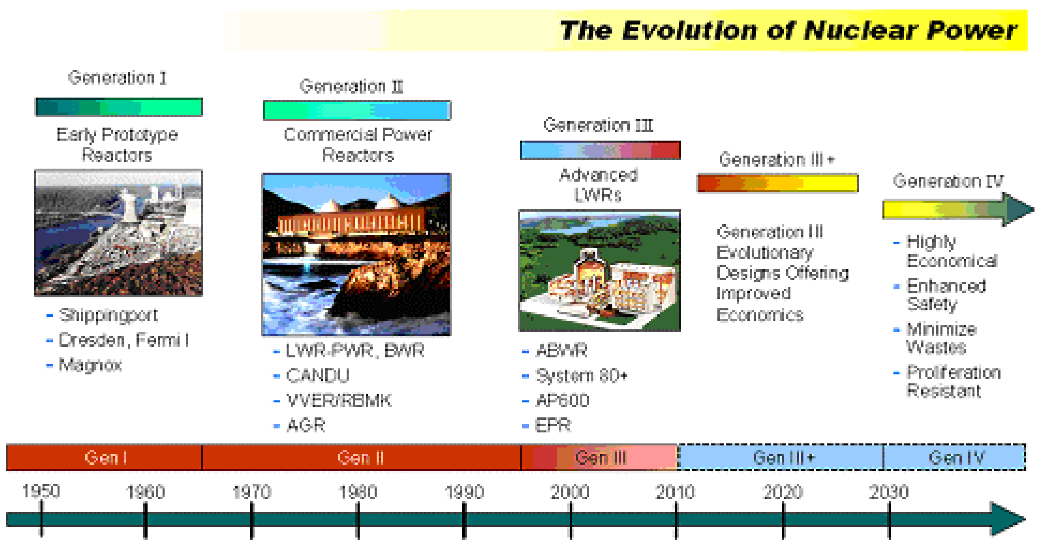

Figure 1. The Evolution of Nuclear Power

Source: GenIV Energy Systems (2007)

Among the technologies that correspond to this once-through fuel cycle, one also needs to make a distinction between old and new technologies: if indeed built, the new nuclear fission plants would be different from the current reactors. More precisely, the historical evolution of nuclear technology (Figure 1) has given rise to a rough classification based on several reactor "generations." Generation I corresponds to the research and prototype reactors of the 1950s and early 1960s. Generation II gathers most of the existing commercial nuclear power plants, built between the late 1960s and the early 1990s. Generation III refers to the advanced designs that are now being constructed or about to be licensed, with more passive safety systems. A distinction is sometimes drawn between Generation III (current designs) and Generation III+ (designs that should be available in the near-term, within 20 years), but I will not use it. Finally, current nuclear research aims to develop a new generation of reactors, Generation IV, mostly composed of breeder reactors. Since this technology is still at the research stage, and since no cost estimate is available yet, I will focus on Generation III reactors, which are listed in Table 1.

Reactor type	Country and developer	Reactor	Size MWe	Design Progress
Pressurized Water Reactors (PWR)	USA (Westinghouse)	AP-1000	1100	AP-1000 NRC design approval 2004.
	France-Germany (Framatome ANP)	EPR	1600	Future French standard. French design approval. Being built in Finland. US version being developed.
	Japan (utilities, Westinghouse, Mitsubishi)	APWR	1500	Basic design in progress, planned at Tsuruga
	South Korea (KHNP, derived from Westinghouse)	APR-1400	1450	Design certification 2003, First units expected to be operating c 2012.
	Russia (Gidropress)	VVER-1500 V-448	1500	Replacement for Leningrad and Kursk plants
	Russia (Gidropress)	VVER 1000 V-392	950	Two being built in India, Bid for China in 2005.
Boiling Water Reactors (BWR)	US-Japan (GE-Toshiba)	ABWR	1300	Commercial operation in Japan since 1996-7. In US: NRC certified 1997, FOAKE.
	USA (GE)	ESBWR	1550	Developed from ABWR, under certification in USA
	Germany (Framatome ANP)	SWR-1000	1200	Under development, pre-certification in USA
CANDUs	Canada (AECL)	ACR	700 1000	ACR-1000 proposed for UK. undergoing certification in Canada
High Temperature Gas Cooled Reactors (HTGR)	South Africa (Eskom, Westinghouse)	PBMR	165 (module)	prototype due to start building 2006
	USA-Russia et al (General Atomics - OKBM)	GT-MHR	285 (module)	Under development in Russia by multinational joint venture

Table 1. Main Types of Generation III Reactors

(adapted from World Nuclear Association, 2005)

b. Advantages and Disadvantages of Nuclear Power

The advantages and disadvantages of nuclear power are here presented, to determine whether nuclear power could be part of the solution portfolio to address climate change.

Key advantages include the extremely low greenhouse gas emissions, the abundance and distribution of uranium resources, and the low dependence of nuclear power costs on fuel prices. Conversely, the main disadvantages include proliferation, safety and waste management issues.

Given the rising concerns about climate change explained in Section 1, the most significant advantage of nuclear power is the extremely low emissions of greenhouse gases over the plant lifetime. Electricity generation accounted for about 40% of the total greenhouse gas emissions in the US in 2004 (EPA, 2006), coal power representing the majority of them (Figure 2). Replacing coal power plants with nuclear technologies would thus significantly help reduce anthropogenic emissions. To be accurate, tiny emissions actually come from the nuclear fuel extraction and the nuclear repository construction, but they can be neglected when compared to the emissions of fossil-fueled power technologies.

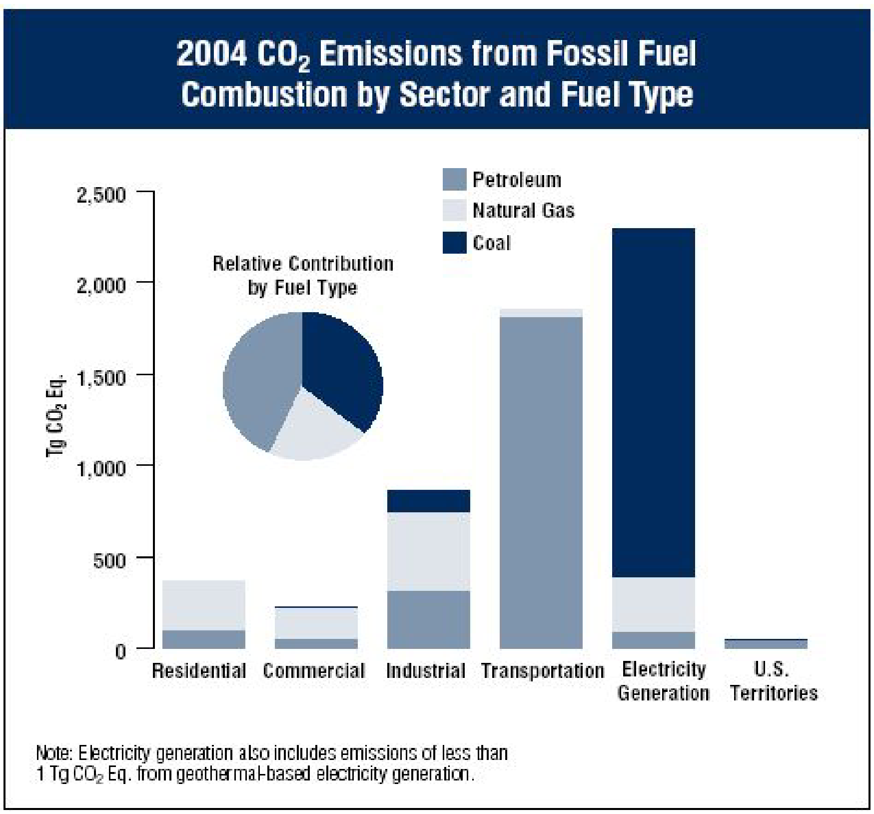

Figure 2. US Emissions of Greenhouse Gases by End-Use Sector

(from EPA, 2006)

A second advantage is the amount and distribution of uranium resources around the world. Their assessment involves much uncertainty because the global exploration for uranium is, and is bound to be, only partial. Several categories of resources exist to account for the different degrees of confidence in the existence of these resources, the identified resources referring to the highest level of confidence within the conventional resources. The amount of resources available therefore depends on the uncertainty level, but also on the price we are willing to pay to get them, and on the fuel cycle, as already explained. Accordingly, Table 2 presents different resource estimates in terms of the number of years of supply at the current consumption rate, as a function of the fuel cycle and of the fuel category. Note that this table does not take seawater uranium into account, the extraction of which would be much more expensive than that of conventional resources, but which would be about one hundred times as abundant as uranium from conventional resources and phosphates. Since many OECD countries such as Australia or the United States have significant uranium reserves, nuclear power is often seen as a way of improving energy security. Indeed, some European countries have no national resource in gas or coal to produce electricity, but they could have secured supplies of uranium, and they could easily store large amounts of energy with a small volume of uranium. However, as pointed out in Joskow (2006), there is no energy security case for nuclear power investments in the United States, because of the significant US coal reserves that already provide energy security, at least regarding the generation of electricity.

Reactor/Fuel cycle[1]	**Years of 2004 world nuclear electricity generation[2] with Identified resources[3]**	**Years of 2004 world nuclear electricity generation[2] with total conventional resources[4]**	**Years of 2004 world nuclear electricity generation[2] with total conventional resources and phosphates[5]**
Current fuel cycle (LWR, once-through)	85	270	675
Pure fast reactor fuel cycle with recycling	2 570	8 015	19 930

Table 2. Global Uranium Resources as a Function of the Fuel Cycle and of the Type of Resource

(from IEA/NEA, 2006)

A third significant advantage of nuclear power is the fact that its costs depend only very little on nuclear fuel prices, because of the small share of fuel costs in the total cost. Fuel price variations therefore do not add any significant uncertainty in the nuclear cost; historical nuclear cost variations actually arose mostly from regulatory changes. This situation is very different from the case of gas technologies in which variable fuel expenses account for approximately 70% of the total cost, which implies that gas power costs depend strongly on the gas price.

Nuclear weapon proliferation risks probably constitute the most important current disadvantage of nuclear power. Civilian nuclear facilities could indeed be used to get the materials required for nuclear weapons, namely highly enriched uranium and plutonium. Although the nuclear fuel cannot be used directly to fabricate weapons because it is not enriched enough in U-235, enrichment plants can produce highly enriched uranium, and reprocessing generates plutonium. Since getting the materials constitutes the most difficult step in fabricating nuclear weapons, the existence of enrichment facilities and reprocessing plants in high-risk countries can be regarded as a security threat. A Non-Proliferation Treaty has therefore been signed by most countries to avoid nuclear weapons from spreading further, while promoting the use of civilian nuclear power. This agreement prohibits weapon countries from helping non-weapon countries get nuclear weapons, and forbids non-weapon countries from acquiring them. In exchange, these non-weapon states receive help in getting peaceful uses of nuclear power. They must also accept inspections conducted by IAEA inspectors who make sure that they do not divert materials from the civilian facilities in order to produce weapons. However, current main concerns include the North Korean efforts to get nuclear weapons, and the Iranian plan to build enrichment plants. Note that another path to nuclear weapons exists, especially for terrorist groups, which is to simply buy or steal some of the existing stockpiles of nuclear weapons, highly enriched uranium or plutonium. Finally, the different fuel cycles are not equivalent regarding the proliferation risks. As is argued in MIT (2003), the reprocessing fuel cycle involves separating, transporting and having stocks of plutonium, which increases the short-term proliferation risks, as opposed to the once-through fuel cycle in which the plutonium remains in the waste and cannot be diverted easily. As is argued in

MIT (2003), this proliferation issue should be addressed, for example through a strengthening of the IAEA role, for a significant deployment of nuclear power to happen.

Regarding nuclear safety, two major accidents – at Three Mile Island in the US in 1979 and at Chernobyl in Ukraine in 1986 – contributed to the significant public fears in this regard. The current research (MIT, 2003) shows, however, that more work should be devoted to other stages of the fuel cycle, such as the reprocessing plants, instead of focusing only on the nuclear reactors. MIT also states that the reactor safety standard should be tightened to keep the same overall level of risk, if a nuclear renaissance were to increase significantly the number of reactors worldwide. However, there seems to be a significant mismatch between the public risk perception and the expert analysis regarding the safety of nuclear plants. Twenty-five years ago, a study for example showed that the risk of nuclear accident was ranked first by the public, whereas it corresponded only to the twentieth risk in terms of expected fatalities per year (Slovic et al., 1980). This study estimated that the risk posed by motor vehicles was for example five hundred times as high as that of nuclear power, and that even commercial aviation was more risky than nuclear power. This mismatch is partly due to inaccurate risk estimation from the public (Slovic et al, 1980), but also to differences in the preferences among risks. In particular, people tend to prefer risks of small accidents that occur often, to risks of catastrophic accidents that almost never happen, such as nuclear accidents. A political question then emerges, namely whether the risk estimate should be based on expert analysis using expected values, or on public preferences for controllable, immediate, known and common risks.

The third main disadvantage of nuclear power is the production of nuclear waste. As already mentioned, the once-through fuel cycle generates waste that is expected to remain more radioactive than natural uranium for hundreds of thousands of years. The main options available to deal with this waste are disposal in geological repositories (or deep borehole), reprocessing, or separation and transmutation. These last two approaches do not eliminate the need for geological repositories, but they reduce the timescales involved. Reprocessing is used essentially in Europe and Japan, while the US has taken the lead on the geologic repository path. Such a repository is to be constructed in Yucca Mountain (Nevada), but the project suffers from local political opposition and delays.

Finally, nuclear power is currently not competitive for so-called shoulder- and peak-demand, because it cannot be easily cycled on and off as electricity demand changes over the course of a day or year. Indeed, since nuclear power technologies are very capital-intensive, the capital cost per unit of power generated rises substantially if they are not operating at full capacity. Conversely, gas power technologies are less capital intensive and therefore more flexible: shutting the plant down cuts fuel costs, which account for a significant part of the total costs. As a result, nuclear power is currently not competitive for peak capacity electricity generation; however, this might change in the future if nuclear plants were to be used to produce hydrogen in off-peak periods, if other storage technologies were available, or if there were other ways of managing the load.

All these advantages and disadvantages have implications in terms of costs. Internalizing the costs of greenhouse gas emissions makes nuclear power more competitive since the price of electricity generated through fossil-fueled technologies increases. The abundance of fuel and the weak dependence of nuclear costs on fuel prices also play a part in decreasing the eventual nuclear power cost. Conversely, tightening the safety standards through regulation increases the plant costs and the construction time. Proliferation concerns also impose designing and paying for institutional mechanisms that have distortionary economic effects, which are usually not internalized (the cost of the IAEA for example, or the potential loss in economic growth because of the ban of nuclear energy for non-proliferation reasons). Finally, the costs of waste are currently internalized in the United States through a waste fee that nuclear operators have to pay.

These advantages and disadvantages also imply a number of political choices. Waste management raises for example the question of whether one should rely on future generations to deal with the consequences of current nuclear power generation, once new techniques and more economic resources are available. Besides, safety concerns imply determining whether tiny probabilities of dramatic accidents are acceptable, which also belongs to the political realm. Defining the amount of resources that should be allocated to non-proliferation also implies a political trade-off between national security concerns and the benefits of supposedly inexpensive nuclear power.

Finally, one should note that new generations of nuclear power aim to address the aforementioned disadvantages. As specified by the nuclear industry (World Nuclear Association, 2005), the improvements brought by Generation III advanced reactors include a standardized "simpler and more rugged design" to reduce costs and increase safety, a "higher availability and longer operating life - typically 60 years" to increase revenues, a "higher burn-up to reduce fuel use and the amount of waste," a "minimal effect on the environment," and higher safety. Generation IV technologies also share the same overall purposes, but aim to go one step further through the subsequent use of more innovative technologies (Gen IV Forum, 2003).

3. Thesis Framework and Focus

As explained in Section 1, climate change is very likely to have significant consequences on the environment, for example through the impact on biodiversity or the increase in the number of storms and droughts. Mitigating climate change also involves economic policies such as tax policies or cap-and-trade systems, and requires political commitment to support and design global agreements. Three dimensions are therefore involved in the climate change issue: the environment, the economics and the politics.

Similarly, the deployment of advanced nuclear technologies could affect the environment, both adversely through the nuclear waste and positively through the high power density (the capability of generating significant amounts of power on a small area). Economic and political considerations would also be involved, since the different advantages and disadvantages of nuclear power have consequences in terms of economics and politics, as already explained.

In order to analyze how climate change concerns and the potential development of nuclear power interact, one should therefore acknowledge the three important dimensions of the problem, namely the environment (the physical world), the economics (the allocation of resources), and the politics (the value judgments), as shown in Figure 3. The interactions among these dimensions are numerous. For example, political decisions have a strong influence on the economics of electricity generation through public subsidies and through the definition of standards (such as nuclear safety standards). Conversely, the politics of energy policy are affected by the economics: countries that need strong economic growth to fight against poverty are unlikely to be as concerned about climate change as developed countries. Political decisions can also have a direct influence on the environment through law, by prohibiting actions that would significantly damage the environment, which is arguably not an economic tool. Of course, the environment plays a part in shaping policies: for example, politicians take the environmental consequences of nuclear waste into account when deciding whether to expand nuclear power. Furthermore, changes in the environment can have a significant impact on the world economy: according to the IPCC, climate change is "very likely to impose net annual costs which will increase over time as global temperatures increase" (IPCC, 2007b). Finally, the economics of energy policies have a strong influence on the environment, for example through the impact of economic growth, which increases the emissions of greenhouse gases, or through the economic incentives of climate policies, which limit the emissions of greenhouse gases.

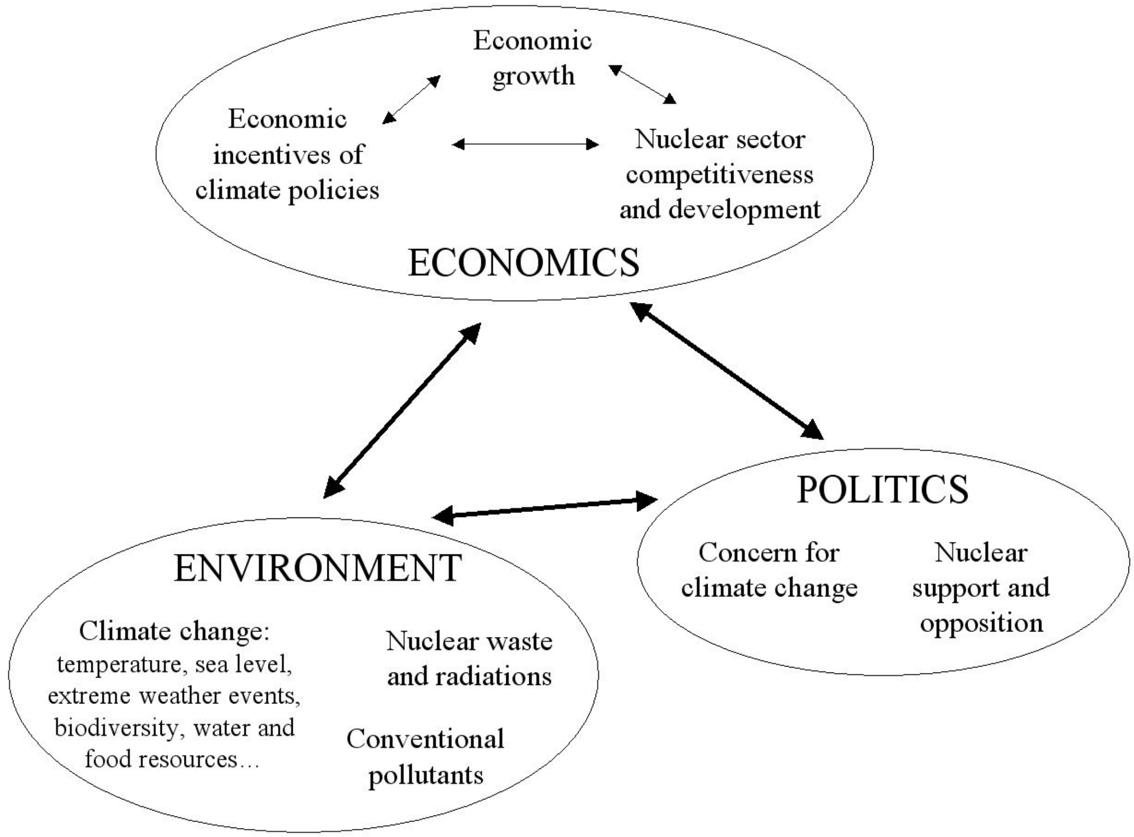

Figure 3. Interaction Between the Economic, Political and Environmental Stakes of Climate Change and of a Potential Nuclear Renaissance

Among the different links described in Figure 3, this thesis focuses on the interactions within the economic field, on the impact of the economics on the environment, and on the effect of a political decision regarding nuclear power on the economics. More precisely, within the economic field, I aim to answer the following questions:

- To what extent would the implementation of climate change mitigation policies strengthen the development of nuclear power?
- How would a development of nuclear power affect social welfare?
- How much should the society be willing to spend to get inexpensive carbon-free nuclear technologies, given the costs of climate policies?

Regarding the impact of economics on the environment, the following issues will be addressed:

- To what extent would competitive advanced nuclear technologies help reduce greenhouse gas emissions?
- What would be the side effects of a deployment of nuclear technologies, for example regarding pollution reduction?

As for the political aspects, I aim to study the impact on the economics and on the environment of a political decision to abandon the nuclear option. In economic terms, this corresponds to the value of keeping the nuclear option open, given the internalization of climate policies costs.

In order to analyze these questions, I use the Emissions Prediction and Policy Analysis model of the MIT Joint Program on the Science and Policy of Global Change. This economic model is meant to assess the impacts of climate change mitigation policies on the economy, and to predict the corresponding greenhouse gas emissions. It represents most electricity generation technologies, to which I add Generation III nuclear power, which enables me to determine the conditions under which advanced nuclear technologies correspond to an efficient way of addressing the climate change issue. Most importantly, the EPPA model is a general equilibrium model, namely a model in which all revenue and expense flows are accounted for, such that the entire economy is at equilibrium. This feature enables me to assess the impact of nuclear power development and of climate policies on the whole economy, and to compute the value of keeping the nuclear option open (or, equivalently, the cost of the political decision to abandon nuclear technologies).

This thesis thus aims to analyze the interaction between climate change mitigation policies and the potential development of nuclear power. Advanced nuclear technologies need to be implemented within the EPPA model, which in turn requires determining the cost of these nuclear technologies. Accordingly, Part 2 assesses the cost of power generated through Generation III nuclear technologies. Part 3 describes in greater detail the EPPA model as well as the new economic sector representing the advanced nuclear technologies. Part 4 assesses the economic interactions between climate policies and the development of the nuclear sector. Part 5 analyzes the impact of a development of nuclear power on two key environmental concerns, the emissions of greenhouse gases and pollution. Finally, Part 6 determines the value of keeping the nuclear option open.

II. How Much Does Nuclear Power Cost?

Estimates of the nuclear power cost are required to analyze the role of advanced nuclear technologies in mitigating climate change. Several recent studies have computed this cost using a standard model called a levelized cost model, which is described in Part 1. Part 2 reviews the results of the different cost studies, which arrive at estimates that vary widely. Part 3 then analyzes the reasons accounting for the cost estimate differences, which are twofold: the cost model inputs and the cost calculation methods. Acknowledging the uncertainty in many cost parameters, Part 4 finally develops nuclear cost scenarios using the model described in Part 1 and the cost model inputs from Part 3.

1. Cost Assessment Principles: a Levelized Cost Model

Assessing the electricity cost requires a few concepts of finance theory. Indeed, electricity generation involves costs that are spread over time, which implies that opportunity costs of capital need to be taken into account. In short, spending money today instead of later involves a cost because the money could have been invested in-between, and thus have yielded interest or dividends. These opportunity costs are extremely important in this case which involves comparisons across technologies that do not have the same cost distribution over time.

The different cost assessments rest upon a "levelized busbar cost model," using discounted cash flow analysis. More precisely, the model computes the constant price that should be sustained over time for the plant owner to be able to pay all costs, including interest and returns on equity. The cost is "levelized" insofar as the model yields only one constant figure, although the costs vary over time. Furthermore, it is a "busbar" cost because it does not include any transmission or distribution expense. This type of model has been widely used in previous studies, for example in MIT (2003), University of Chicago (2004), and IEA/NEA (2005). It has the advantage of being simple: since it yields only one aggregate cost, it makes comparisons across technologies very easy.

The following paragraphs describe the steps to calculate this levelized cost of electricity generation. If R_t and C_t correspond respectively to the revenues and costs that occurred in period t, the "present value" (value in period 0 assuming a discount rate r) of the cash flows that occurred at time t is $\frac{R_t - C_t}{(1+r)^t}$. The Net Present Value of the project then amounts to the sum of these present values: $NPV = \sum_t \frac{R_t - C_t}{(1+r)^t}$. With revenues equal to the price p multiplied by quantities, $NPV = \sum_t \frac{p.Q_t - C_t}{(1+r)^t}$. Given a discount rate and streams of costs and revenues over time, the model then solves for the constant p such that the NPV is equal to zero. This price p corresponds to the levelized cost of electricity.

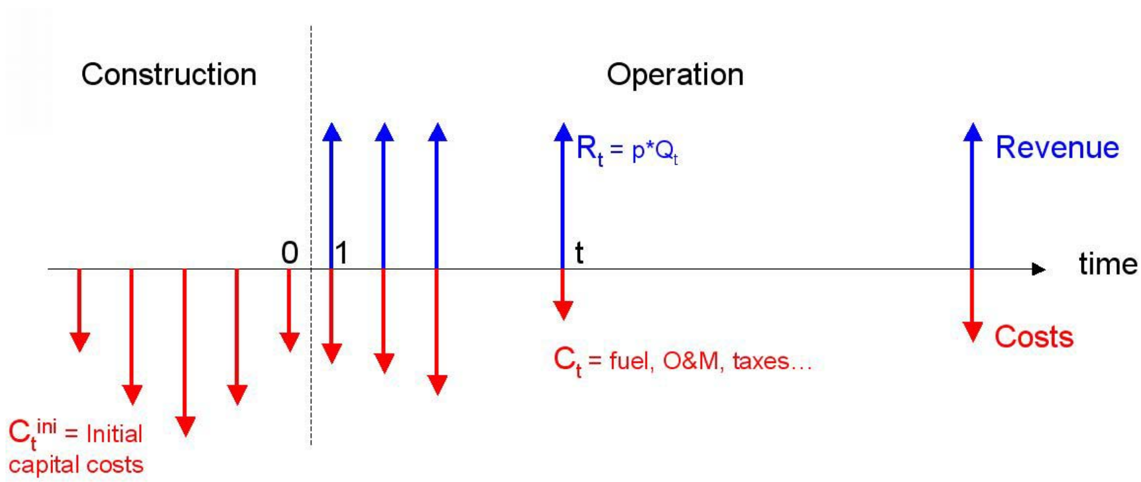

Figure 4. Cash Flow Diagram for the Calculation of the Levelized Cost of Electricity

During the construction period, the total costs C_t include only the initial capital expenditures C_t^{ini}, which are assumed to be financed through a mix of equity and debt. As depicted on Figure 4, the allocation of this capital investment is assumed to follow a sinusoidal function in real terms, in order to replicate the typical behavior with a peak in the middle of the investment period.

During the operation phase, C_t is the sum of taxes (T_t) and of the costs before tax (C_t^b):

$C_t = T_t + C_t^b$.

These costs before tax include:

- nuclear fuel costs, including uranium ore purchase, enrichment and fuel fabrication,
- a waste fee to cover the disposal of the waste,
- operation and maintenance costs, separated into fixed and variable costs,
- an allowance for decommissioning,
- incremental capital expenditures.

Taxes are calculated using the 2004 US tax structure, therefore without the tax credits provided in the 2005 Energy Policy Act. Taxes are equal to the product of the tax rate (τ) and of the taxable income (TI): $T_t = \tau \, . \, TI$. The taxable income is computed as revenues (R_t) minus costs before tax (C_t^b), and minus allowable deductions, which include the depreciation (D_t) and interest payments (I_t). The depreciation term corresponds merely to the deduction of the initial investment costs (plus the fuel expenses), acknowledging that these costs need to be spread over a certain depreciation schedule, which corresponds to the plant lifetime for tax purposes. Several depreciation schedules exist; I here use the accelerated depreciation schedule called MACRS, with a 15-year asset life. A schedule must also be defined for the debt repayment, so as to compute the interest payments I_t: I assume constant principal repayments in nominal terms.

The total costs during the operation phase are therefore $C_t = \tau.(R_t - D_t - I_t) + (1-\tau).C_t^b$.

The levelized cost is therefore:

$$p \quad such \quad that \qquad 0 = -\sum_{t \le 0} \frac{C_t^{ini}}{(1+r)^t} + \sum_{t>0} \frac{p.(1-\tau).Q_t + \tau(D_t + I_t) - (1-\tau).C_t^b}{(1+r)^t}$$

For the discount rate r, I use the "unlevered opportunity cost of capital", derived from the Weighted Average Cost of Capital (WACC) method, which gives a weighted average between the bond rate (r_b) and the expected rate of return on equity (r_e), before tax: $r = x_b.r_b + (1 - x_b).r_e$, where x_b is the bond share (the percentage of debt used to finance the project, also known as the leverage ratio). Assuming that r is derived this way implies that either r or r_e has to vary because the weights (i.e x_b) vary as debt is repaid. Different studies take different approaches in this regard.

The discount rate formula implicitly takes into account the economic risks of long-term, capital intensive projects like nuclear plants through a risk premium that is included in the expected rate of return on equity: r_e is typically higher for nuclear plants than for shorter and less capital-intensive coal plants. Roques et al (2006) argue, however, that "[t]he levelized cost approach was well suited to the stable environment of the electricity industry before liberalization," and that it "continues to be widely used by utilities post liberalization, despite its inappropriateness for evaluating investment choices under uncertainty." I acknowledge that the levelized cost approach is a crude way of addressing risk issues and that it fails to capture portfolio effects, but it does take uncertainty into account through the aforementioned risk premium. A more explicit treatment of uncertainty can be important but then depends on accurately assessing the various risk factors and expectations about the probability density functions that characterize each.

Note finally that inflation has an impact on this cost calculation through depreciation: depreciation is not adjusted for inflation in nominal terms. This means that the deduction of initial investments from the taxable income does not depend on the inflation rate, in nominal terms; a lower inflation rate therefore yields lower electricity costs in real terms.

2. Overview of Previous Studies on Nuclear Power Costs

As of January 2007, the most recent studies on the economics of nuclear power are[1]:

- DGEMP (2003), a French study of a series of 10 EPRs to be built in France,
- MIT (2003), a study that assesses the cost of new nuclear reactors in the US by relying on past experience (instead of engineering estimates of a specific new design),
- RAE (2004), examining the cost construction in the UK,
- University of Chicago (2004), a study comparing costs of an ABWR, an ACR-700, an AP1000 and an SWR in the US,
- CERI (2004), examining the cost of construction an ACR-700 in Canada (the study also addresses the case of the CANDU6, but I will not consider it since it is more expensive),
- IEA/NEA (2005), comparing data from twelve OECD countries covering thirteen different nuclear power plants; however, only five plants belong to Generation III, namely those in Canada (ACR-700), the US (no specific design), France (EPR), Germany (EPR), and Japan (ABWR).

These studies use a levelized cost model, and provide the information for the cost comparison below. Additional recent studies include Scully (2002), a report commissioned by the US DOE, and OXERA (2005), a UK study. Rather than compute levelized cost, both studies evaluate the competitiveness of nuclear power for a given electricity price by computing a project internal rate of return and comparing it to usual industry rates. Given this methodology difference, I do not rely on them to assess the cost of electricity produced by advanced nuclear technologies.

Table 3 shows the main technical and financial assumptions of the first five studies, as well as the resulting levelized costs. All amounts are expressed in 2003 dollars; inflation has been accounted for using the US GDP implicit price deflator (see OMB, 2005). As for exchange rates issues, I use the rates provided in the original studies, out of

[1] A short but more detailed presentation of most of these studies can be found in Thomas (2005), p.18

consistency concerns (these rates are used in the original studies among others to convert the fuel costs from dollars to national currencies). In the DGEMP case, given the parity fluctuations before 2003, an exchange rate of 1 euro/dollar is chosen. The CERI study assumes a rate of 0.7 US$/C$. In RAE, the overnight cost is reported both in dollars and in pounds, which defines the exchange rate I use. Note that both MIT and Chicago report the interest rate and the required rate of return on equity in nominal terms. The discount rate I report here is therefore converted from nominal to real terms, using their inflation rates of 3%.

Study		**DGEMP**	**MIT**	**CERI**	**Chicago**	**RAE**
Year		2003	2003	2004	2004	2004
Operating Life (years)		60	40	30	40	40
Capacity Factor (%)		90	85	90	85	>90
Capital Costs	Overnight Capital Cost (2003 USD/kW)	1,330	2,040	1,640	1,200 – 1,500 – 1,800	2,040
	Construction Time (years)	4.8	5	6	5 - 7	5
	Real Discount Rate (%)	8.0	8.3	10	9.2	7.5
O&M Costs	Fixed (2003 USD/kW)	53	64	NA	60	73
	Variable (2003 USD/MWh)	0.63	0.48	7.6	2.1	NA
Fuel Costs (USD/MWh)		4.6	6.0	3.8	5.4	7.1
Levelized Cost (2003 USD/MWh)		**29**	**68**	**51**	**47 - 71**	**40**

Table 3. Main Assumptions and Best Estimates of Five Levelized Cost Models

Table 4 summarizes the IEA/NEA results for Generation III nuclear plants, with two different real discount rates, 5% and 10%. Detailed assumptions are not available, but all national studies within IEA/NEA include an 85% capacity factor and a 40-year operating life. Compared to the other studies, IEA/NEA leads to low nuclear power costs. For instance, among the six plants analyzed, the electricity cost average amounts to $30.2/MWh with a 5% discount rate, and to $44.6/MWh with a 10% discount rate, which is in the lower part of the range in Table 3. One could argue that comparisons among countries within the IEA/NEA study are dubious because IEA/NEA consists in the aggregation of separate national studies. However, the example of the US only leads to the same conclusion: the IEA/NEA figures are lower than the previous two US studies (MIT and Chicago), even when the discount rate is higher.

Plant	Overnight capital cost (2003 USD/kW)	Busbar power cost (in 2003 USD/MWh)	
		5% Discount Rate	10% Discount Rate
CAN-N	1,300	24.6	35.1
USA-N	1,890	30.1	46.5
FRA-N	1,360	22.2	34.4
DEU-N	1,550	25.0	36.8
NLD-N	1,880	31.3	46.5
JPN-N	2,510	48.0	68.6

Table 4. IEA/NEA Nuclear Power Generation Costs

Astonishingly, the nuclear power cost estimates from the original studies are spread in an extremely wide range, from 25 to 71 USD/MWh. In the next section I use my own levelized cost model, as well as the raw data from the original studies, to investigate the factors that contribute to this wide variation.

3. Reasons Accounting for the Differences Among Studies

This part aims to understand the significant differences among nuclear cost estimates, and to disentangle the influence of cost calculation inputs from that of cost calculation methods. Section a shows that cost model inputs explain some of the cost estimate variations, but not all of them. Section b proves that cost calculation methods also have a significant impact, especially when making comparisons across electricity generation technologies.

a. Differences in the Cost Calculation Assumptions

In order to analyze the impact of the cost parameters, this section first assesses the differences in the parameter assumptions across studies. It then determines whether these differences explain some of the cost variations, and finally whether they explain all of them.

Table 5 presents the assumptions made in the five models for which detailed parameters are available. Notably, the MIT nuclear cost study is on the high end, with low capacity factors, a short economic life and high overnight costs. Conversely, DGEMP is clearly on the low end, with low overnight costs, low taxes and a long economic life. RAE is a bit difficult to assess because only few figures are available. The study by the University of Chicago carried out extensive multi-parameter sensitivity analyses that cover a large range of values; CERI also conducted sensitivity analyses, but it focused essentially on single-parameter uncertainty.

	MIT	Chicago	DGEMP	CERI	RAE
Plant Characteristics					
Capacity Factor	75% - 85%	85% - 90% - 95%	52% - 62% - 72% - 82% - 90% (a)	85% - 90% - 95%	>90%
Construction Time (years)	4 - 5 (b)	5 - 7	4.8	5 - 6	5
Economic Life (years)	25 - 40	40 - 60	60	20 - 40	20 - 45
Cost Parameters					
Overnight Cost (2003$/kW)	2040 - 1530	1200 - 1500 - 1800	1330	1440 - 1640 - 1970	2040
Decommissioning ($)	350	350	258	532	included in overnight cost
Capital Increment ($/kW)	20	21	0	5	NC
Fixed O&M ($/kW)	63	60	53	NA	73
Variable O&M ($/kWh)	0.00047	0.0021	0.0006	0.0076	NA
O&M Escalation Rate (real)	0.01	0	0	0	NC
Fuel Cost ($/MMbtu)	0.47	0.42	0.44	0.33 - 0.37 - 0.40	0.68
Heat Rate (BTU/kWh)	10400	10400 (c)	10400 (c)	10400 (c)	10400 (c)
Fuel Escalation (real)	0.5%	0%	0%	0%	NC
Waste Fee ($/kWh)	0.001	0.001	0	0.001	NC
Financial Assumptions					
Inflation Rate	3%	3%	0%	2%	NC
Bond Rate (real)	4.9%	3.9% - 6.8%	NA	7.8% to 9.8%	NA
Equity Return (real)	8.7% - 11.7%	8.7% - 11.7%	3% - 5% - 8% - 11% (d)	11.8% to 19.6%	7.5% nominal (d)
% Debt Finance	50% - 60%	50% - 60% - 70%	NA	50% - 70%	NA
Tax Rate	38%	38%	5% (e)	30%	NC
MACRS Life (years)	15	15	30	20 - 40	NC

Table 5. Detailed Assumptions of the Levelized Cost Models

(Including the Main Sensitivity Analyses)

(a) These factors were calculated from assumptions on the number of hours of operation. The low capacity factors correspond to moments of demand shortage, but not to plant operation problems.

(b) Without the additional year for final licensing and testing

(c) This heat rate was assumed to be equal to that of the MIT study, in order to convert the fuel cost from $/MWh to $/MMbtu

(d) These studies used only a discount rate, without distinguishing between bonds and equity rates; I assume later that the plant is financed only through equity with a required rate of return equal to this discount rate, in order to avoid interest effects in the treatment of depreciation.

(e) This figure is a simplification of a more detailed tax analysis

In order to determine whether these differences in cost model assumptions have a significant impact on the result, I carry out a sensitivity analysis on the cost model, based on the ranges defined in Table 6. I included most of the parameter values from the studies already quoted. The very low capacity factors from DGEMP were excluded because they correspond to the specific French case with a very high share of nuclear power, which makes demand shortages likely. The very high required rates of return on equity from CERI were also omitted since they were simply aimed to "illustrate the impact of assumed real return on equity," but not to reflect observed market conditions.

	Sensitivity study		
	Low	**Medium**	**High**
Plant Characteristics			
Capacity Factor	75%	85%	95%
Construction Time (years)	5	6	7
Economic Life (years)	20	40	60
Cost Assumptions			
Overnight Cost (2003$/kW)	1200	1600	2000
Decommissioning ($)	250	350	550
Capital Increment ($/kW)	0	20	25
Fixed O&M ($/kW)	0	63	60
Variable O&M ($/kWh)	0.0076	0.0005	0.0021
O&M Escalation Rate (real)	0%	0.5%	1.0%
Fuel Cost ($/MMbtu)	0.3	0.45	0.7
Heat Rate (BTU/kWh)		10400	
Fuel Escalation (real)	0	0.25%	0.50%
Waste Fee ($/kWh)	0	0.0005	0.001
Financial assumptions			
Inflation Rate		3%	
Bond Rate (real)	3.9%	4.9%	6.8%
Equity Return (real)	8.7%	10.2%	11.7%
% Debt Finance	50%	60%	70%
Tax Rate	5%	38%	40%
MACRS Life (years)		15	

Table 6. Assumptions of the Sensitivity Analysis

(Fixed and Variable O&M Costs Aggregated when Defining the Scenarios)

These ranges lead to the Tornado diagram of Figure 5, which corresponds to a series of single-parameter uncertainty analyses. The "Medium" assumptions define the reference cost (about $43/MWh) around which the impact of each parameter is assessed separately. For example, the capacity factor bar corresponds to a change in the capacity factor – and only in the capacity factor – with regard to the reference. If several parameters were changed simultaneously, interaction effects might arise. For instance, the combination of a high discount rate and a high overnight cost is likely to result in a more severe cost increase than the sum of the single-parameter variations. The bars are sorted by decreasing width, that is, by decreasing impact on the electricity cost uncertainty. Finally, this diagram shows the combined effect of two factors: first, the uncertainty in the cost model assumptions, and second, the sensitivity of the model to these assumptions.

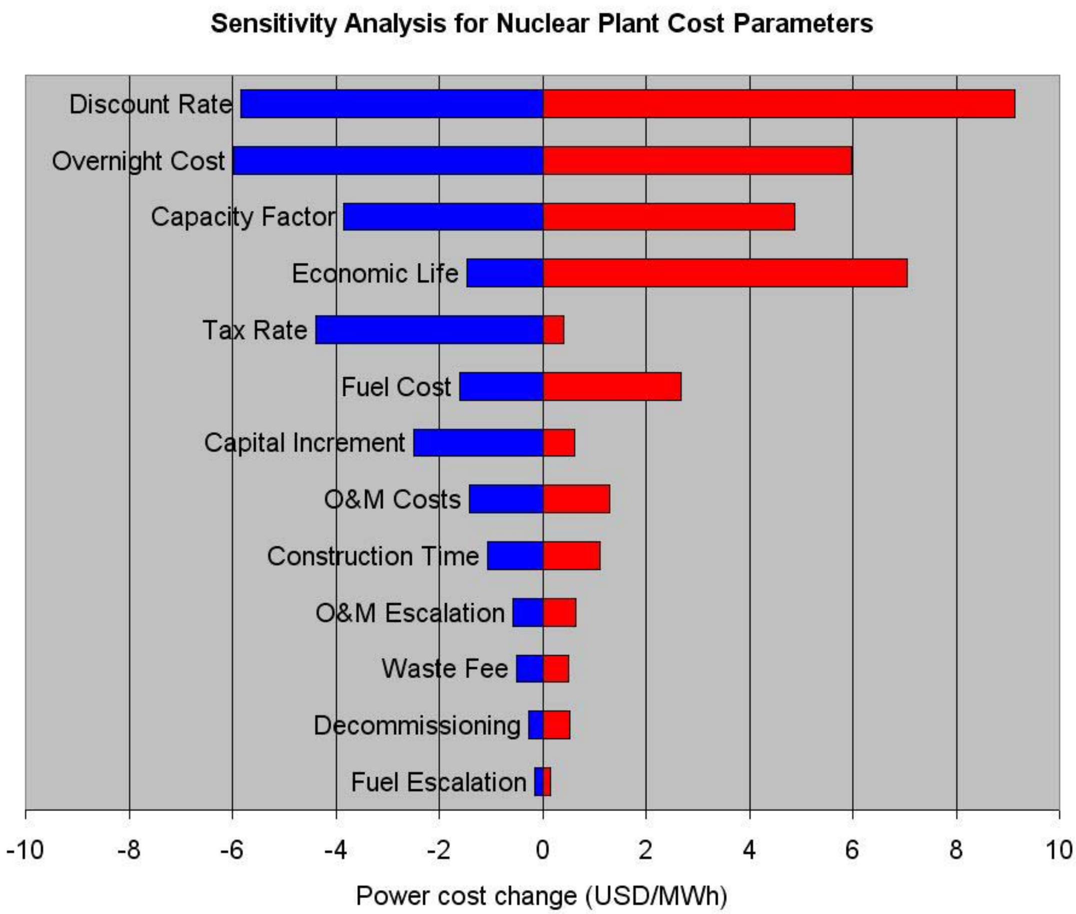

Figure 5. Tornado Diagram of the Sensitivity Analysis for Nuclear Plant Cost Parameters

Figure 6 next disaggregates the discount rate effects by analyzing the impact of the different financing parameters.

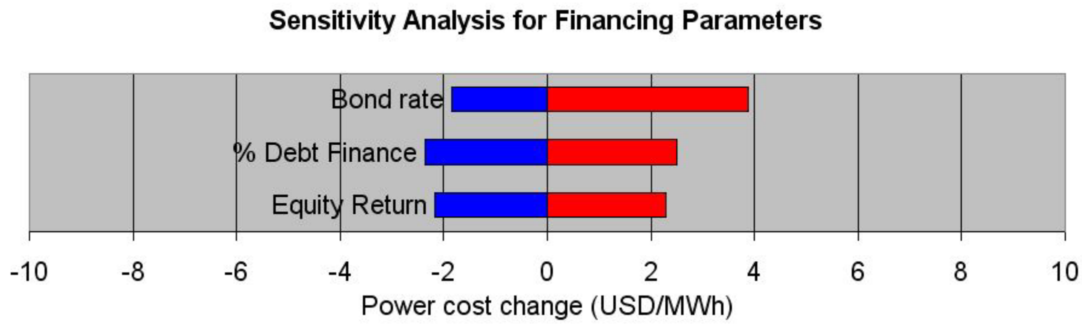

Figure 6. Tornado Diagram of the Sensitivy Analysis for Financing Parameters

The cost model inputs therefore do have a significant impact on the levelized cost of nuclear power generation. More precisely, the uncertainty regarding the discount rate accounts for a cost variation range of $15/MWh around the reference scenario of $43/MWh, and the overnight cost uncertainty implies a range of $12/MWh. Similarly but to a lesser extent, the uncertainty in the capacity factor and in the economic life account for ranges of around $8/MWh. Tax rate differences also have non-negligible effects, but they do not really constitute "uncertain" parameters to the extent that they represent differences in the tax structures of different countries.

After determining that the cost model inputs explain some of the differences in the nuclear power cost, I now turn to the question of whether they explain all these differences. If the cost model inputs explained all the nuclear cost variations, different studies should find similar levelized costs when they use similar input values. This is not the case, as can be seen in Table 7 and Table 8, in which I compare the results of the original studies when they make similar assumptions for the four most sensitive parameters. For example, Table 7 compares the original results from the different studies when they assume an overnight cost around $1300/kW, a discount rate around 5%, a capacity factor around 85% and an economic life around 40 years. A first group of studies, group A, finds consistent values around $25/MWh, but Chicago predicts a cost of

$32/MWh. Similarly in Table 8, IEA/NEA computes a cost of $37/MWh, while another set of studies, hereafter called group B, predicts values around $54/MWh.

Group	**A**			**B**
Study	IEA/NEA (Canada)	DGEMP	IEA/NEA (France)	Chicago
Overnight Cost ($/kWe)	1300	1330	1360	1200
Discount Rate	5.0%	5.0%	5.0%	5.3%
Capacity factor	85%	82%	85%	85%
Operating life (years)	40	60	40	40
Levelized cost (2003 USD/MWh)	**24.6**	**23.9**	**25.4**	**32.0**

Table 7. Levelized Cost Comparison between Two Groups of Studies, for a Discount Rate around 5%

Group	**A**	**B**		
Study	IEA/NEA (Germany)	MIT	Chicago	CERI
Overnight Cost ($/kWe)	1550	1530	1500	1640
Discount Rate	10.0%	8.3%	9.2%	10.0%
Capacity factor	85%	85%	85%	85%
Operating life (years)	40	40	40	30
Levelized cost (2003 USD/MWh)	**36.8**	**56.0**	**54.0**	**54.1**

Table 8. Levelized Cost Comparison between Two Groups of Studies, for a Discount Rate around 9%

The trend identified in these two tables is more general, and can be observed by comparing sensitivity studies. Nuclear cost studies can be gathered into two groups: on the one hand, group A with DGEMP and IEA/NEA, on the other hand group B with CERI, Chicago and MIT. Within each group, studies seem consistent with each other once the assumptions about the main cost parameters have been accounted for. However, the two groups do not agree with each other. For example, as can be seen in Table 8, with a discount rate around 9%, an overnight cost around $1500/kW and a capacity factor around 85%, group B predicts a cost around $54/MWh, while IEA/NEA concludes that it should be around $37/MWh, that is, a difference of $17/MWh (38%).

Differences in the cost calculation inputs therefore do explain part of the differences among cost estimates, but they do not explain all of them. In the following sections, I aim to understand where this significant difference across groups comes from.

Note that the impact of taxes is too small to explain these cost differences. They are much lower for DGEMP (around 5% instead of 38%) and they are even excluded from the calculation in IEA/NEA (except for the USA-N plant which corresponds to the cases with an overnight cost around $1900/kW). However, as can be seen on Figure 7, a decrease in the tax rate from 38% to 5% results in a levelized cost decrease of only $4/MWh, and totally excluding taxes decreases the electricity cost by around $4.5/MWh. While this effect is far from negligible, it does not exhaust the problem of a $17/MWh difference.

Finally, exchange rates affect both the cost assumptions and the resulting levelized costs. Consequently, exchange rates cannot explain the cost differences when comparing the results of studies that make approximately the same cost assumptions in dollars (as in Table 7). They do, however, have an influence on the best estimates of the different studies (Table 3). In particular, the DGEMP and IEA/NEA results rely on exchange rates that introduce uncertainty; the Canadian study CERI uses, however, cost estimates that are originally in American dollars, which excludes such an influence.

b. Differences in the Cost Calculation Methods

Section a proved that the differences in cost model inputs are not enough to explain all the variation in nuclear cost estimates. This part shows that another factor responsible for this significant variation is the fact that nuclear power cost studies use slightly different methods of discounting, which has a significant impact on the final levelized costs, especially when making comparisons across electricity generation technologies.

As explained in Section II.1, the calculation of a levelized cost involves discounting expenses into present values. All studies rely on an explicit or implicit "unlevered opportunity cost of capital", derived from the WACC method, to determine the relevant discount rate: $r = x_b.r_b + (1 - x_b).r_e$. They therefore assess the market values for the leverage ratio x_b, the bond rate r_b, and the required rate of return on equity r_e on the specific case of nuclear power plants. However, the two groups of studies mentioned above differ in the way they address the fact that repaying debt implies that the leverage ratio varies over time.

As I understand the different study reports, group B (MIT, Chicago and CERI) assumes that the required rate of return on equity r_e and the bond rate r_b do not change over time. This implies that the discount rate r varies as the leverage ratio varies. For example, assuming that x_b=50%, r_b=5% and r_e=12%, the discount rate r will be equal to 8.5% at the beginning, but it will next increase as debt is repaid, and it will eventually be equal to the required rate of return on equity, namely 12% when debt is totally repaid. This method will be referred to as method B.

Conversely, group A (DGEMP, IEA/NEA) assumes that the discount rate r does not vary over time (method A). These studies actually assume a given discount rate without explicitly modeling debt repayment. This implies that the rate of return on equity r_e varies when the leverage ratio x_b varies. The justification for this effect is that the risks borne by equity holders change as debt is repaid. Assuming the same initial values for x_b, r_b and r_e as in the previous example, the discount rate according to this method will always be equal to 8.5%. As debt is repaid (the leverage ratio x_b decreases), the required rate of return on equity r_e will adjust so that the relationship $r = x_b.r_b + (1 - x_b).r_e$ remains valid: r_e will decrease over time as x_b decreases, and will finally be equal to 8.5%.

Besides these discount rate adjustment issues, the MIT study assumes a one-year time lag between the end of the construction phase and the beginning of operation, to account for final licensing and testing. My understanding of the study is that this year of licensing and testing justifies the discounting convention they use: investments are incurred at the beginning of the period, while revenues and operating expenses occur at the end of the period. This convention adds a year that is not included in the reported construction period: the first positive cash flow occurs two years after the last construction outlay. As a result, a 5-year construction period assumption from MIT is equivalent to a construction period of more than 6 years with a model using a discounting convention in which all cash flows are incurred at the same time across periods (for example in the middle of each period). Based on the different reports, it is unclear whether other studies made the same assumption as MIT, but this one-year time lag could explain why MIT gives rise to the highest costs among the models of group B.

These method differences matter all the more as significant overnight costs, long construction times and long economic lives are involved, which precisely corresponds to the nuclear case. Using the cost assumptions from Metcalf (2006) for the different electricity generation technologies (see Table 9), the different methods give the costs listed in Table 10, based on a levelized cost model I developed.

	Nuclear	PC	IGCC	Gas-CC	Biomass	Wind	Solar Thermal	PV
Capacity Factor	85%	85%	85%	85%	83%	35%	31%	21%
Construction Time	6	4	4	3	4	3	3	2
Fuel Cost ($/MMbtu)	0.47	0.994	0.994	5.94	2.15	0	0	0
Heat rate (BTU/kWh)	10,400	8,844	8,309	7,196	8,911	10,280	10,280	10,280
Fixed O&M ($/kW)	61.82	25.07	35.21	11.37	48.56	27.59	51.70	10.64
Variable O&M ($/kWh)	0.00045	0.00418	0.00265	0.00188	0.00313	0	0	0
Decommissioning ($)	350	na	na	na	na	na	na	na
Capital Increment ($/kW)	18	15	15	6	0	0	0	0
Capital Increment (years 30+)	44	21	21	12	0	0	0	0
% Debt Finance	50%	60%	60%	60%	60%	60%	60%	60%
% Equity Finance	50%	40%	40%	40%	40%	40%	40%	40%
Discount Rate	11.5%	10.8%	10.8%	10.8%	10.8%	10.8%	10.8%	10.8%
Overnight Cost ($/kW)	2,014	1,249	1,443	584	1,809	1,167	3,047	4,598
Economic Life	40	30	25	25	20	20	20	20
MACRS Life	15	15	15	15	5	5	5	5

Table 9. Plant Specific Parameters for Levelized Cost Analysis

(from Metcalf, 2006)

Technology	Method A	Method B		Method B + one-year lag	
	Power cost ($/MWh)	Power cost ($/MWh)	% change with method A	Power cost ($/MWh)	% change with method A
IGCC	37.3	41.1	10.0%	43.6	16.8%
Pulverized Coal	38.5	43.0	11.7%	45.6	18.7%
Nuclear	42.9	48.7	13.6%	54.0	25.9%
Wind	51.5	55.5	7.7%	61.9	20.3%
Biomass	59.3	62.5	5.3%	67.0	12.9%
Gas-CC	65.4	67.1	2.6%	68.3	4.5%
Solar thermal	106.7	115.0	7.7%	128.3	20.2%
Photovoltaics	194.9	211.9	8.7%	240.9	23.6%

Table 10. Impact of the Discounting Method on the Levelized Cost of Electricity

Using exactly the same assumptions, the MIT model (method B and a one-year lag between construction and operation) leads to a cost that is 26% higher than a standard model using method A for the nuclear case. Cost calculation methods therefore do have a significant impact on the levelized cost results.

Most importantly, the difference in calculation method does not only offset the absolute cost values, it also changes the relative costs across technologies. Switching from method A to method B with the one-year lag implies a 26% increase in nuclear power cost, but only a 5% increase in Gas-CC power. Since the studies about electricity generation costs are meant to assess the relative costs of the different technologies, the choice of methodology is crucial to the comparison.

As an illustration of the importance of this methodology choice, Table 11 recalculates the electricity power costs with the MIT cost assumptions, but using different cost calculation methods. In particular, with method A, nuclear technologies are competitive with gas when the fuel price is high (which is currently the case), and the cost gap between nuclear and coal technologies is very small in the optimistic nuclear scenarios.

	Original MIT findings	Method B + one-year lag	Method A	% change
Base Case				
Nuclear	67	67	55	-18%
Coal	42	42	38	-11%
Gas (low)	38	38	36	-4%
Gas (moderate)	41	41	40	-1%
Gas (high)	56	55	56	-1%
Gas (high) Advanced	51	50	51	-1%
Reduce Nuclear Costs Cases				
Reduce construction costs (25%)	55	55	46	-16%
Reduce construction time by 12 months	53	53	45	-16%
Reduce cost of capital to be equivalent to coal and gas	44	44	39	-12%

Table 11. Levelized Power Costs, Using the MIT Model Inputs, but Different Cost Calculation Methods

(Case with an 85% Capacity Factor and a 40-Year Economic Life, Amounts in 2002$/MWh)

Using my levelized cost model with method A, I recalculate in Table 12 the best estimates of four studies (RAE was not recalculated because of a lack of cost data). When a consistent methodology is used across studies, the nuclear cost range is reduced to $31/MWh - $60/MWh, much smaller than the initial range of $25/MWh to $71/MWh.

Study		DGEMP	MIT	CERI	Chicago	RAE
Year		2003	2003	2004	2004	2004
Operating Life (years)		60	40	30	40	40
Capacity Factor (%)		90	85	90	85	>90
Capital Costs	Overnight Capital Cost (2003 USD/kW)	1,330	2,040	1,640	1,200 – 1,500 – 1,800	2,040
	Construction Time (years)	4.8	5	6	5 - 7	5
	Real Discount Rate (%)	8.0	8.3	10	9.2	7.5
O&M Costs	Fixed (2003 USD/kW)	53	64	NA	60	73
	Variable (2003 USD/MWh)	0.63	0.48	7.6	2.1	NA
Fuel Costs (USD/MWh)		4.6	6.0	3.8	5.4	7.1
Levelized Cost (2003 USD/MWh)		**31**	**56**	**47**	**43 - 60**	**-**

Table 12. Recalculation of the Best Estimates Using Method A

As a result, if I use my levelized cost model with method A to recalculate the values reported by the different studies, and if I correct for the $4/MWh that arises from legitimate national tax policy variations, I get a nuclear power cost that ranges from $35/MWh to $60/MWh in the US.

4. Scenarios of Nuclear Power Costs

Acknowledging the cost uncertainty analyzed in the previous part, this section defines six nuclear power cost scenarios. As explained in Section a, each scenario is defined by values for the overnight cost and the discount rate, because both involve significant conceptual choices that need to be stated clearly. Arguably, other cost components involve numerical uncertainty but no significant conceptual choice; I therefore model them through a probability distribution function. This method leads to the six probability distribution functions described in Section b, with means ranging from $31/MWh to $50/MWh. I also define an overall scenario based on my assumptions regarding the conceptual choices, which gives a wider probability distribution function with a mean of $37/MWh.

a. Scenario Construction Principles

The previous section evaluated reasons for the considerable variation in published estimates of nuclear power cost. One factor is the tax policy as it varies across countries, a second is the calculation methods, and the third is fundamental differences in estimates of the cost components. I argue here that it makes sense to rely only on one cost calculation method (which I have referred to as method A). I choose to study the range of nuclear costs in the United States, and thus do not consider the variation introduced by tax policy across countries. My focus here is therefore on the third uncertainty factor, namely the differences in estimates of basic cost components.

As already mentioned, I hereafter rely exclusively on method A, following the Modigliani-Miller theorems, which are explained for example in Bailey (2004). Under certain assumptions including a zero tax rate, these theorems state that the value of a project does not depend on the amount of debt that is used to finance it. This implies that the project discount rate before tax (as defined and used in part II.3.b) should not depend on the leverage ratio, which precisely corresponds to method A.

The reasons accounting for differences in cost component estimates are twofold: conceptual choices and numerical uncertainty. Conceptual choices must be made about the way of assessing the overnight costs and the discount rate. Certain analyses such as MIT choose for example to rely on past experience to assess overnight costs, whereas others choose to believe engineering estimates about future plant costs. Similarly, the choice of a discount rate implies determining whether the construction of future nuclear plants will involve more economic risks than other electricity generation technologies, which implies adding a risk premium to the discount rate. Another way to interpret these conceptual choices is to distinguish between long-term and short-term costs. One could argue that in the long run nuclear plant costs should tend towards engineering estimates of future costs and towards lower discount rates as economic data is collected, whereas the first few plants should correspond to the current estimates for the overnight cost and for the financing conditions. These methodological differences reflect more than uncertainty, they correspond to important conceptual assumptions that I argue should be stated very clearly. I therefore choose the scenario approach to account for the uncertainty in the overnight cost and the discount rate. Conversely, parameters other than the overnight cost and the discount rate involve numerical uncertainty that I address through probability distribution functions.

Thus, the cost scenarios are defined by an overnight cost and a discount rate. As already seen on Figure 5, these two parameters account for most of the cost uncertainty, all the more as the focus on future generations of nuclear plants in the US limits the uncertainty about the capacity factor, the economic life and the tax rate, as explained later. Table 13 presents the six cost scenarios I am studying hereafter. The high discount rate (8.5% real) is defined by a 12% real rate of return on equity, a 5% real bond rate and a 50% initial leverage ratio, which is what most studies regard as the current financing conditions for new nuclear plants given the significant economic risks involved with regard to other technologies (high and uncertain capital costs, long construction times and payback periods). The low estimate (6.6% real) corresponds to the financing conditions offered to other electricity generation technologies, which could be applied to nuclear plants in the future if the first plants are built successfully, which would reduce the economic uncertainty. The three values for the overnight cost reflect the range of assumptions from previous studies: the high value accounts for the MIT estimate of past experience of new nuclear plants, while the low value is the estimate from the Chicago study for mature Generation III nuclear plants. These two parameters define six scenarios, referred to by two letters, corresponding respectively to the discount rate for the first, and to the overnight cost for the second.

		Overnight Cost		
		Low ($1200/kW)	Medium ($1600/kW)	High ($2000/kW)
Discount Rate	Low (9% real equity return, 60% leverage ratio)	LL	LM	LH
	High (12% real equity return, 50% leverage ratio)	HL	HM	HH

Table 13. The Six Cost Scenarios, Defined by the Overnight Cost and the Financing Parameters

The other cost parameters are less controversial, and are therefore assumed to follow a probability distribution function common to all scenarios. All distribution functions have the shape of a symmetrical normal distribution with an initial standard deviation equal to the difference between the average and the lower bound of the estimate range. Distributions are next truncated at the low and high bounds of the ranges, as shown on Figure 7 on the example of the capacity factor.

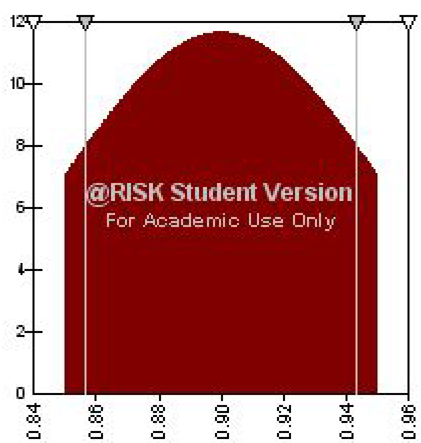

Figure 7. Truncated Normal PDF, Example of the Capacity Factor

The parameters defining the normal curves are available in Table 14. I follow the assumptions of the previous cost studies detailed in Table 5, except for the capacity factor and the economic life. Since I focus on Generation III plants, I do not take into account the low capacity factors from the MIT study, which relies on the past experience and not on the current performance. Given that the capacity factor of nuclear power plants has steadily increased from 55% in the 1980s to around 90% in 2005, and since the purpose of new generations of nuclear plants is to increase their efficiency and competitiveness, I do not foresee any reason why future power plants should have lower capacity factors than current plants. Using the same rationale, I exclude low economic lives from the analysis because the licenses of many current nuclear plants are being extended to 60 years, and because next generations of nuclear plants aim to increase these economic lives.

	Low	High
Plant Characteristics		
Capacity Factor	85%	95%
Construction Time (years)	5	7
Economic Life (years)	40	60
Cost Assumptions		
Overnight Cost ($/kW)	Defines the scenario	
Decommissioning ($)	250	550
Capital Increment ($/kW)	0	25
Fixed O&M ($/kW)	50	60
Variable O&M ($/kWh)	0.0004	0.002
O&M Escalation Rate (real)	0%	1%
Fuel Cost ($/MMbtu)	0.30	0.55
Heat Rate (BTU/kWh)	10,400	10,400
Fuel Escalation (real)	0.00%	0.50%
Waste Fee ($/kWh)	0.001	0.001
Financial assumptions		
Inflation Rate	3%	
Bond Rate (real)	4.9%	
Equity Return (real)	Defines the scenario	
% Debt Finance	Defines the scenario	
Tax Rate	38%	
MACRS Life (years)	15	

Table 14. Ranges Defining the Distributions of the Cost Parameters

Finally, an overall long-term scenario is defined, with probability distribution functions for all parameters including the overnight cost and the financing parameters (Table 15). This overall scenario is approximately equivalent to a weighted average of the previous six scenarios since it attributes probabilities to both controversial assumptions.

	Low	High
Overnight Cost ($/kW)	1200	1600
Equity Return (real)	9%	12%
% Debt Finance	60%	50%

Table 15. Additional Cost Parameter Ranges for the Overall Long-Term Scenario

In this long-term scenario I assume that financing parameters follow a truncated normal distribution over the whole range of values previously defined. New plants may reveal data that would decrease the uncertainty regarding capital costs, but some of the economic risks are structural and would not be affected by the construction of new plants. In particular, a development of nuclear power depends on political decisions that shape the electricity sector through law and economic incentives. Were a major accident to occur, or serious proliferation concerns to arise, investors would be likely to fear government intervention against nuclear power, which would increase the risk premiums that bear on the discount rate. I therefore choose to keep the whole range of financing parameter values. Conversely, I assume that overnight costs are distributed only between the low and medium values already mentioned, because the high value corresponds to the cost of the first plants (First Of A Kind plant costs), as explained in MIT and Chicago. Since these FOAK costs are valid only for the first few plants, they are irrelevant to the analysis of a long-term deployment of several thousand plants (Nth Of A Kind plant costs). I do not address the issue of how the first few expensive plants would be financed if their construction were indeed more expensive, but I simply note that governments might subsidize them, and that companies could even pay for FOAK costs if they anticipate significant learning curves and low economic risks.

b. The Different Scenarios

Method A and the parameters described in the previous section lead to the nuclear power cost averages of Table 16, and to the probability distribution functions of Figure 8.

		Overnight Cost		
		Low ($1200/kW)	Medium ($1600/kW)	High ($2000/kW)
Discount Rate	Low (9% real equity return, 60% leverage ratio)	31.2	36.1	41.0
	High (12% real equity return, 50% leverage ratio)	36.7	43.5	50.2

Table 16. Nuclear Power Cost Averages of the Six Scenarios (in $/MWh)

These results are consistent with the original cost studies. For example, MIT corresponds to the high end of the highest scenario (HH), and the best estimates from the Chicago study are equivalent to a range that extends from the high end of HL to the high end of HH. DGEMP, the most optimistic best estimate from Table 12, corresponds roughly to scenario HL, and is consistent with the result from Table 16 when tax effects are corrected.

One should note that all original best estimates of nuclear costs assumed a high discount rate (they all correspond to a scenario with the first letter H). In this regard, a few figures presented in Table 16 can seem slightly more optimistic than the original studies. Nevertheless, MIT, Chicago and DGEMP also considered the case of a low discount rate in sensitivity studies, to account for a potential decrease in the economic risks of nuclear plant operation. The MIT panel for example regards this case as “plausible but unproven,” and the Chicago study states that this assumption describes what would happen if the first plants were built in an economically successful way. They are not considered “best estimates” because they do not correspond to the financing conditions of the near future, but only to potential improvements in the medium to long term. The most optimistic scenario LL is therefore more optimistic than the “best estimates,” but corresponds to the optimistic cases of the original sensitivity studies, and makes sense as a potential long-term cost scenario.

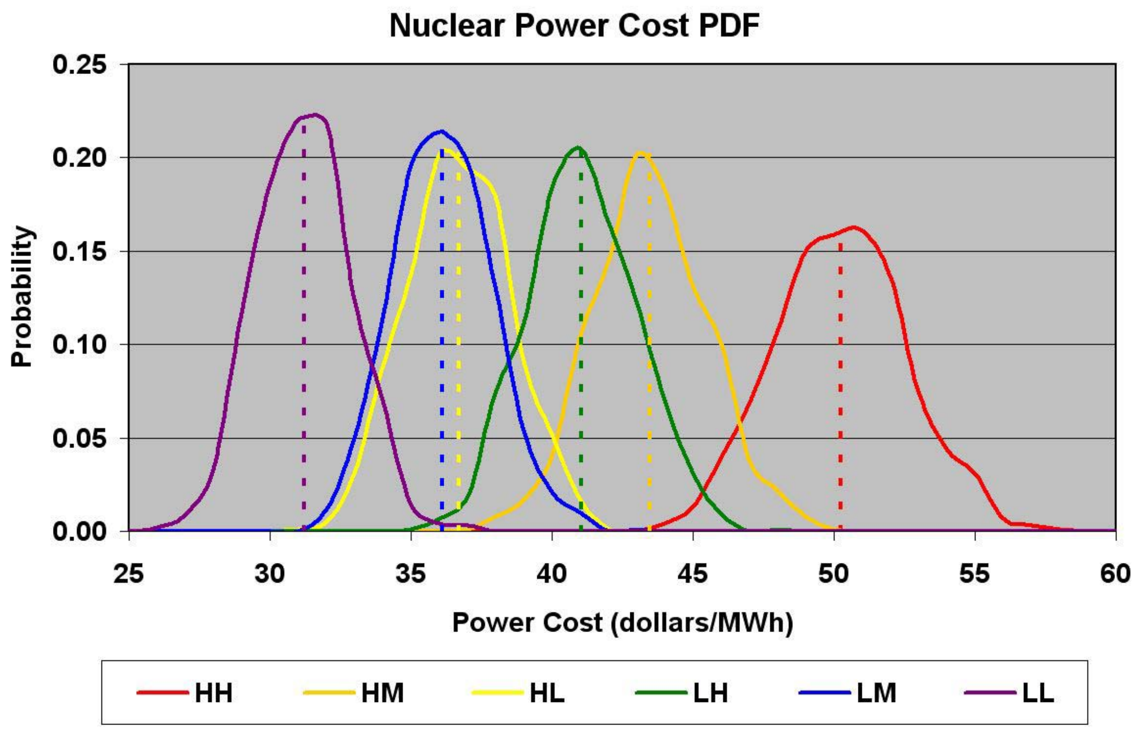

Figure 8. Probability Distribution Functions of the Six Cost Scenarios

As expected, the overall long-term scenario (Figure 9) is an average of the four scenarios that do not have high overnight costs (LL, LM, HL and HM, namely all curves but the red and green ones), and therefore ranges from approximately \$25/MWh to \$50/MWh.

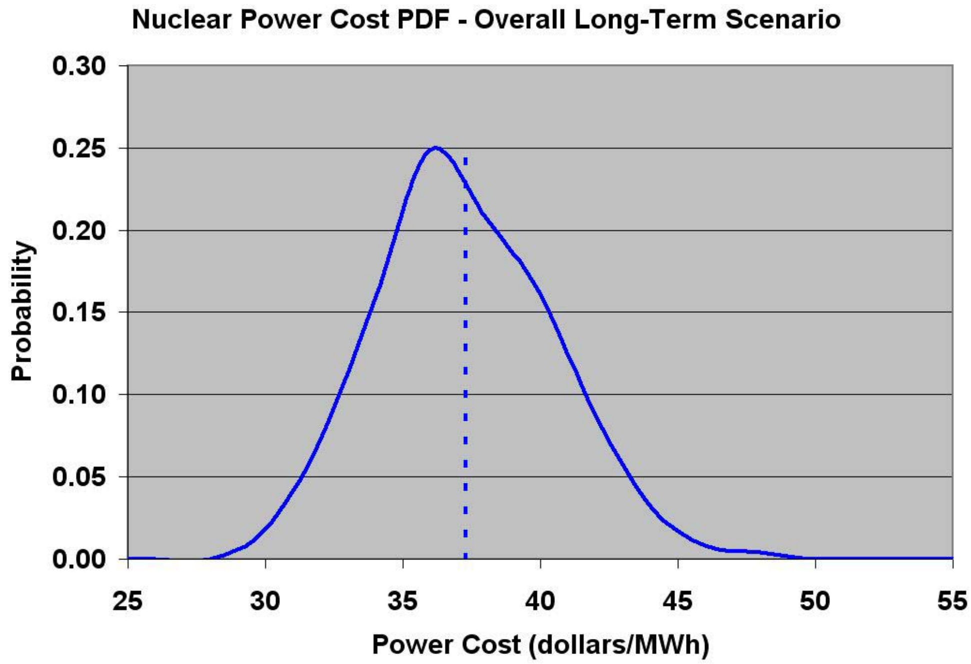

Figure 9. Probability Distribution Function for the Overall Long-Term Scenario

In the next chapters, these nuclear cost scenarios will be used to analyze the interaction between climate policies and the development of nuclear power.

III. Implementing Nuclear Technologies Within EPPA

To examine the potential role of nuclear power, an advanced nuclear technology representing Generation III reactors is introduced into the Emissions Predictions and Policy Analysis economic model. The most important feature of this sector is its cost relative to competing power generation technologies; the scenarios from the previous chapter provide the basis for this comparison. Section 1 presents the EPPA model, while Section 2 details the economic sectors that represent nuclear power technologies. In the following chapters, the EPPA model with the advanced nuclear sector will be used to examine how climate policies and the development of nuclear power affect the economy and the environment at the global scale.

1. Analyzing Climate Policy Impacts: the EPPA Model

The Emissions Prediction and Policy Analysis of the Joint Program on the Science and Policy of Global Change aims to predict the emissions of greenhouse gases and other air pollutants over time, as well as to assess the impact of climate change mitigation policies on the economy.

Technically, EPPA "is a recursive-dynamic multi-regional general equilibrium model of the world economy" (Paltsev et al., 2005). It is a general equilibrium model insofar as it models the whole economy, so that the interactions between the different markets are taken into account – as opposed to a partial equilibrium model in which a few markets are cleared independently from other markets. As can be seen in Figure 10, all flows of goods, services, revenues and expenditures are therefore accounted for in such a general equilibrium model. Goods, services and primary factors enter a first circular flow: consumers supply labor and capital to producer sectors, which use them to produce goods, which are in turn provided to the consumers. In exchange for the primary factors they supply, consumers receive income, which they use to purchase the goods and services provided by the production sectors: this defines the reverse flow of payments.

The economic model is closed in the sense that these different flows must be balanced when the model finds a solution. In other words, there is no external creation of goods or wealth (apart from the initial endowments of consumers): the only goods that can be consumed are those that are provided by the production sectors (or that exist as endowments, such as natural resources), and the only primary factors that are available to production sectors are those supplied by consumers, who own them.

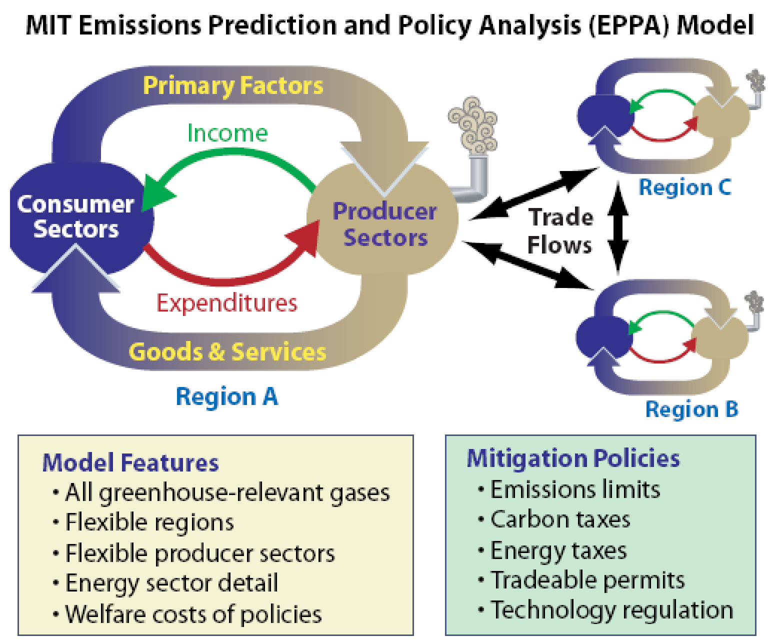

Figure 10. The Circular Flow of Goods and Resources in EPPA

Given unavoidable computational limitations, the world has to be divided into a limited number of regions; one cannot model the economy of the entire world with details at the national level for all countries. Accordingly, certain economic models define only one single region, the entire world. EPPA4 is, however, "multi-regional": it includes 16 regions (see Table 17), which can trade goods and services among each other.

Country or Region†	Sectors	Factors
Developed	***Non-Energy***	Capital
United States (USA)	Agriculture (AGRI)	Labor
Canada (CAN)	Services (SERV)	Crude Oil Resources
Japan (JPN)	Energy-Intensive Products (EINT)	Shale Oil Resources
European Union+ (EUR)	Other Industries Products (OTHR)	Coal Resources
Australia & New Zealand (ANZ)	Transportation (TRAN)	Natural Gas Resources
Former Soviet Union (FSU)	Household Transportation (HTRN)	Nuclear Resources
Eastern Europe (EET)	***Energy***	Hydro Resources
Developing	Coal (COAL)	Wind/Solar Resources
India (IND)	Crude Oil (OIL)	Land
China (CHN)	Refined Oil (ROIL)	
Indonesia (IDZ)	Natural Gas (GAS)	
Higher Income East Asia (ASI)	Electric: Fossil (ELEC)	
Mexico (MEX)	Electric: Hydro (HYDR)	
Central & South America (LAM)	Electric: Nuclear (NUCL)	
Middle East (MES)	Electric: Solar & Wind (SOLW)	
Africa (AFR)	Electric: Biomass (BIOM)	
Rest of World (ROW)	Electric: Natural Gas Combined Cycle (NGCC)	
	Electric: Coal with CSS	
	Electric: Gas with CSS	
	Oil from Shale (SYNO)	
	Synthetic Gas (SYNG)	
	Liquids from Biomass (B-OIL)	

Table 17. EPPA Model Details

(from Paltsev et al., 2007)

The model is recursive-dynamic insofar as it solves for an economic equilibrium in each period without taking into account future periods. Once the model has reached equilibrium for a given period, it updates a number of exogenous factors such as population and productivity (of labor, land, and energy), and accounts for changes in stock variables including investment, depreciation of capital and depletion of natural resources. The model next solves for a new equilibrium in the following period. Recursive-dynamic models can be contrasted with forward-looking models, which solve for price and quantities in all markets in all periods at once, assuming that the future is known with certainty, and assuming a certain discount rate.

In EPPA, production sectors maximize their profits by choosing the most economical combination of inputs to produce a given quantity of output. Their ability to make this tradeoff among inputs is modeled through an elasticity of substitution: with a zero elasticity producers cannot change the share of the different inputs in the production of the output. Conversely, an infinite elasticity of substitution implies that the different inputs are equivalent from an economic point of view, and that producers can use the most economical one to produce an output. The specific functional form used here is the constant elasticity of substitution (CES) function. In the case of more than two inputs, this function is limited in that the substitution elasticity between any two pairs of inputs must be the same. To overcome this limitation, the CES production functions are here nested: separate elasticity parameters allow flexibility to set the rate of substitution between a specific input and a bundle of other inputs. By assumption, producers do not make any profit at the economic equilibrium in a computable general equilibrium model, which is consistent with the hypothesis of working competitive markets. Since the main purpose of EPPA is to predict the emissions of greenhouse gases and to assess policies affecting these emissions, not all production sectors need to be represented with the same level of detail. The energy sector is for instance modeled in greater detail than other sectors, relying on bottom-up analysis to represent the different energy generation technologies. In particular, nuclear power competes against the sectors listed in the electric energy section of Table 17.

Consumers are assumed to maximize a utility function by choosing their preferred goods and services, given their budget constraints. Again, this preference is modeled through elasticities of substitution, which can vary from zero to infinity; consumer sectors are therefore also implemented as nests of goods that can be substituted for each other, depending on the values of the elasticities of substitution.

EPPA solves for an equilibrium that maximizes the producer profits and the consumer utilities, given the initial consumer endowments, the existing production and consumption sector structures, and the policy constraints imposed on the economy. These constraints include taxes, whether on carbon emissions or on factors such as labor or capital, as well as emission limits to represent cap-and-trade systems. The model can therefore be used to assess the impact of mitigation policies by adding constraints to the economy and assessing their impacts on the resulting economic equilibrium. Interesting parameters then include the shadow price on carbon emissions (which can be interpreted as the price of emission permits), and the change in economic welfare (roughly, the aggregate consumption).

2. The Nuclear Power Sectors

Nuclear power is one of the electricity generation technologies already modeled in EPPA. Its representation needs, however, to be improved so as to carry out an assessment of the potential for a large development of advanced nuclear technologies, as is explained in the first part. Section b then describes the representation of the economic sectors that account for nuclear power in the version of EPPA I use.

a. Previous Representation of Nuclear Technologies

The existing nuclear sector within EPPA is modeled as depicted in Figure 11, with a nest that includes a nuclear resource, labor and capital. The shares of these different factors vary by region, but on average they are close to 60% for capital, 25% for labor and 15% for the nuclear resource.

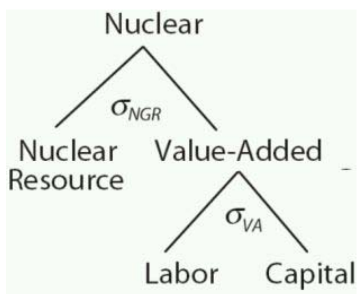

Figure 11. Nest of the Nuclear Sector as Implemented in Previous Versions of EPPA

The distinctive feature of this existing nuclear sector is the fact that the evolution over time of the nuclear resource is determined exogenously. Given the low elasticity of substitution between this resource and the value-added bundle, the evolution of the nuclear resource determines the evolution of the nuclear market share. An advantage of this approach is that the paths of nuclear capacity expansion or retirement can be preserved, as they were politically determined. Limitations include the fact that the economics of nuclear power generation plays a very limited role in determining the amount of nuclear electricity produced.

This representation of the nuclear sector is not well suited to analyze the prospects for an expansion of nuclear power, for two main reasons. First, the current nuclear sector represents accurately the cost of operating existing nuclear plants, but not the cost of constructing new reactors. Since existing reactors are to be decommissioned, an accurate representation of future nuclear power requires the implementation of a new economic sector within EPPA. Second, the market share of nuclear power should be determined endogenously so as to be able to assess the impact of climate change mitigation policies: if the market share is determined exogenously, climate policies do not have any impact on the evolution of nuclear power, by assumption, which is questionable. The new representation of nuclear power described in the next section addresses both these issues.

b. Enhanced Representation of the Nuclear Power Sector

In order to account for the existence of several generations of nuclear power plant technologies – which correspond to different competitiveness levels – two economic sectors are implemented within EPPA. The current nuclear power sector is slightly modified to represent the plants built before 2010, and disappears between 2010 and 2050, to account for the gradual decommissioning of existing reactors. A second nuclear sector models more advanced nuclear technologies – namely, Generation III plants built after 2010 – which may replace existing electricity generation technologies, depending on their competitiveness with regard to other electricity generation technologies.

i. A Sector Modeling the Existing Nuclear Plants

Nuclear power plants built before 2010 are modeled using the existing EPPA nuclear sector, assuming a linear growth path between 1997 and 2010, based on data for nuclear electricity generation in 1997 (IEA, 2001 and NEA, 1999) and in 2005 (WNA, 2007). IEA reports the gross production of electricity, whereas NEA and WNA report the net production, which is on average lower by 5.3% in OECD countries. Since only IEA data are available for non-OECD countries, I rely on the IEA gross production for these non-OECD countries, and I apply a uniform 5.3% correction factor. I also assume that nuclear power starts growing very slowly in regions such as the Middle-East (MES), but still accounts for a negligible market share of the electricity sector.

The main new feature within this sector is an assumption about the plants decommissioning schedule. Since this sector is now meant to represent only the plants built before 2010, one can approximately predict their remaining lifetime as well as the disappearance of the aggregate sector. It therefore makes sense to set exogenously the evolution of the nuclear power sector in that case, by defining the evolution of the nuclear resource. Some uncertainty is involved in that prediction, especially because of the potential extension of the plant licenses (typically from 40 years to 60 years). I here rely on a study conducted by the IAEA, which assesses the decommissioning cost schedule for the next 40 years (Figure 12). According to that study, most of the decommissioning of the existing plants will occur between 2025 and 2045.

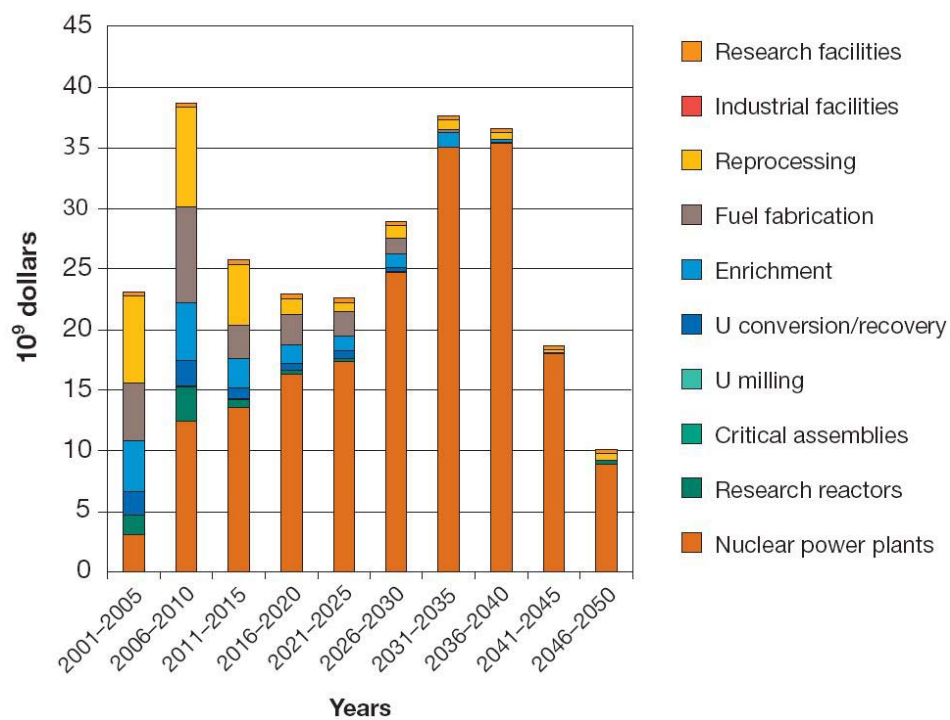

Figure 12. Decommissioning Costs for Different Types of Nuclear Facilities, from 2001 to 2050
(from IAEA, 2004)

I assume that the number of plants decommissioned will approximately follow the decommissioning cost pattern from Figure 12. This implies a decrease in the amount of nuclear resources available to the sector (Figure 13), which is proportional to the decommissioning costs in the next period. Given the production structure for existing nuclear, this has the effect of gradually reducing capacity since fuel is not supplied to the sector.

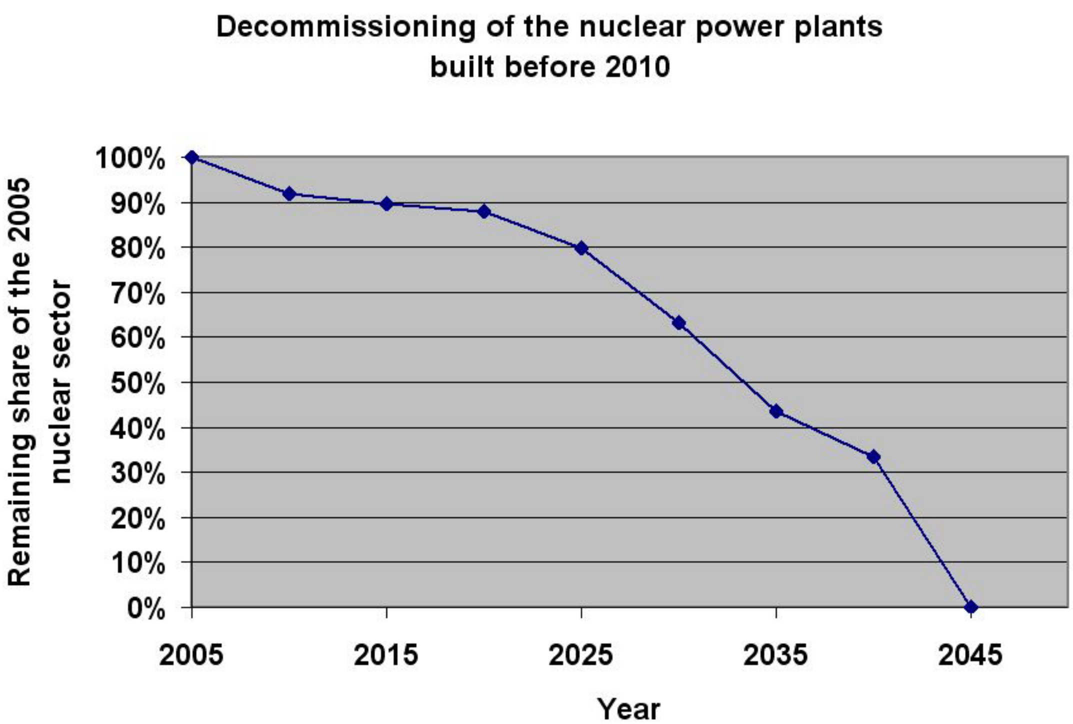

Figure 13. Decommissioning Schedule of Power Plants Built before 2010

(Adapted from IAEA, 2004)

ii. A Sector Modeling Advanced Generation III Plants

Following the representation of other advanced technologies for power generation (Paltsev et al., 2005), the sector that models advanced Generation III nuclear power is structured as described in Figure 14.

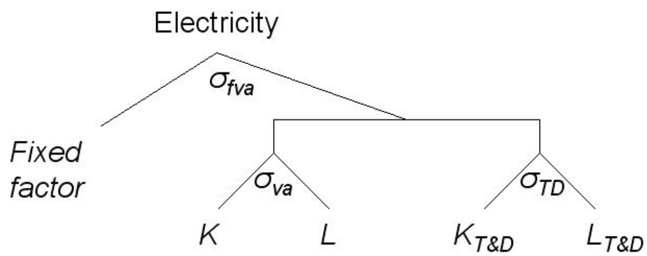

Figure 14. Nest of the Sector Representing Advanced Generation III Nuclear Technologies

In particular, a fixed factor controls the market penetration speed of the new technology, to account for adjustment costs that occur with rapid expansion (see McFarland et al., 2004). Its evolution over time is designed so as to replicate the behavior of the rapidly developing nuclear industry in France in the early 1980s. This fixed factor has an impact on the nuclear market share only at the beginning of the development of the technology: contrary to the nuclear resource from the previous nuclear sector, it does not set the eventual nuclear power production, which is determined endogenously by the model. In the short run and under rapid pressure for expansion, it has an impact on the nuclear cost by increasing the amounts of capital and labor that are required to produce a given amount of power, and by creating fixed factor rents.

Capital and labor initially account for 68% and 32% of the total nuclear power cost; these shares next change over time, depending on the relative prices of capital and labor. They are separated into two value-added bundles, which correspond to electricity generation costs (78%), and to transmission and distribution costs (22%). In both cases the elasticity of substitution is assumed to be similar to that of value-added bundles in other electricity generation sectors, namely 0.5.

Nuclear fuel is not directly represented in the nest of Figure 14, because most of the fuel cost comes from the enrichment and fuel fabrication stages, which involve essentially labor and capital costs. Besides, as already explained, the resources in uranium are significant and relatively well distributed around the world. I therefore assume that there is no significant scarcity rent associated with the ownership of uranium deposits. Fuel costs, which typically account for only 15% of the bus-bar nuclear cost, are therefore distributed between capital and labor within the value-added bundle for electricity generation.

Finally, the relative competitiveness of the advanced nuclear sector with regard to other power generation technologies is modeled through a so-called "mark-up", which is defined as the ratio of the cost of power generated through the new technology, over the price of electricity in 1997. I here compute this mark-up as the ratio of the nuclear power cost over the coal power cost, using the same levelized cost model described in part II. This approach assumes that the marginal cost of electricity production in 1997 corresponds to conventional coal power, which is represented in EPPA in the conventional fossil electricity sector (ELEC). This leads to the six cost scenarios of Figure 8 for nuclear power, and to a PDF for the coal power cost (Figure 15). As in the nuclear case, the different coal power cost parameters are assumed to follow a truncated normal distribution with the low and high bounds defined in Table 18. These bounds are based on the coal power cost studies of MIT (2003), University of Chicago (2004), DGEMP (2003), and CERI (2004).

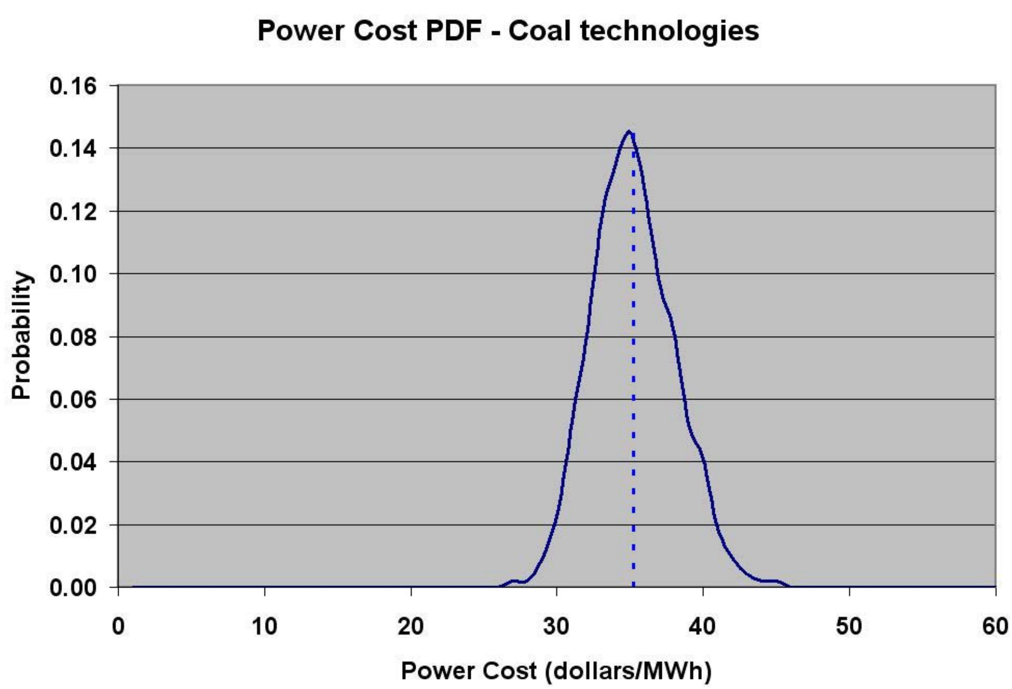

Figure 15. Probability Distribution Function for the Coal Power Cost

	Low	High
Plant Characteristics		
Capacity Factor	85%	95%
Construction Time (years)	2	4
Economic Life (years)	20	40
Cost Assumptions		
Overnight Cost ($/kW)	1,050	1,450
Decommissioning ($)	0	
Capital Increment ($/kW)	0	15
Fixed O&M ($/kW)	23	26
Variable O&M ($/kWh)	0.003	0.005
O&M Escalation Rate (real)	0%	1%
Fuel Cost ($/MMbtu)	1.00	1.25
Heat Rate (BTU/kWh)	8,500	9,300
Fuel Escalation (real)	-0.50%	0.50%
Waste Fee ($/kWh)	0	
Financial assumptions		
Inflation Rate	3%	
Bond Rate (real)	5.0%	
Equity Return (real)	9%	12%
% Debt Finance	50%	70%
Tax Rate	12%	
MACRS Life (years)	15	

Table 18. Assumptions for the Calculation of the Coal Power Cost PDF

All the power costs computed so far are bus-bar costs insofar as they do not include transmission and distribution costs, which need however to be included in the final mark-ups. In order to assess these T&D costs, I rely on the data that was used to model other electricity generation sectors in EPPA (McFarland et al., 2004). They were evaluated at $24.3/MWh, for coal power costs of $47.3/MWh. Since the levelized cost model does not predict the same average coal power cost, I adjust the absolute values of T&D costs, in order to have the same T&D share in the cost of coal power. I then add this adjusted T&D cost to the average bus-bar costs previously calculated (Figure 8 and Figure 15), which leads to the average mark-ups of Table 19. Again, these mark-ups are crucial insofar as they determine the relative competitiveness of advanced nuclear technologies.

		Overnight Cost		
		Low ($1200/kW)	Medium ($1600/kW)	High ($2000/kW)
Discount Rate	Low (9% real equity return, 60% leverage ratio)	0.92	1.02	1.11
	High (12% real equity return, 50% leverage ratio)	1.03	1.15	1.28

Table 19. EPPA Nuclear Mark-Ups

(Ratio of Advanced Nuclear Power Cost Including T&D, over Coal Power Costs Including T&D)

IV. Economic Interaction between Climate Policies and the Development of the Nuclear Sector

The Emissions Predictions and Policy Analysis model described in part III is hereafter used to assess to the economic interactions between climate change mitigation policies and the electricity sector structure. Section 1 studies the extent to which climate policies can shape the structure of the electricity generation sector, and assesses in particular the impact they can have on the development of the advanced nuclear power sector. Conversely, Section 2 analyzes the impact of a development of the nuclear sector on the costs of climate policies, which leads to an estimate of what advanced nuclear technologies are worth to the society under different assumptions about their base costs.

1. *Impact of Climate Policies on the Structure of the Power Production Sector*

As explained in part I.1, climate change mitigation policies involve some form of greenhouse gas emission constraint, from command-and-control measures to cap-and-trade mechanisms. Besides the reference case in which no climate policy is implemented, I here focus on cap-and-trade policies, with greenhouse gas concentration targets in 2100 ranging from 450ppm to 750ppm.

These concentration targets do not, however, define completely the cap-and-trade policies, because different emission reduction schedules can be used to meet the same concentration target. Emission paths over time must therefore be defined, which implies determining whether stringent constraints should be set earlier or later. Early carbon emission reductions have a greater impact on the concentration of carbon dioxide, which accumulates over time in the atmosphere, but these early reductions also imply higher economic costs. The analyses below are based on the EPPA emission paths defined in the CCSP report (Clarke et al., 2006), which correspond to a carbon price that increases by 4% per year. Advanced nuclear technologies were, however, not represented in these

CCSP scenarios; given that the new nuclear sector is added into the version of EPPA I use, the previous CCSP scenarios do no longer necessarily lead to a 4% price increase. Emission reduction paths could be adjusted for each nuclear cost case, in order for the carbon price to increase at a rate equal to the 4% discount rate, and for the emission reduction timing to be economically optimal[2]. I here instead choose to keep the emission reduction paths from the CCSP scenarios, and I analyze the impact of the introduction of advanced nuclear technologies. This approach corresponds to the idealized case in which emission reduction targets are set once and for all without considering advanced nuclear technologies, and in which competitive advanced nuclear power emerges unexpectedly after the targets are defined.

The relative burdens placed on the different regions also need to be determined for the policy to be properly defined. The CCSP emission scenarios I use here assume that all countries reduce their emissions at the same rate, and that a constant marginal cost of abatement is applied across economic sectors. The different regions are also allowed to trade their emission permits until equilibrium is reached; consequently, these policies involve a single worldwide price of carbon emissions.

Climate policies such as cap-and-trade mechanisms are expected to have an influence on the electricity sector by internalizing the costs of greenhouse gas emissions. In particular, since the different electricity generation technologies do not have the same carbon-intensiveness, climate policies are likely to change the relative market shares of the different technologies. Coal is for example very carbon-intensive, and is therefore likely to be negatively affected by climate policies, whereas nuclear power, which is nearly carbon-free, should be positively affected. The following sections analyze quantitatively this effect using the nuclear cost scenarios defined in part III (which correspond to the "mark-ups" of part IV).

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[2] As discussed in the CCSP report (Clarke et al., 2006) and as shown in Gurgel et al. (2007), a price path that rises at a constant rate equal to the discount rate approximates well some aspects of forward-looking behavior but not necessarily the welfare implications.

a. Evolution of the Worldwide Nuclear Capacity

To analyze the impact of cap-and-trade policies on the advanced nuclear sector, I here compare the evolution of the nuclear power production capacity in the reference case (no climate policy) to that of a 550ppm policy.

Reference Case

Assuming that no climate change mitigation policy is implemented, the market share of advanced Generation III nuclear power increases over time as depicted in Figure 16. Notably, advanced nuclear technologies take over almost the entire electricity market by 2040 in the three lowest nuclear cost scenarios. But even in the high nuclear cost scenarios, advanced nuclear technologies do become competitive because of the rise in the fuel prices of conventional electricity generation technologies. More precisely, the market share of the advanced nuclear sector reaches 10% in 2015, 2025 and 2035 for the LH, HM and HH scenarios respectively.

Thus, all the nuclear cost scenarios – even the highest ones – involve at least some deployment of advanced nuclear technologies in the future.

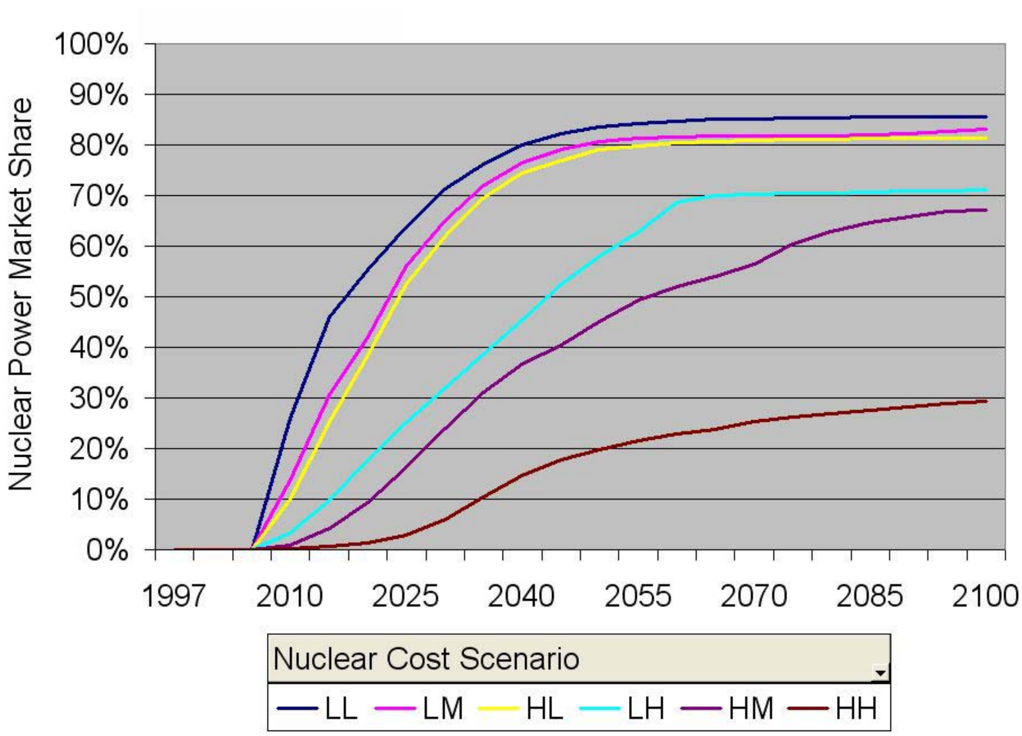

Figure 16. Evolution of the Market Share of the Advanced Nuclear Sector, No Climate Policy Case

Assuming a 90% capacity factor, these market shares translate into the nuclear power production capacities of Figure 17. In the lowest cost scenario (LL), advanced nuclear technologies are expected to be so inexpensive that about 120 1GWe reactors would be built per year worldwide. The penetration speed is, however, smaller in the other low cost scenarios (LM and HL), with approximately 75 new 1GWe plants built per year in the first decade, increasing to 90 1GWe plants built per year around 2050. The market penetration speed of these advanced nuclear technologies would therefore be very high, despite the adjustment costs designed to replicate those of the large development of nuclear power in the 1980s. In short, nuclear power would be so inexpensive under these scenarios that the market penetration speed should be very high even with the adjustment costs.

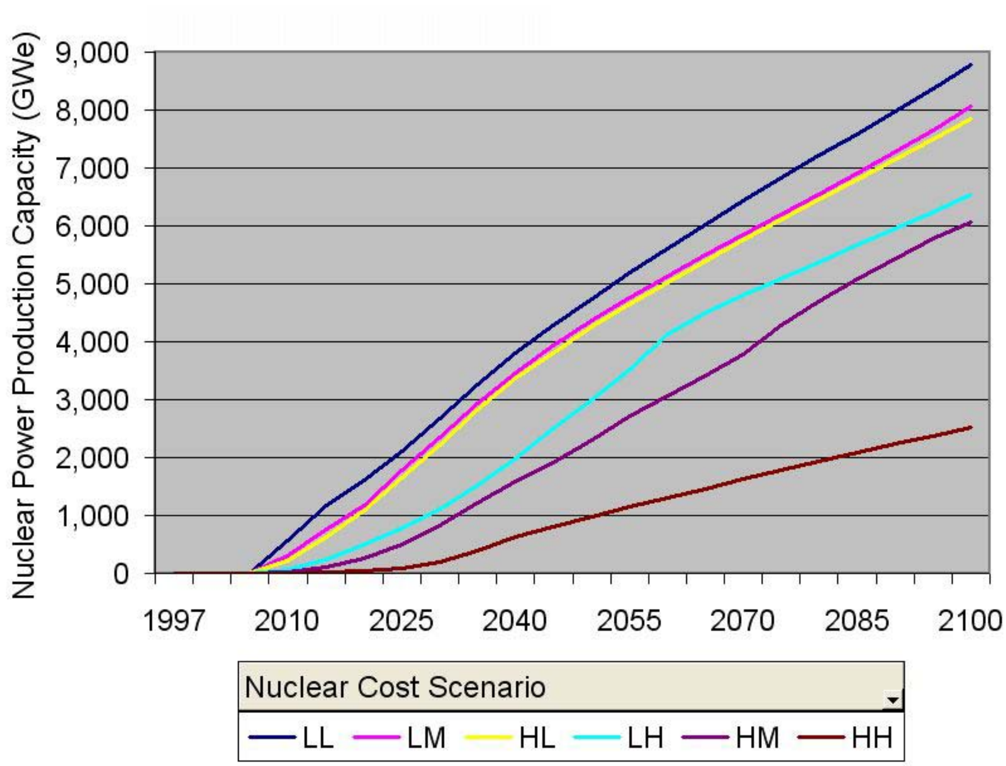

Figure 17. Worldwide Advanced Nuclear Capacity (in GWe), No Policy Case

<u>550ppm Policy</u>

If a 550ppm policy is implemented, the high nuclear cost scenarios are most affected (Figure 18), while the low cost scenarios are almost unchanged. Indeed, in these low cost scenarios, advanced nuclear technologies are more competitive than other electricity generation technologies, even without climate policy. The climate policy makes advanced nuclear even more competitive, but it cannot take over the market much faster because of the adjustment costs embedded in the fixed factor. In this case, imposing a climate policy affects merely the eventual nuclear market share, which increases from 86% to 93% (these numbers are likely overly optimistic, as explained later). Conversely, in the high cost scenarios, the market share of the advanced nuclear sector increases significantly: for example in the LH and HM scenarios, the nuclear market shares in 2050 are higher than 80%, whereas they amounted to 58% and 45% in the reference scenario.

Thus, a 550ppm policy increases strongly the deployment of advanced nuclear technologies in the high nuclear cost scenarios.

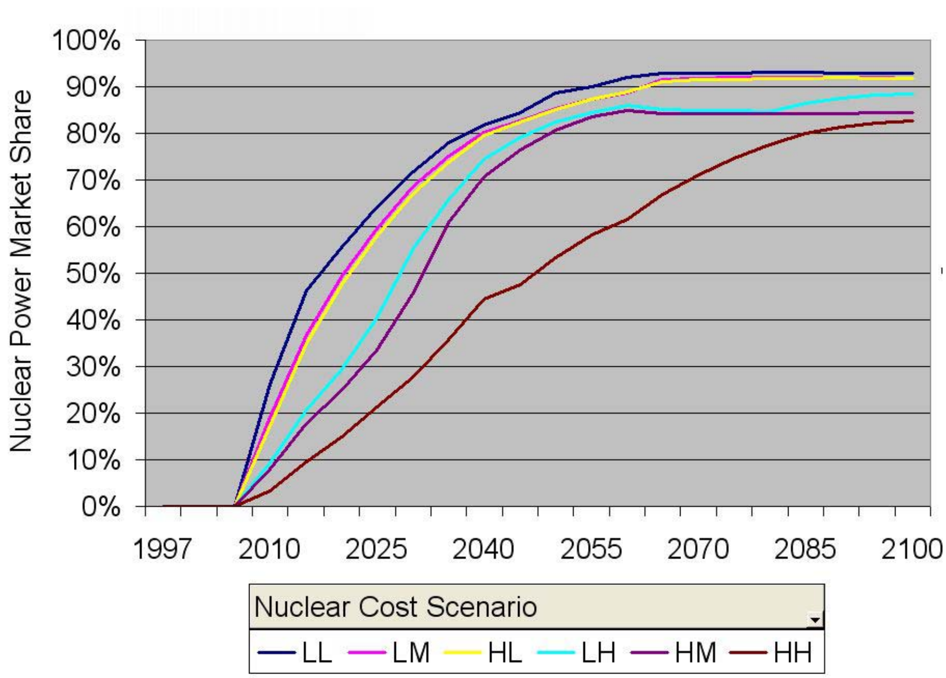

Figure 18. Worldwide Market Share of the Advanced Nuclear Sector, 550 ppm Scenario

Again, assuming a 90% capacity factor, these market shares translate into the worldwide advanced nuclear capacities of Figure 19.

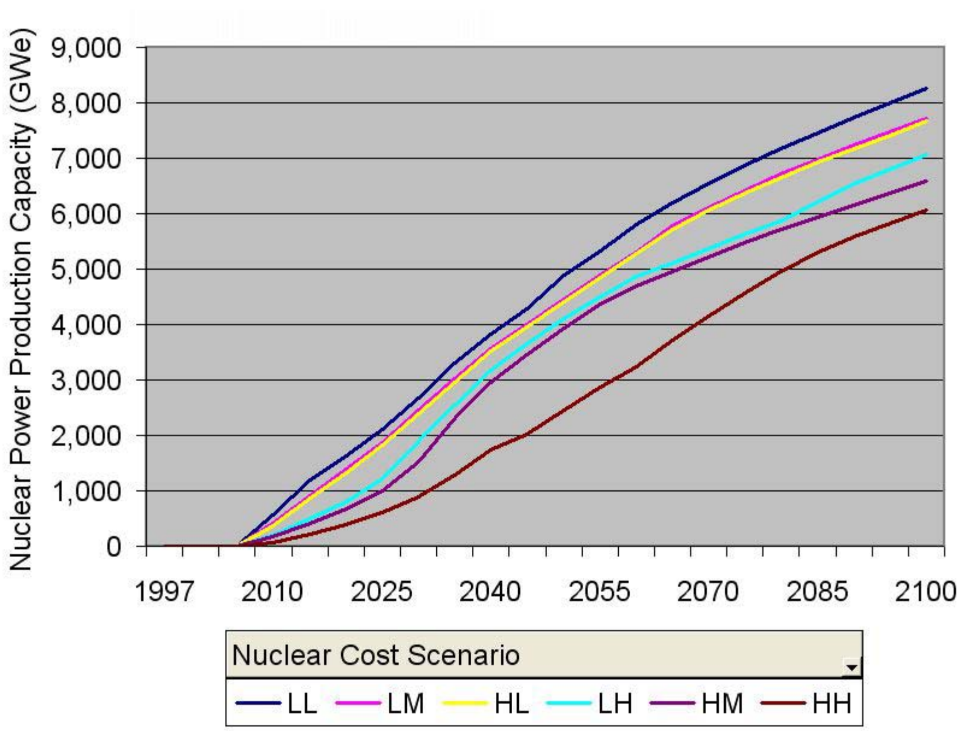

Figure 19. Worldwide Advanced Nuclear Capacity (in GWe), 550 ppm Scenario

<u>Effect of the Stringency of the Policy</u>

The same analysis is carried out for different levels of stringency of the climate policy, from the reference case to a 450ppm policy. This leads to Figure 20, which presents the nuclear market share in 2050 as a function of the stringency of the policy, and of the nuclear cost scenario.

Again, the flat shapes of the curves for the low nuclear cost scenarios show that the nuclear market shares in 2050 do not depend much on the climate policy, because nuclear power is very competitive anyway. Conversely, the stringency of the policy affects strongly the nuclear market shares in the high nuclear cost scenarios: the tighter the constraint, the higher the market shares in 2050, because of the variation in the competitiveness of nuclear power. Note, however, that a 450ppm policy is not stringent enough for nuclear to take over the entire market by 2050 in the HH scenario.

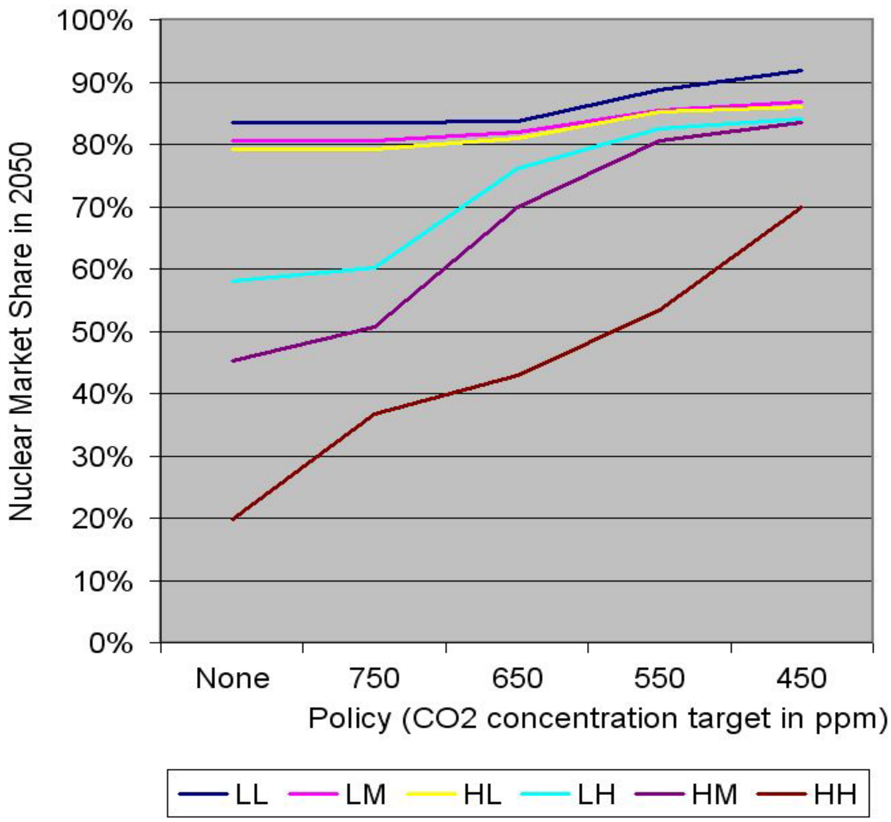

Figure 20. Effect of the Stringency of the Climate Policy on the Nuclear Market Share in 2050

<u>Overestimation of the Market Shares</u>

The previous graphs likely are overly optimistic in terms of the nuclear market share, because they do not account for the fact that nuclear is much less competitive for peaking electricity generation than for base-load. If this effect were taken into account, one would expect the overall nuclear market share to be capped at about 80% worldwide, instead of reaching levels over 90% as in Figure 18. The following paragraphs explain this effect in greater detail.

The demand for electricity involves natural daily, weekly and annual cycles. Figure 21 shows for example the demand for thermal electricity production in France: the electricity consumption is higher in the daytime than at night, during weekdays than during weekends, and in the winter than in the summer. The annual trend would be somewhat different in countries that use more air conditioning in the summer (such as the United

States), in which case the electricity consumption might be higher in the summer than in the winter, with a lower demand during the spring and the fall.

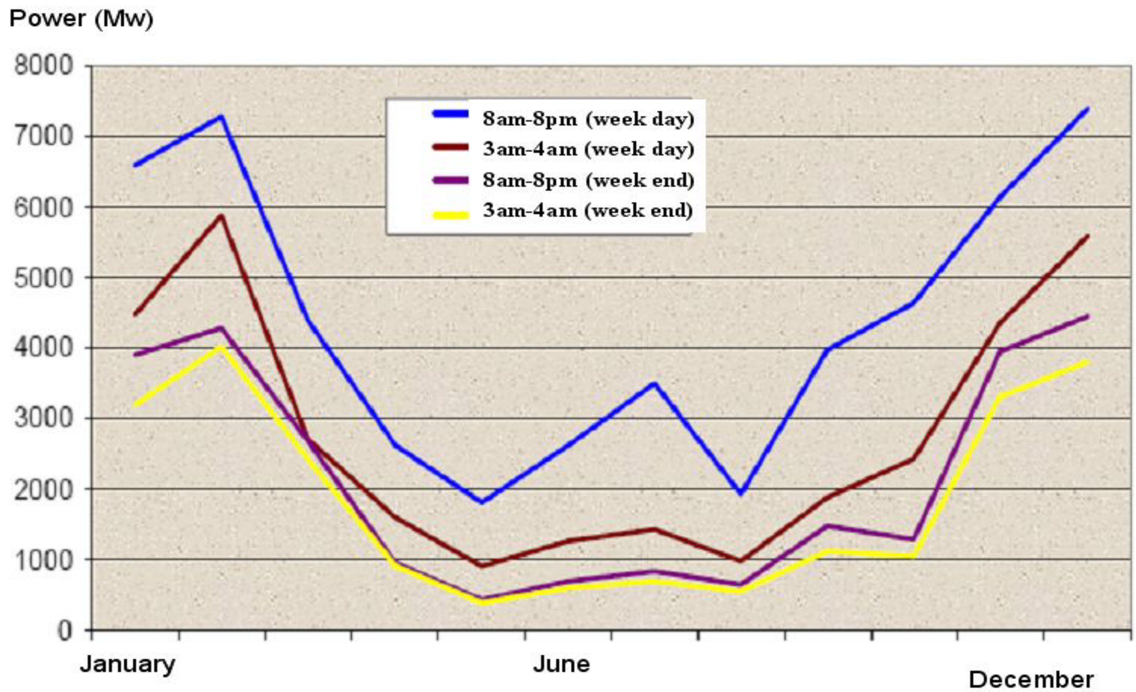

Figure 21. Thermal Electricity Production in France in 1999
(from DGEMP-DIDEME, 2003)

Since the demand for electricity varies significantly over time, and since electricity cannot be stored directly in large quantities, the supply of electricity must adapt to these variations. Several types of power generation capacity therefore exist: a base-load capacity, which operates all the time, a shoulder capacity, which operates often, and a peak capacity, which operates only rarely. This distinction is all the more important as certain technologies are well suited to produce base-load electricity, while others are more appropriate for shoulder and peak capacity. Gas power technologies belong for example to the latter category, because most of the costs (i.e. fuel costs) are not incurred when the plant is shut down. These gas plants can therefore be operated in a flexible way while remaining competitive. Conversely, nuclear technologies are an example of base-load capacity because of their capital-intensiveness: operators face capital costs regardless of whether the plant is operating, which implies that current nuclear plants would be at a competitive disadvantage if they were operated for peak capacity. Note however that this might change in the future if nuclear plants were used to produce hydrogen for transportation during off-peak periods in a hydrogen-based economy, if other electricity storage technologies were available, or if the load could be better managed. Changes in technology and electricity pricing could shift electricity load to off-peak periods: e.g. with the right incentives and if they were viable in other ways, electric vehicles might be recharged at night.

b. Evolution of the Electricity Sector Structure

After the analysis of the impact of climate policies specifically on the nuclear sector, this section assesses their broader effect on the whole electricity generation sector.

Figure 22 and Figure 23 show the structure of the electricity sector in the low nuclear cost scenario (LL), respectively without and with a 550ppm policy. As expected, climate policies have very little impact on the electricity sector structure, because advanced nuclear power is very competitive in any case. The only notable effect is the total replacement of conventional fuel-powered technologies by nuclear electricity after 2060.

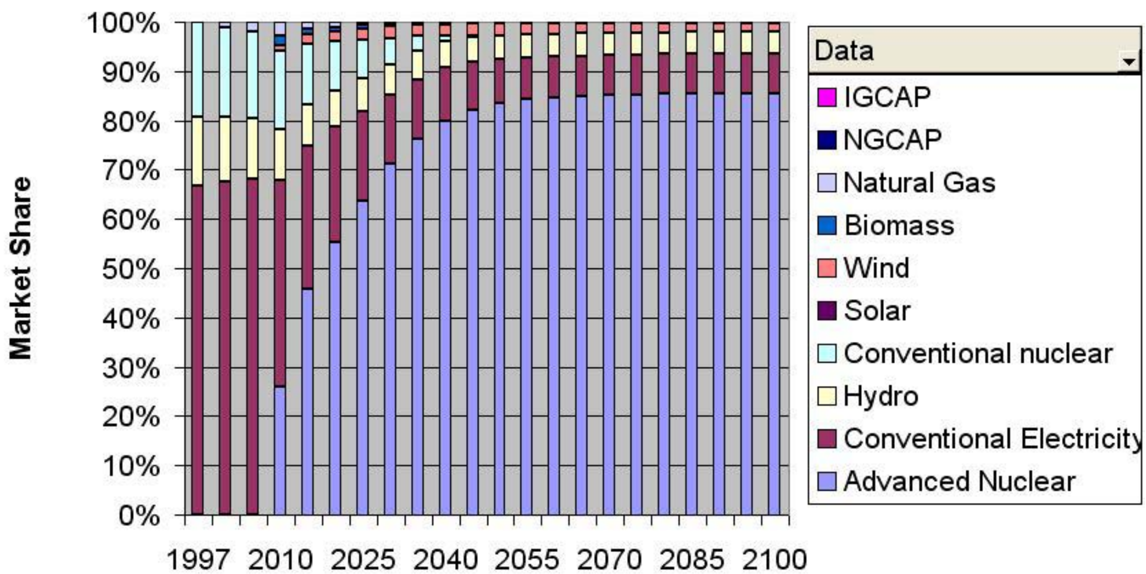

Figure 22. Structure of the Electricity Sector, LL Nuclear Cost Scenario, No Climate Policy Case

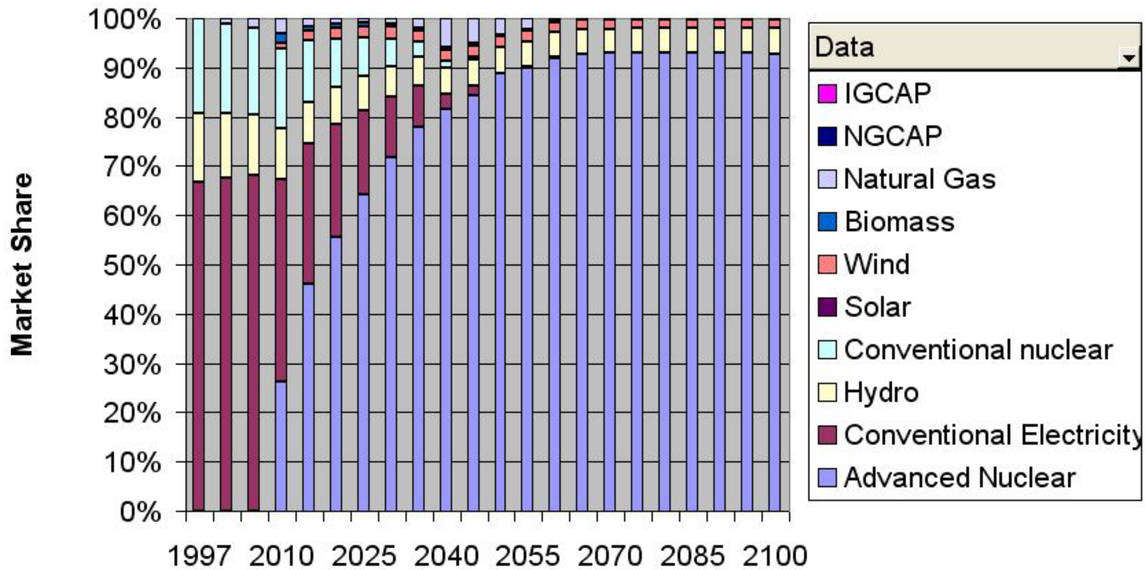

Figure 23. Structure of the Electricity Sector, LL Nuclear Cost Scenario, 550ppm Scenario

Conversely, Figure 24 and Figure 25 show that in the high nuclear cost scenario (HH), climate policies radically change the electricity sector structure. Without climate policy, conventional fuel-powered electricity generation technologies account for more than 70% of the electricity sector starting in 2020 until the end of the century, because nuclear power remains uncompetitive. However, a 550ppm policy triggers a much larger deployment of NGCC technologies, which replace the conventional electricity sector (mostly coal-fueled) starting in 2010, because gas power is less carbon-intensive than coal power. Next, as greenhouse gas emission constraints become tighter, these two technologies are replaced by IGCAP (integrated gasification of coal with carbon capture and sequestration) and advanced nuclear technologies, which emit less greenhouse gas. Again, even in the cases that are unfavorable to nuclear power (HH nuclear cost scenario), some deployment of advanced nuclear technologies is observed.

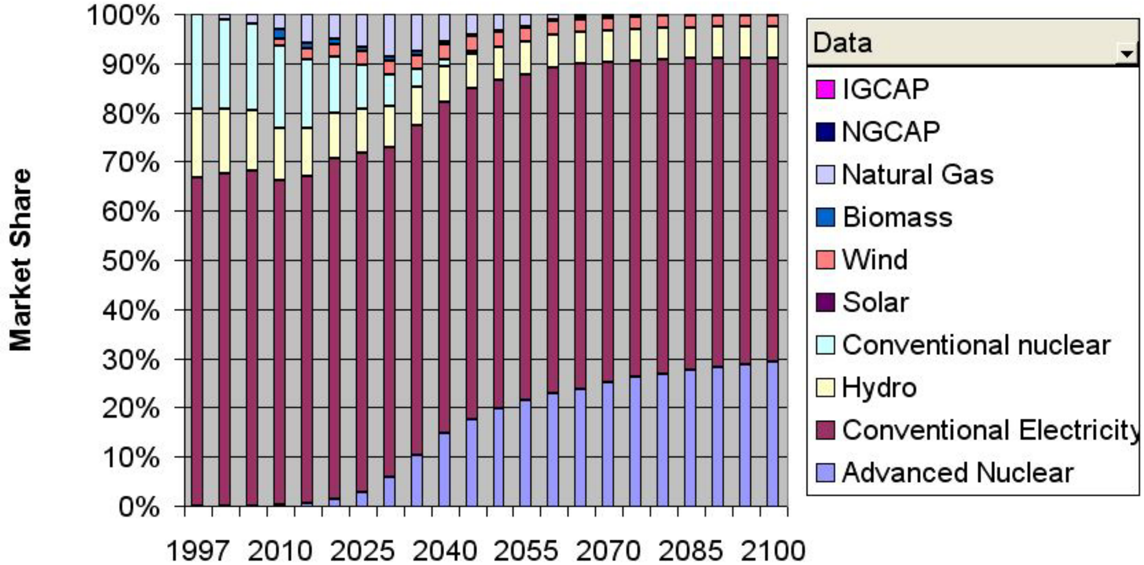

Figure 24. Structure of the Electricity Sector, HH Nuclear Cost Scenario, No Climate Policy Case

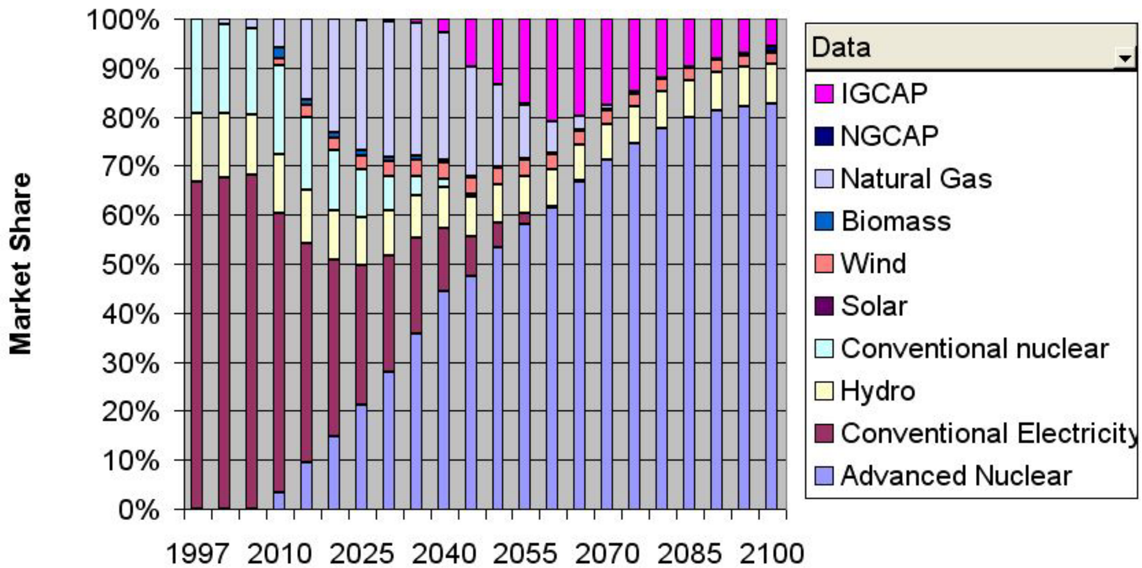

Figure 25. Structure of the Electricity Sector, HH Nuclear Cost Scenario, 550ppm Scenario

c. Issue of Uranium Depletion

Based on the simulation runs of the previous section, the evolution of the electricity generation sector is likely to involve a significant development of advanced nuclear technologies, which would imply substantial uranium requirements. Consequently, I here analyze whether uranium resources are large enough to sustain such a nuclear development.

The assessment of worldwide uranium resources is actually not straightforward, because not all the uranium deposits are known yet, and because those that are known are not always well known. More precisely, the uranium price constitutes a signal that provides incentives or disincentives to look for new uranium deposits, depending on the exploration and extraction cost with regard to that price. Thus, if the uranium price were to increase significantly, exploration for uranium ore would be encouraged, which would be very likely to increase the known uranium resources. Also, the existence of many uranium deposits has only been inferred from indirect evidence, which means that experts are less confident about the quantity and quality of such deposits than they are about deposits that have been more extensively explored. Accordingly, uranium resources assessments involve significant uncertainties, both because the current price does not provide enough incentive to explore for expensive resources, and because the level of confidence about the actual existence of many deposits is low.

Acknowledging these uncertainties, the most recent and comprehensive assessment was released in 2006 by the OECD Nuclear Energy Agency and by the International Atomic Energy Agency in their so-called “Red Book” (NEA/IAEA, 2006). Adding up the resources of all confidence levels from this publication (both conventional and unconventional phosphate resources), the cost distribution is shown on the left part Figure 26 (from $0/kgU to $130/kgU). The right part of this figure accounts for seawater uranium, which would be available in extremely large quantities at a cost around $300/kgU (NEA/IAEA, 2004).

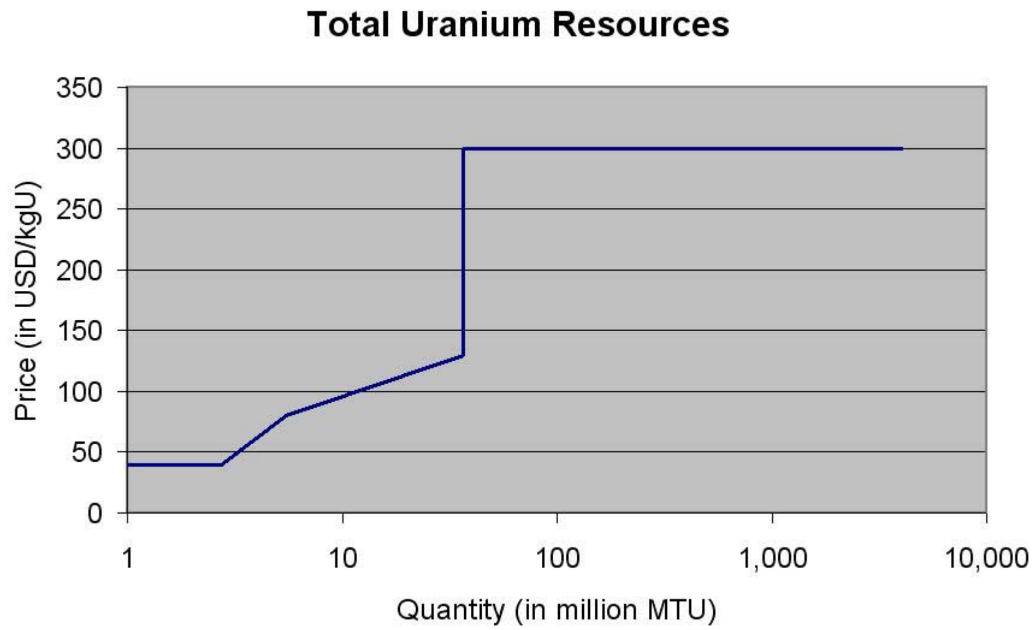

Figure 26. Total Uranium Resources (in Millions of Metric Tons of Uranium)
from NEA/IAEA (2003) and NEA/IAEA (2005)

One can then compare these resources to the uranium requirements of the most optimistic scenario for nuclear power (LL nuclear cost scenario, and a 450ppm policy). Assuming the same nuclear fuel consumption as in the MIT study (MIT, 2003), namely 226.5 MTU/(GWe.yr), the total uranium requirements until 2100 in this case amount to 92.1 million MTU (to produce 3,569TkWh of nuclear power between 1997 and 2100). According to Figure 26, this would mean that seawater uranium would have to be extracted, and that the uranium price would reach \$300/kgU by 2100. Although this possibility is not strictly impossible, known uranium resources are more likely to increase over time as the uranium price increases.

In conclusion, the large development of nuclear power implied by our lowest nuclear cost scenario involves the depletion of currently known deposits of conventional and phosphate uranium by the end of the century. Based on this scenario and given the current estimates of uranium resources, seawater uranium would therefore need to be extracted in order to sustain such a large deployment of nuclear power using a once-through fuel cycle. The impact on the price of uranium ore would be significant, since seawater uranium is currently estimated to cost around $300/kgU. However, given the large resources in seawater uranium, no nuclear fuel shortage should occur before the end of the century.

2. *Impact of Nuclear Power on the Cost of Climate Policies*

After the impact of climate policies on the nuclear sector evolution, I turn to the impact of nuclear power on the costs of climate policies. I address two aspects of the cost of climate policies: first, the price of carbon, which represents the marginal abatement cost of greenhouse gas emissions, and second, the consumption loss due to the climate policy, which represents the overall welfare loss. This second analysis enables me to estimate the willingness to pay to get more competitive advanced nuclear technologies.

a. Change in the Carbon Price

Under cap-and-trade policies, the "carbon price" refers merely to the price of the greenhouse gas emission permits. Since the policies analyzed here involve international trading, these prices are equal across regions. In economic terms, the carbon price is equal to the marginal abatement cost of greenhouse gas emissions; in other words it corresponds to the additional cost of further reducing emissions by an additional ton of carbon. If switching from coal to nuclear power is the most economical way of reducing the emissions, the carbon price should be equal to the cost of this change in the electricity sector. Conversely, if the most economical way of reducing emissions does not involve the electricity sector, the carbon price should not be linked to the electricity sector features, for a given level of emissions reductions.

The carbon price is shown on Figure 27 under different nuclear cost scenarios, including a scenario without advanced nuclear technologies. The same 550ppm policy is applied to all cases. As can be seen on the graph in 2010 (when the policy starts), the cost of nuclear power has a large impact on the initial carbon price, which ranges from $2.6/tC in the LL scenario to $50/tC if advanced nuclear technologies are not available.

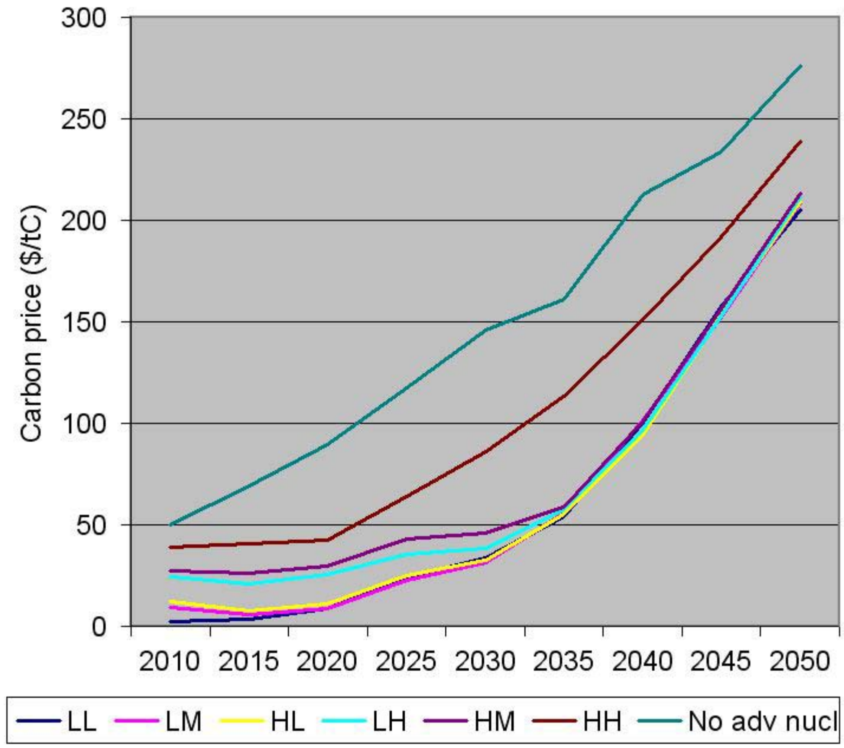

Figure 27. Short-Term Evolution of the Carbon Price (in $/tC), 550ppm Policy

Thus, the short-term marginal emission abatement cost depends strongly on the nuclear power cost: the lower the nuclear cost, the lower the marginal abatement cost. This can be due to two effects: first, the development of carbon-free nuclear power in the reference case (without climate policy) decreases the required level of emission reduction when a policy is implemented; second, for a given level of emission reduction, inexpensive nuclear power provides an economical way of reducing these emissions.

The significant variation in the carbon price due to the change in the nuclear power cost suggests that competitive nuclear power would provide a very efficient way of reducing the emissions of greenhouse gases in the short-term. Quantitatively, the greenhouse gas emission reductions when advanced nuclear technologies are not available are about twenty times as expensive, on a marginal cost basis, as when these technologies are very competitive (scenario LL). The society as a whole should therefore be willing to pay a certain amount to reduce nuclear power costs, if these costs are high; conversely, the society should get significant benefits if these costs are already low. The quantitative assessment of this willingness to pay is carried out in the next section.

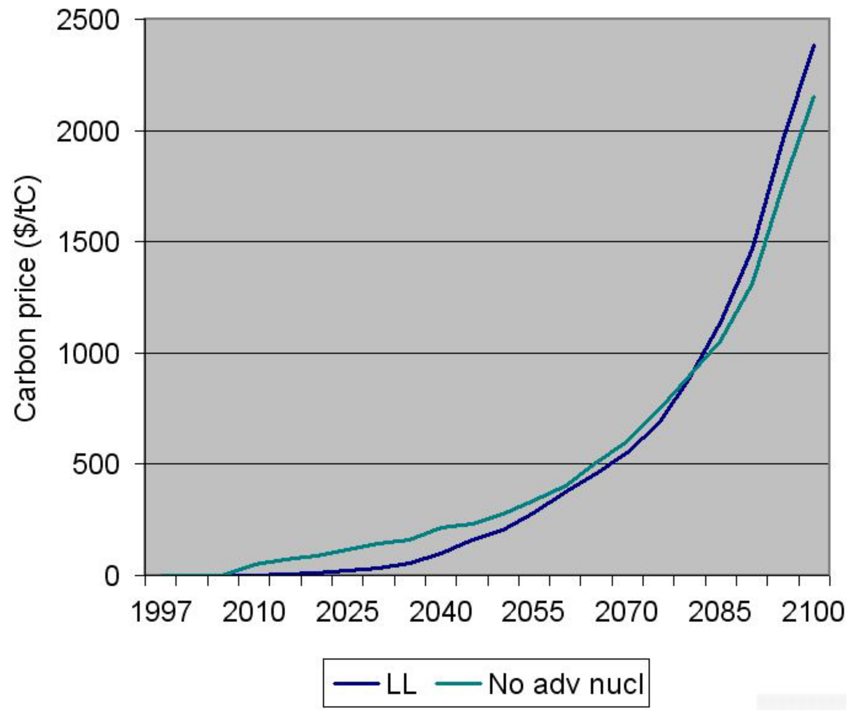

Figure 28. Long-Term Evolution of the Carbon Price (in $/tC), 550ppm Policy

In the longer term, the nuclear cost scenario has a smaller influence on the carbon price (Figure 28), because the electricity sector is completely de-carbonized after 2065 in the 550ppm policy. In the LL scenario, advanced nuclear technologies take over almost the entire market before 2065, while in the HH case there is a mix of IGCAP and nuclear power, both of which are carbon-free. As emission constraints become tighter after 2065, the price of carbon increases, but corresponds to the marginal cost of emission abatement in other sectors of the economy.

In the very long term (after 2080), the effect of the nuclear cost on the carbon price may actually seem counter-intuitive: the higher the nuclear cost, the lower the carbon price. Removing an inexpensive solution to mitigate emissions would reduce the climate policy cost in the long term. This can be attributed to the indirect effect of consumption: as explained in the following section, the higher the nuclear cost, the lower the consumption. A lower consumption implies lower emissions, which means that the carbon constraint is easier to achieve, and that the carbon price could be lower even with higher nuclear costs. Finally, the timing of this long-term effect depends strongly on the climate policy: it appears for example only in 2100 in the 650ppm policy.

b. Change in the World Aggregate Consumption

The total economic cost of climate policies can be assessed through the loss in the world aggregate consumption. While the previous analysis based on the carbon price addressed the marginal cost of emission abatement, the consumption loss is a measure of the total economic welfare loss associated with the climate policy. In other words it does not deal with the additional cost of further reducing emissions by an additional ton of carbon, but with the total cost of reducing emissions by the total abatement amount. This total cost of emission reduction should theoretically depend on the cost of nuclear power since nuclear technologies provide carbon-free electricity; the following paragraphs assess this effect, first in the short-run, next in the long-run, and finally in NPV terms. I conclude with an estimate of the total economic benefit provided by advanced nuclear technologies, depending on the climate policy that is implemented.

Impact of Nuclear Costs on Climate Policy Costs

The short-term evolution of the consumption loss is shown on Figure 29. Strikingly, more competitive advanced nuclear technologies both reduce and delay significantly the costs of a 550ppm policy. For example, the policy cost is reduced by 83% in 2030 in the LL scenario with regard to the HH scenario, and by 49% in 2050. Thus, reducing the cost of nuclear power also significantly reduces the short-term costs of climate change mitigation policies, assuming that the emissions reduction targets are not adjusted when nuclear power becomes less costly.

If the CCSP emissions reductions paths were redefined to take into account the existence of inexpensive advanced nuclear technologies, lower nuclear costs would have a more complex effect on the carbon price and the overall short-term costs. The carbon price would then increase at a rate equal to the discount rate in all scenarios, in order for the emission reduction timing to be economically optimal, as already explained. Low-cost nuclear technologies would lower the required emissions reductions and provide low-cost abatement options, especially in the short run. As a result, short-term emissions abatements would be less costly than those of the CCSP case without advanced nuclear power. In order to take advantage of this abatement cost reduction, actual emission constraints should be tighter than the original CCSP scenarios in the short-term, and less stringent than them in the longer term. Thus, the existence of low-cost nuclear technologies implies weaker short-term cost reductions than those mentioned above, because optimal short-term reductions would be larger than the original CCSP scenarios if the emission reductions paths were readjusted.

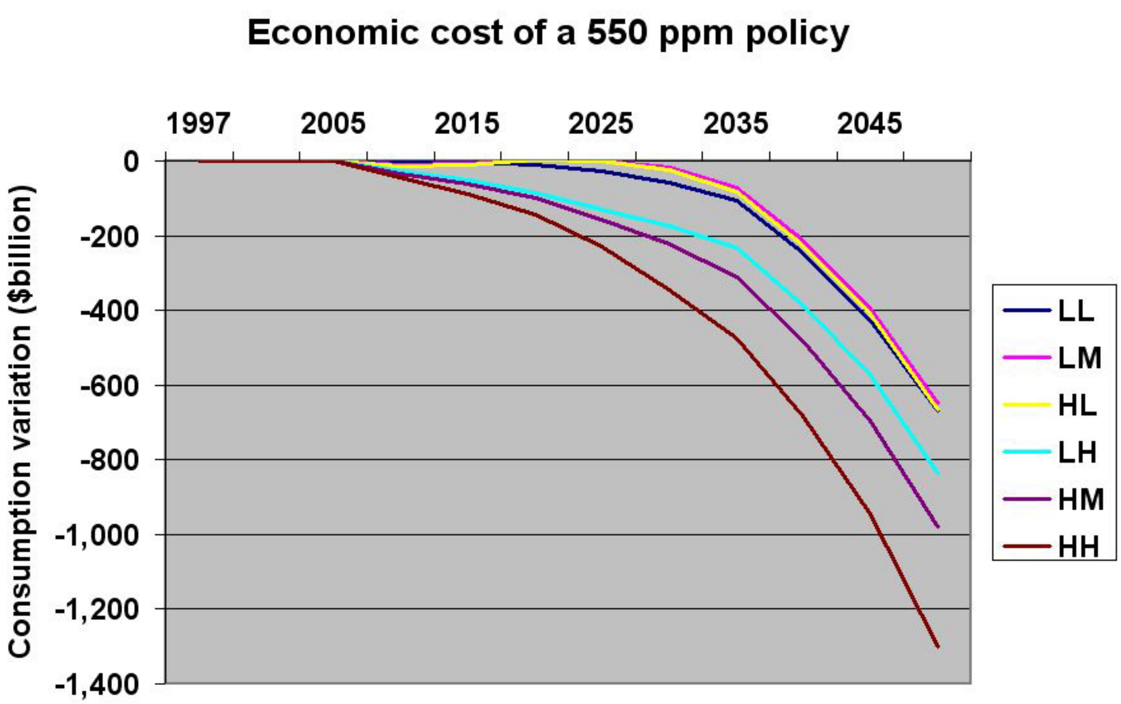

Figure 29. Short-Term Cost of a 550ppm Policy, in Terms of Consumption Loss per Year, under Different Nuclear Cost Scenarios

The cost of nuclear power has also an effect on the long-term consumption loss (as depicted on Figure 30). This is due to the fact that consumption losses are linked to the total abatement cost, and not to the marginal cost. Even if the electricity sector is no longer affecting the marginal cost of emission reductions, nuclear power is still used to abate emissions: the share of nuclear power no longer increases, but it doesn't decrease either. As a result, more expensive nuclear power implies some consumption loss, and therefore a higher cost for the climate policy, even in the long term.

The consumption losses involved here are significant, on the order of a few percents of total consumption. As a basis for comparison, consumption in the HH scenario in the reference case is projected to be approximately $52,300 billion in 2030, $88,600 billion in 2050, and $209,000 billion in 2100. The corresponding economic costs of the 550ppm policy in the HH scenario are then equivalent to a consumption loss of 0.7% in 2030, 1.5% in 2050 and 5.0% in 2100.

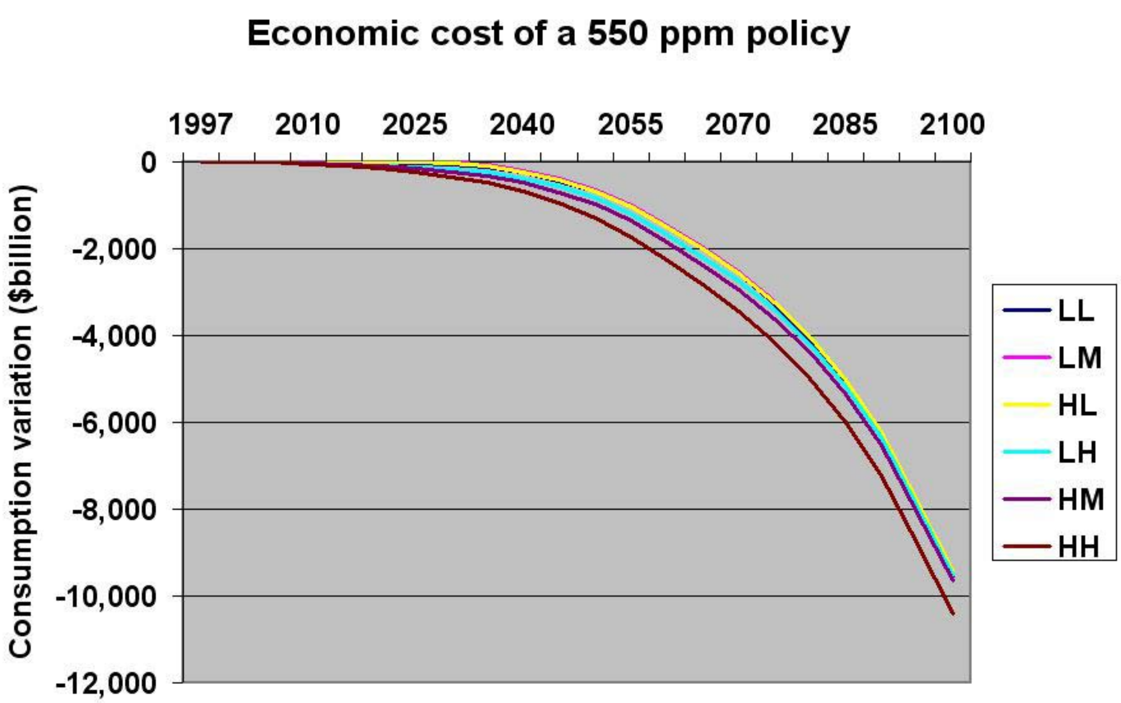

Figure 30. Cost of a 550ppm Policy, in Terms of Consumption Loss per Year, under Different Nuclear Cost Scenarios

Using a standard discount rate of 4% and the formula from part II.1, one can next calculate the Net Present Value (NPV) of these consumption losses, and then make comparisons across levels of climate policy stringency. Figure 31 thus presents the total cost of different climate policies, in 1997 dollars, for different nuclear cost scenarios. Again, the cost of advanced nuclear technologies has a significant impact on the consumption NPV losses: switching from scenario HH to LL reduces the climate policy cost by respectively 14%, 36%, 63%, and 81% in the 450ppm, 550ppm, 650ppm and 750ppm policies (the reference consumption NPV is around $1,200,000 billion). Thus, in NPV terms, less expensive nuclear technologies could reduce climate policy costs by several thousand billion dollars.

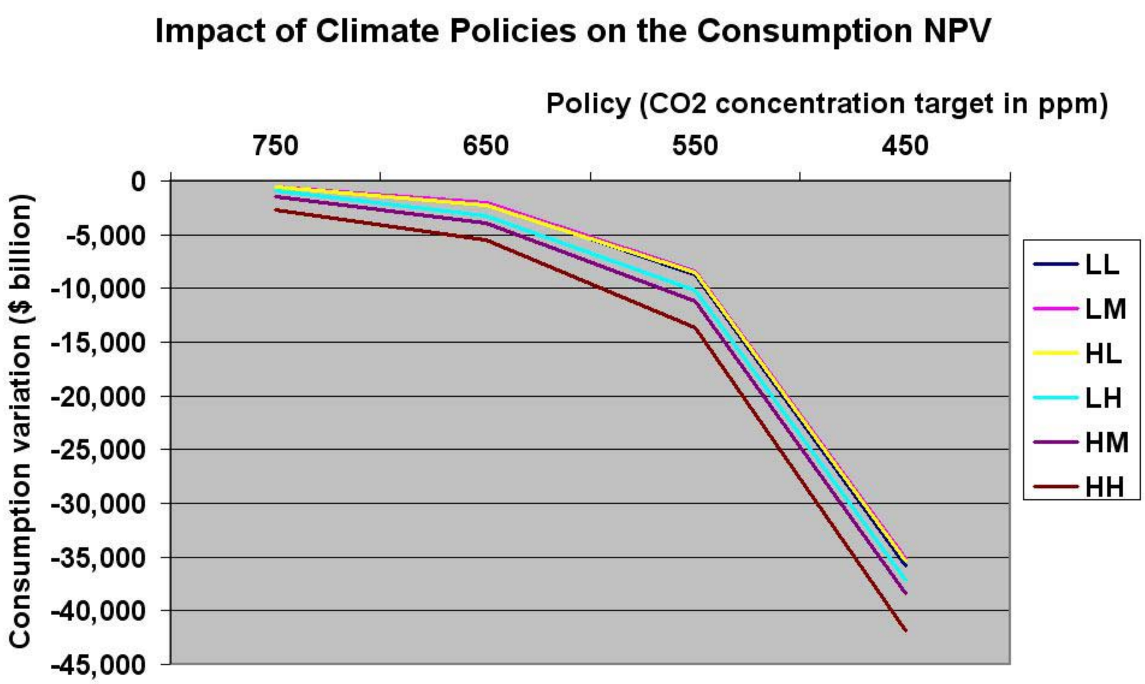

Figure 31. Cost of Climate Policies, in Terms of Consumption NPV Loss, under Different Nuclear Cost Scenarios

Given the magnitude of the cost reductions at stake, the cost of nuclear power can be regarded as one of the main drivers of the climate policy costs, which implies that less expensive nuclear electricity could provide significant economic benefits. I hereafter assess more precisely these benefits.

<u>Total Willingness to Pay to Get Less Expensive Advanced Nuclear Technologies</u>

The benefits of having low nuclear costs are twofold: first, they increase consumption in the reference case because nuclear electricity is less expensive; second, they lower the cost of emission abatement policies by reducing the required emissions reductions and providing a less expensive carbon-free source of electricity. The total willingness to pay to get less expensive advanced nuclear technologies is therefore the sum of these two effects. Regarding the first one, the consumption NPV difference in the no climate policy case amounts to around $5,000 billion (0.4% of the total consumption NPV). To this amount should be added the difference in the climate policy cost between the LL and HH nuclear cost scenarios, which corresponds merely to the range between the curves on Figure 31. The final result on Figure 32 shows that the benefit of having less expensive nuclear power indeed increases with the stringency of the climate policy, and goes up to around $11,000 billion in the 450ppm policy.

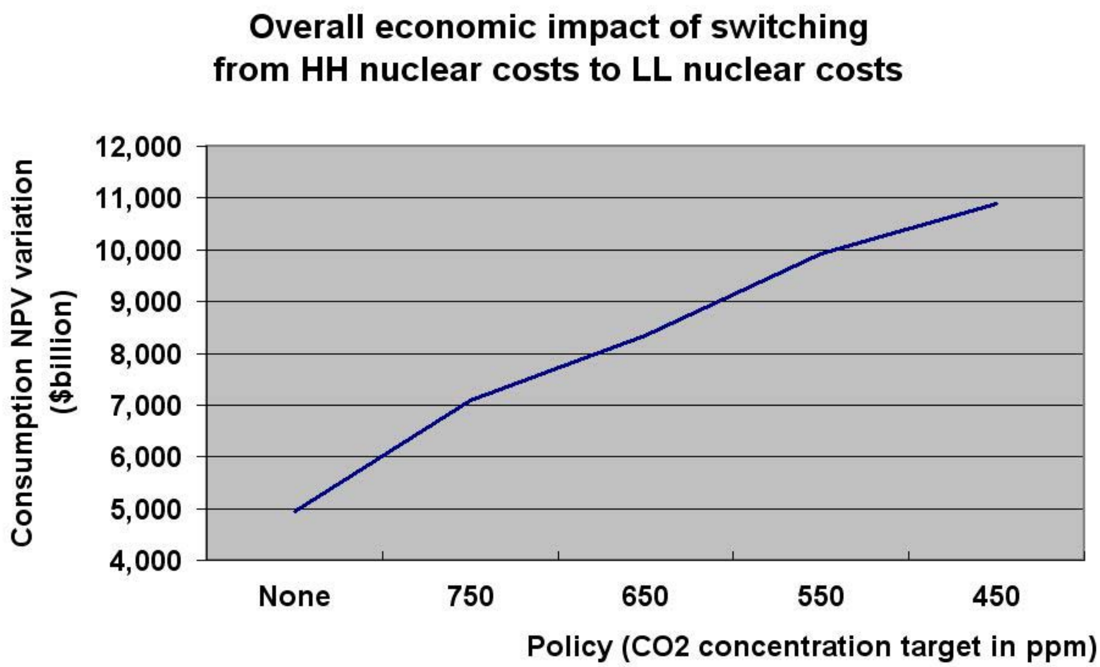

Figure 32. Willingness to Pay to Switch from Scenario HH to Scenario LL, as a Function of the Climate Policy Target

In conclusion, lowering nuclear costs from scenario HH to scenario LL is theoretically worth \$5,000 billion if no climate policy is implemented (in NPV terms), value which goes up to \$11,000 billion in the case of a 450 ppm policy. The payoffs of lowering nuclear costs from scenario HH to scenario LL would therefore be very large, and could offset the money spent on R&D or subsidies to overcome first-of-a-kind costs.

V. Environmental Benefits of a Development of Nuclear Power

Chapter IV showed that the development of nuclear power would have a strong influence on the economics of climate change mitigation policies. In this part, I assess the impact of such development of nuclear power on the environment. Section 1 addresses greenhouse gas emissions, while Section 2 deals with pollution.

1. Mitigation of Climate Change

Since nuclear energy is a carbon-free source of power, one would expect that a significant development of low-cost nuclear power would result in greenhouse gas emission reductions, even in the absence of climate policy. This is indeed the case, as shown on Figure 33: if the costs of advanced nuclear technologies are low, their development triggers significant CO_2 emission reductions.

Quantitatively, 2050 CO_2 emissions in the lowest nuclear cost scenario are 32% lower than those of the scenario in which advanced nuclear technologies are not available (whether for economic or political reasons). In 2100, if advanced nuclear technologies have developed following the LL scenario, they account for 36% of the CO_2 emission reductions required to meet a 650ppm policy, with regard to the reference scenario without advanced nuclear power.

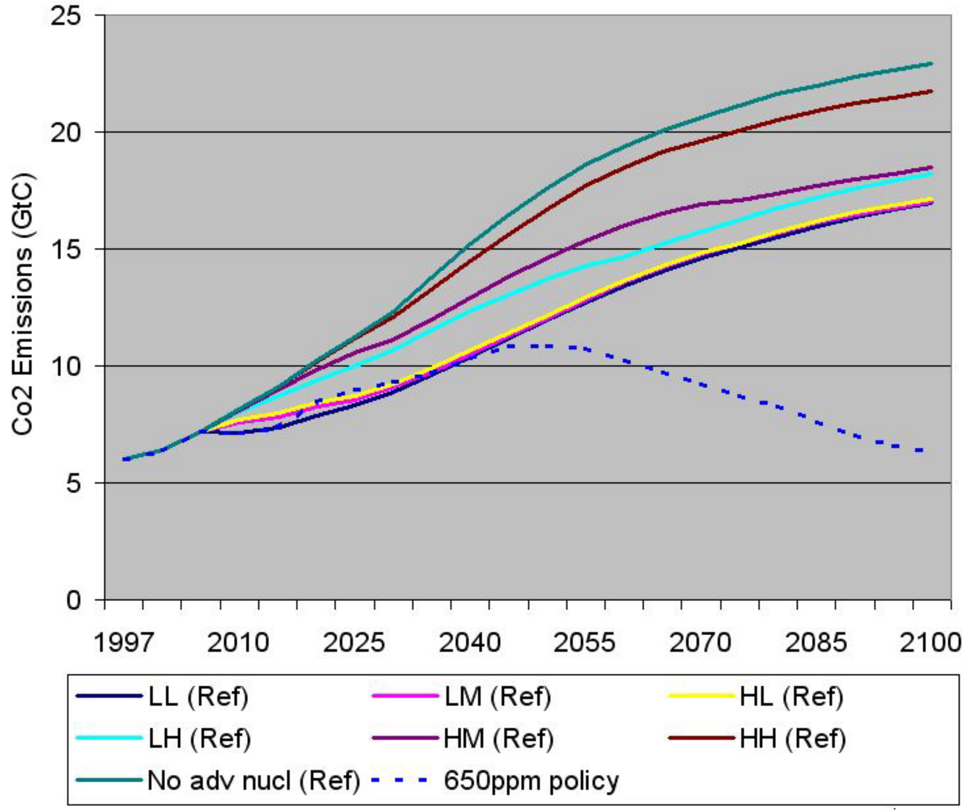

Figure 33. CO_2 Emissions, in Billions of Metric Tons of Carbon, Reference Scenarios & 650ppm Policy

Interestingly, the three lowest nuclear cost scenarios are actually roughly equivalent to a 650ppm policy (without advanced nuclear technologies) until 2045, as shown on Figure 33. If a 650ppm target is considered stringent enough, but that climate policies cannot be implemented on an international scale in the short term (for example because of the difficulty in reaching an international agreement), low-cost nuclear technologies might give some time to set up the institutions required to implement carbon constraints on a global scale, as a second-best option.

If a 650ppm policy is implemented while advanced nuclear technologies are available at a low cost, the emission reduction path should actually be different from the 650ppm curve of Figure 33 (which corresponds to a scenario in which advanced nuclear technologies are not available). As already explained, emissions reductions paths are defined such that the carbon price increases at a rate equal to the discount rate, in order for the emission reduction timing to be economically optimal. Low-cost nuclear technologies would lower the required emissions reductions and provide low-cost abatement options, especially in the short run. As a result, the emission constraints should be tighter than the original CCSP scenarios in the short-term, in order for the carbon price to increase at the desired rate. This would allow less stringent emission constraints in the longer term. In other words, the existence of low-cost nuclear technologies does not mean that emission reduction policies are useless in the short term. It actually implies that optimal overall reductions should be stronger in the short run. The best option is therefore to implement a climate policy even if nuclear costs are low; however, if climate policies cannot be implemented in the short term, the development of low-cost nuclear power constitutes a second best approach.

The impact of nuclear costs on the emissions of other greenhouse gases is much smaller (Figure 34), because emissions from the electricity sector account for a small share of the total emissions, except for SF_6 (Table 20).

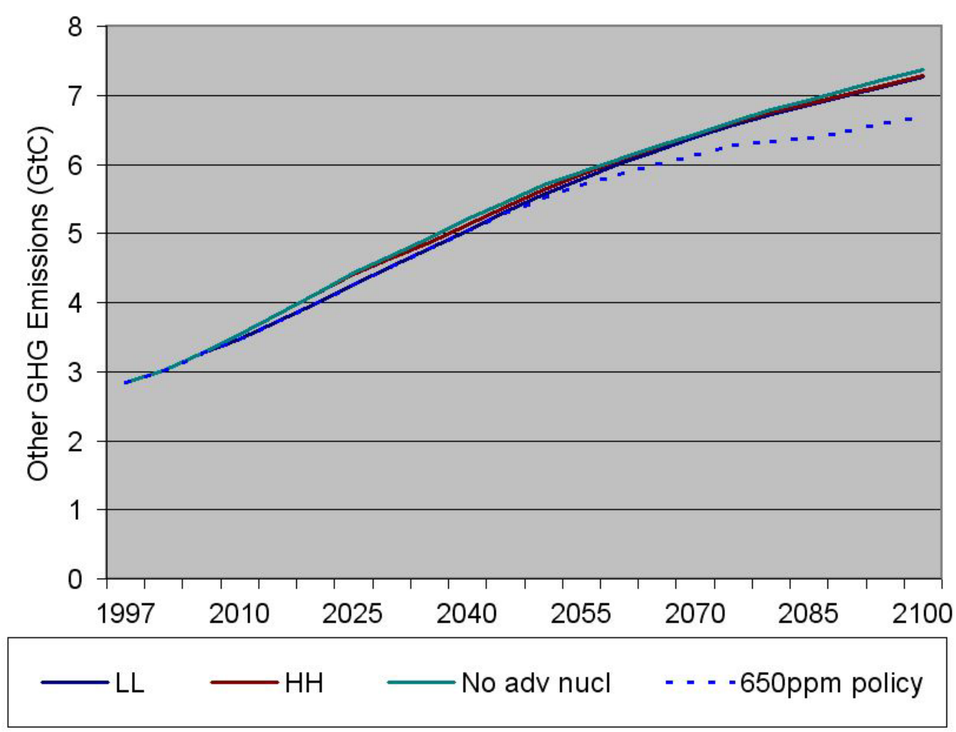

Figure 34. Emissions of Greenhouse Gases Other than CO_2, Reference Scenario

(in Billions of Metric Tons of Carbon Equivalent, Using GWPs)

CH_4	N_2O	PFC	HFC	SF_6
6.4%	2.5%	0.0%	0.0%	61.7%

Table 20. Share of non-CO_2 Greenhouse Gas Emissions from the Electricity Sector in 2000

(when Advanced Nuclear Technologies Are not Available)

More precisely, the introduction of low-cost nuclear technologies induces a small reduction of total CH_4 and N_2O emissions (Table 21), because advanced nuclear technologies replace conventional coal and gas power plants. It also triggers a small increase in the emissions of perfluorocarbons (PFCs) and hydrofluorocarbons (HFCs) from other sectors of the economy, because of the increase in GNP. Conversely, the introduction of advanced nuclear technologies involves a significant increase in SF_6 emissions from electricity transmission and distribution: the introduction of inexpensive nuclear power involves an increase in the quantity of electricity produced and distributed, which in turn implies an increase in SF_6 emissions[3]. SF_6 has a high global warming potential (GWP, equal to 23,900 in EPPA), which implies that low emissions of SF_6 induce a much stronger radiative forcing than comparable emissions of carbon dioxide. However, the emissions of SF_6 are limited in absolute terms; the impact of the increase in SF_6 emissions is therefore negligible, despite the high GWP (the worldwide emissions are equivalent to 0.04GtC in 1997, as compared to 1.9GtC of CH_4).

	CH4	N2O	PFC	HFC	SF6
2025	-4.0%	-1.9%	0.0%	0.2%	9.4%
2050	-1.7%	-2.6%	2.8%	0.9%	17.7%
2100	-1.4%	-1.8%	2.3%	1.5%	30.4%

Table 21. Changes in non-CO_2 Greenhouse Gas Emissions Due to the Introduction of Advanced Nuclear Technologies

(from no Advanced Nuclear to an LL Nuclear Cost Scenario)

[3] SF_6 emissions are not accounted for in the advanced power generation sectors within EPPA; I therefore assume here a linear relationship between SF_6 emissions and the total quantity of electricity produced, instead of relying on the emission reports from the model.

2. Pollution Reduction

Since advanced nuclear technologies would replace coal technologies that emit air pollutants, one could expect the development of nuclear power to be accompanied by some pollution reduction. However, given the shares of pollutant emissions that come from the electricity sector (Table 22), the replacement of conventional fuel-powered electricity generation plants with nuclear power is likely to have a significant effect only on SO_2 and NO_x emissions.

SO_2	NO_x	CO	VOC	BC	OC
40.5%	21.5%	0.2%	0.2%	12.7%	5.2%

Table 22. Worldwide Shares of Pollutant Emissions from the Electricity Sector in 2000

(when Advanced Nuclear Technologies are not Available)

VOC: Volatile Organic Compound; BC: Black Carbon; OC: Organic Carbon

The development of advanced nuclear power actually increases the emissions of CO (Figure 35), and VOC by 2100, because of the increase in GNP. Also, the lower the cost of nuclear power, the higher the GNP increase, and therefore the higher the emissions of CO. The low reductions in CO emissions from the electricity sector are thus offset by an increase in emissions from other sectors of the economy.

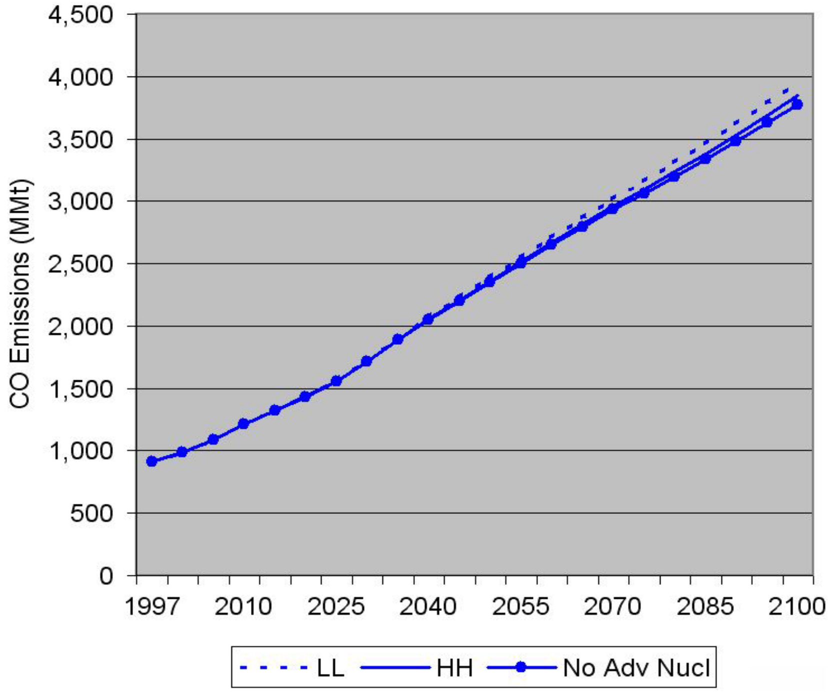

Figure 35. CO Emissions (in millions of metric tons), Reference Scenario

As for the NO_x and SO_2 emissions (Figure 36), they are reduced in 2050 by respectively 14% and 24% between the LL scenario and the scenario without advanced nuclear, assuming no climate policy. Emissions of other pollutants such as black carbon or organic carbon would also be reduced, but by less than 5% in 2100 (Table 23).

	SO_2	NO_x	CO	VOC	BC	OC
2025	-19.8%	-12.6%	0.7%	-4.1%	-10.1%	-5.6%
2050	-24.2%	-13.6%	1.9%	-3.0%	-10.4%	-7.5%
2100	-22.3%	-8.1%	4.8%	2.5%	-3.3%	-4.2%

Table 23. Pollutant Emissions Reductions Due to the Introduction of Advanced Nuclear Technologies

(from no Advanced Nuclear to an LL Nuclear Cost Scenario)

SO_2 emission reductions can appear fairly small given the very significant share of emissions that arise from electricity generation in 2000. This effect is due to the fact that SO_2 emissions are capped in many countries (including Australia, Canada, China, Europe, India, Japan, New Zealand and the US), regardless of whether advanced nuclear technologies replace conventional fuel-powered plants.

Thus, the development of advanced nuclear technologies would have only a limited effect on pollution problems, expect for NO_x and SO_2 emissions that would be reduced by 14% and 24% in 2050.

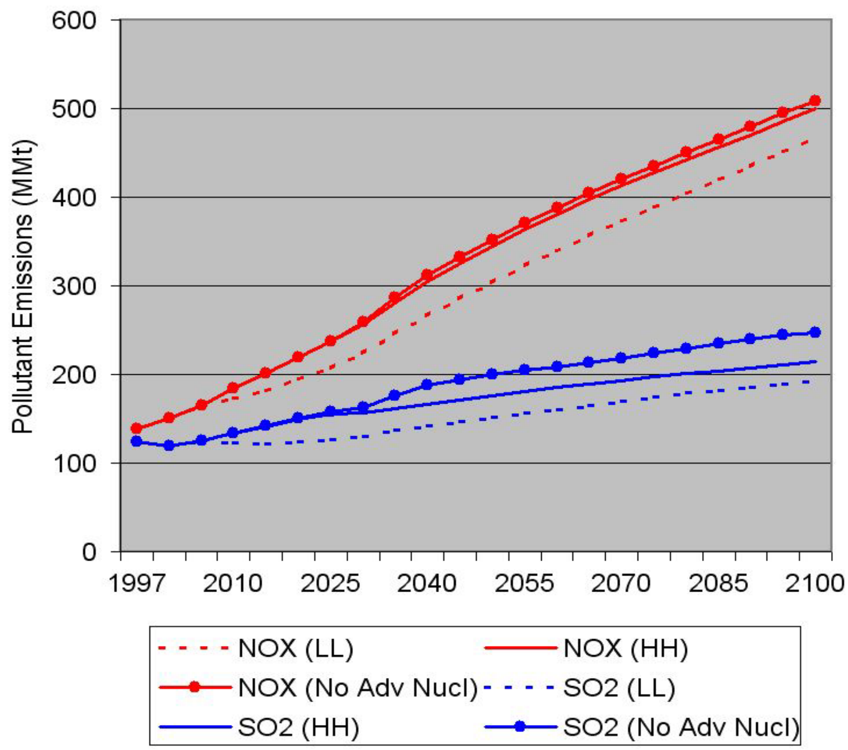

Figure 36. Emissions of NOx and SO_2 (in Millions of Metric Tons), Reference Scenario

VI. Economic Value of the Political Decision to Keep the Nuclear Option Open

This chapter finally assesses the economic benefit associated with the political decision to keep the nuclear option open. The benefit is first evaluated in terms of consumption variation over time, and next in terms in consumption variation NPV.

The development of nuclear power would have an impact on the economic, environmental and political fields, as explained in part I.2. More precisely, nuclear power could provide inexpensive carbon-free electricity, which would come with significant economic benefits through the increase in the world aggregate consumption and welfare, especially if climate policies were implemented. Conversely, a significant development of nuclear power is likely to increase the risks of nuclear weapon proliferation and those of safety accidents, as well as the amount of nuclear waste that would have to be transported, reprocessed or disposed of. Value judgments would therefore be involved when deciding whether the economic benefits of nuclear power are worth the disadvantages in terms of safety, waste and proliferation. Thus, the decision to keep the nuclear option open is essentially political, and involves assessing the safety, proliferation and waste concerns against the economic cost of foregoing inexpensive carbon-free electricity, cost which can be evaluated. Note, however, that the terms of this trade-off would vary if different nuclear technologies and fuel cycles were considered.

A number of political ways could be used to ban the construction of new nuclear reactors. In countries in which the power generation sector is essentially public, such as France, politicians directly shape the nuclear energy policy, and could decide to abandon nuclear power. Even in countries in which the electricity generation market has been liberalized, law could still prohibit the construction of nuclear plants, out of concerns about the proliferation, safety, or waste issues. The definition of regulatory standards through the political process could also indirectly foreclose the nuclear option, for example by requiring levels of accident probability or waste production much lower than what the next generations of nuclear plants could achieve. The design and length of the plant certification process also indirectly affect the relative competitiveness of nuclear power in liberalized markets. Finally, assuming that government subsidies were required to overcome first-of-a-kind costs of new reactor generations (because of free-rider problems), the government might ban nuclear power simply by not supporting it strongly enough.

Accordingly, this part assesses the economic cost associated with the political decision to ban the construction of new Generation III nuclear plants. Equivalently, it assesses the economic benefit associated with the political decision to keep the nuclear option open. This does not prejudge of whether it would be sensible or not to stay away from advanced nuclear power technologies: if policymakers deem safety, proliferation and waste issues to be more important than the economic and environmental benefits of nuclear power, then a ban of nuclear power makes sense, but the economic benefits should be assessed before making the political decision. Thus, I here aim to provide an estimate of the total economic benefits of nuclear power for policymakers to make an informed decision, without prejudging of the outcome of this decision-making process.

This assessment is carried out using a method similar to that of part IV: I compute the variation in the world aggregate consumption due to the political decision to ban advanced nuclear technologies. I therefore run the EPPA model with and without advanced nuclear technologies, all else being equal, and I compare the resulting consumption levels over time (Figure 37). Again, this variation in consumption is due to two effects: if nuclear power is allowed to enter the market, it first makes electricity less expensive in the reference case; second, it provides a competitive carbon-free technology to mitigate emissions when a climate policy is added.

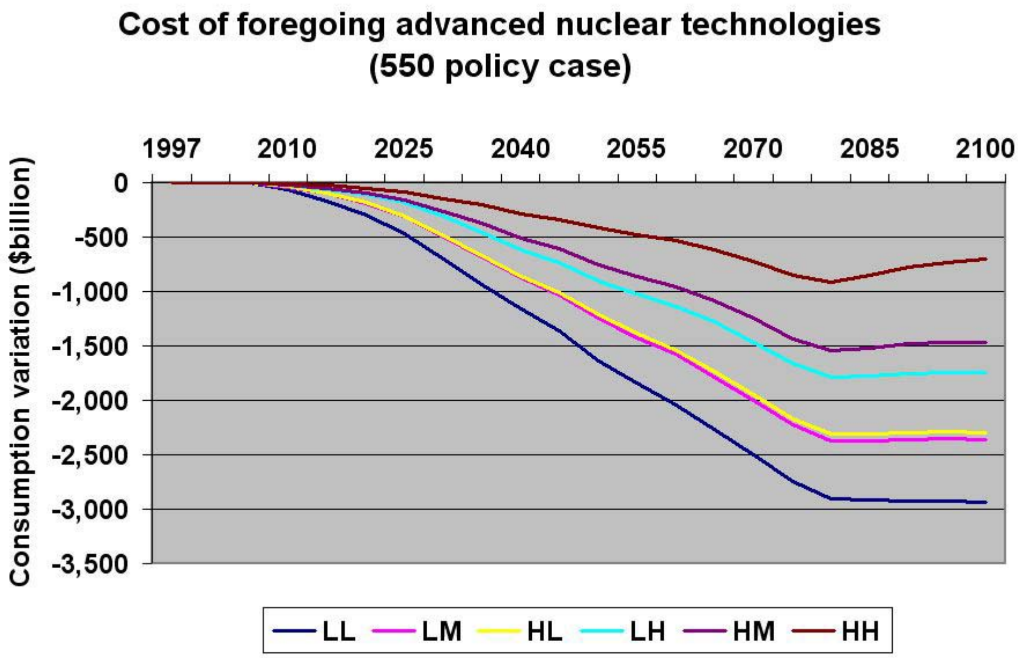

Figure 37. Cost of Foregoing Advanced Nuclear Technologies, in Terms of Consumption Loss per Year, 550ppm Policy

As can be seen on Figure 37, the cost of foregoing advanced nuclear technologies depends on the nuclear cost scenario: the less expensive the nuclear power, the higher the cost of foregoing it. Besides, the cost of such a ban of nuclear power increases over time until 2080, whereas it stabilizes after 2080.

In order to explain these different effects, let the cost of foregoing advanced nuclear technologies be given by: Cost = $C_{w/o}$ (consumption without advanced nuclear technologies) – C_w (consumption with advanced nuclear technologies).

Since advanced nuclear technologies provide more flexibility in the choice of the best alternative to produce electricity, the consumption growth is higher with these technologies than without. Given that $C_{w/o}$ and C_w are equal before advanced nuclear technologies enter the market, the absolute value of their difference increases over time (using the formula above, the cost becomes more and more negative). This explains the left part of Figure 37, for a given nuclear cost scenario.

The impact of the nuclear cost scenario can also be explained: the lower the cost of nuclear energy, the higher the savings, and therefore the higher the growth rate of C_w. Since $C_{w/o}$ is given, the cost of foregoing advanced nuclear technologies should increase over time more significantly in the LL cost scenario than in the HH one, as is indeed the case of the left part of Figure 37.

The flatter parts of the curves on the right of Figure 37 are more complex to interpret. As in the evolution of the carbon price, the timing of the emergence of this flatter curve depends on the stringency of the policy: the tighter the carbon constraint, the earlier the curve flattens. In the 650ppm case for instance, only the left part of the curve is observed. Also, the period in which this curve flattens corresponds to the period in which the carbon price without advanced nuclear technologies crosses the other carbon price curves on Figure 28. This suggests that the curves from Figure 37 flatten when the marginal cost of abatement becomes higher with advanced nuclear technologies than without, because of the indirect effect on consumption.

When a climate policy is implemented, it affects both growth rates of consumption ($C_{w/o}$ and C_w), but not in the same way. Indeed, since C_w increases more quickly than $C_{w/o}$ at the beginning, the emissions also increase more quickly; a given carbon constraint has therefore eventually more impact on C_w than on $C_{w/o}$. In other words, the growth rate of C_w decreases as the carbon constraint becomes tighter in the later part of the century, which is true for $C_{w/o}$ as well, but only to a lesser extent. The growth rate of C_w even becomes lower than the growth rate of $C_{w/o}$ in the HH scenario. This could explain why the difference between $C_{w/o}$ and C_w (namely the cost of foregoing nuclear technologies) stabilizes in the later part of the century, and even decreases in the HH nuclear cost scenario.

Using a discount rate of 4%, one can next compute the Net Present Value of this cost, and make comparisons across climate policies (Figure 38). As expected, the tighter the carbon constraint, the higher the cost of not relying on nuclear power. Indeed, if nuclear power is available, it provides carbon-free power at a low cost. Since a tight carbon constraint implies strong economic losses, the benefits of nuclear power are all the more significant as the economic costs avoided are high.

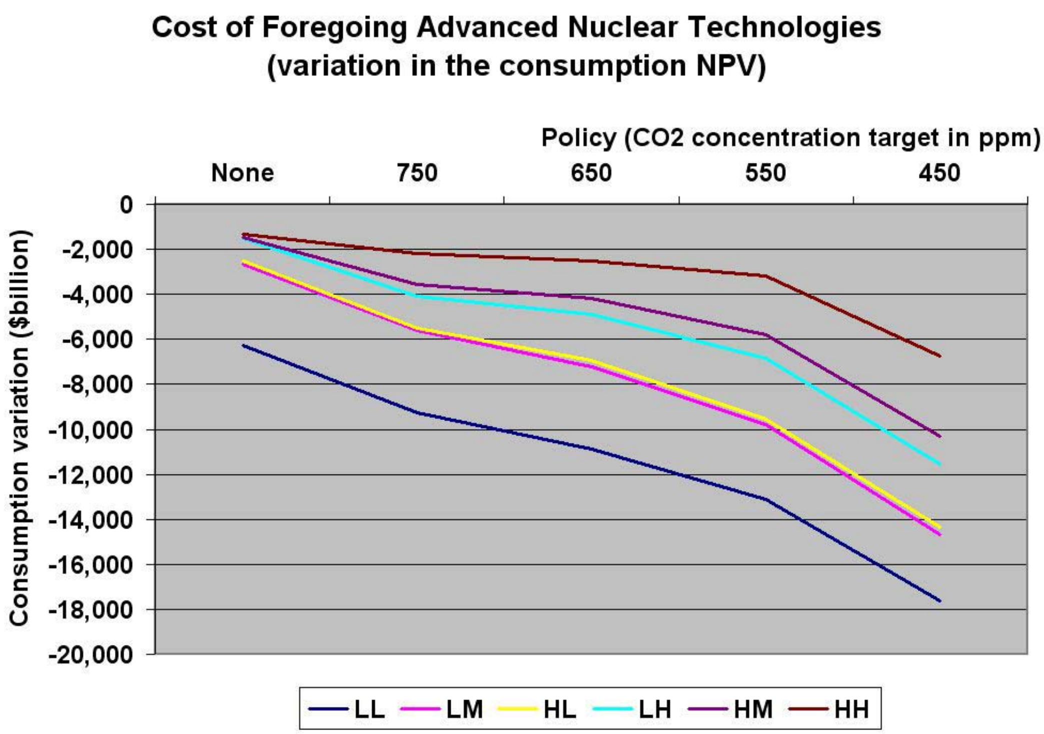

Figure 38. Cost of Foregoing Advanced Nuclear Technologies, in Terms of Consumption NPV Loss

Quantitatively, the cost of foregoing advanced nuclear technologies ranges from 0.11% of the total consumption NPV in the HH nuclear cost scenario without climate policy, to 1.53% in the LL scenario with a 450ppm policy. In absolute values, it ranges between \$1,300 billion and \$17,600 billion in net present value terms, using a 4% discount rate. Whether these significant economic benefits offset the disadvantages of nuclear power is a political question that should be addressed through a political deliberation process.

VII. Conclusions

Three main dimensions shape policies with regard to nuclear power and climate change: the economics, the environment, and the politics. Accordingly, this thesis had the three following objectives:

1. Determine whether the economic incentives of climate policies could foster a nuclear renaissance, and whether a development of nuclear power could lower the costs of climate policies,
2. Assess the environmental benefits of a potential development of nuclear power, especially with regard to climate change,
3. Evaluate the economic value of the political decision to keep the nuclear option open.

These goals required an assessment of the nuclear power cost, in order to implement a new economic sector in the EPPA model, a computable general equilibrium model that projects the emissions of greenhouse gases over time and the impact of climate policies on the whole economy.

Nuclear Power Cost Assessment

Part II assessed the bus-bar cost of nuclear power using Generation III reactors, based on studies that relied on levelized cost models. A literature review showed that these estimates vary widely (Table 24).

Study	DGEMP	MIT	CERI	Chicago	RAE	IEA/NEA
Levelized cost (2003 USD/MWh)	29	68	51	47 - 71	40	25 - 69

Table 24. Best Estimates of Nuclear Power Costs

These differences are due to both the calculation assumptions and the calculation methods. The most important cost parameters are, by decreasing order, the discount rate, the overnight cost, the capacity factor and the economic life. The range of assumptions for these parameters accounts for a nuclear cost variation of respectively \$15/MWh, \$12/MWh, \$9/MWh, and \$8.5/MWh around a reference cost scenario of \$43/MWh.

Studies also differ in their cost calculation methods, especially with regard to discounting: DGEMP and IEA/NEA assume that the project discount rate is constant when debt is repaid, while CERI, Chicago and MIT assume that the required return on equity is constant and that the implied project discount rate varies. These distinct approaches, added to a one-year lag between the construction and operation phases in the MIT study (and possibly in other studies), lead to significant variations in the nuclear power cost. Most importantly, these methodological differences do not affect all electricity generation technologies in the same way (Table 25). Following the Modigliani & Miller theorems, I next relied on the approach used in the DGEMP and IEA/NEA studies.

Technology	DGEMP & IEA/NEA method	CERI & Chicago method	MIT method
Gas-CC	65	67 (3%)	68 (4%)
IGCC	37	41 (10%)	44 (17%)
Nuclear	43	49 (14%)	54 (26%)

Table 25. Impact of the Cost Calculation Method on the Levelized Cost of Electricity

(for a Given Set of Cost Assumptions; the percentages in parentheses refer to the variation with regard to the DGEMP & IEA/NEA method)

<u>Impact of Climate Policies on the Development of Nuclear Power</u>

The EPPA model was used to assess the effect of cap-and-trade policies with concentration targets between 450ppm and 750ppm, international trading and equal burdens across regions of the world.

If no climate policy is implemented (Figure 39), the market share of advanced nuclear technologies increases up to around 85% by 2050 in the low cost scenarios. This would imply a significant rate of construction of new plants (up to 120 new 1GWe plants per year worldwide). Nuclear power expands even in the high nuclear cost scenarios, because of the rise in fuel prices of conventional electricity generation technologies.

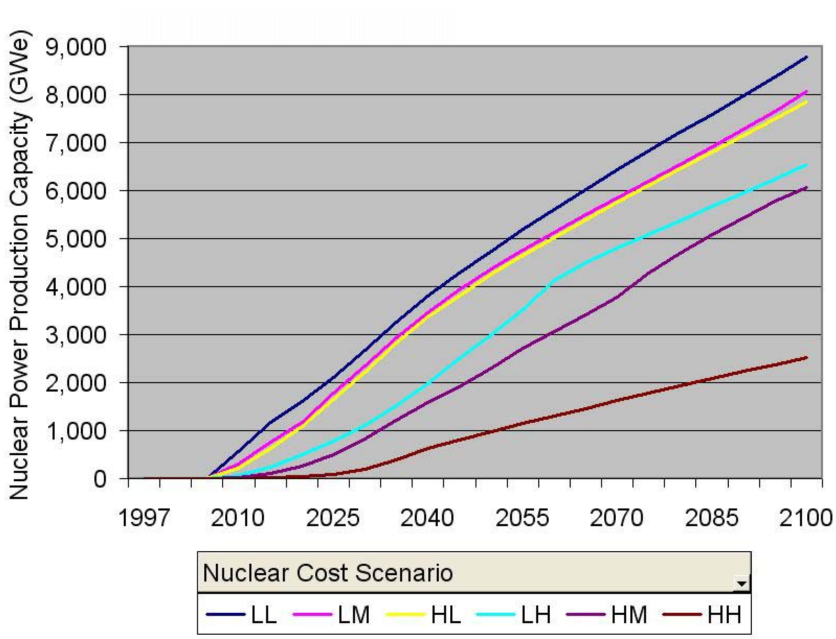

Figure 39. Worldwide Advanced Nuclear Capacity (in GWe), No Climate Policy Case

The internalization of greenhouse gas emission costs through a 550ppm cap-and-trade policy (Figure 40) does not affect much the low nuclear cost scenarios, because nuclear power is very competitive in any case. Conversely, the climate policy triggers a significant increase in the nuclear market share in the high cost scenarios: advanced nuclear technologies would account for more than 50% of the electricity generation market in the highest cost scenario (HH). This effect is all the more significant as the climate policy is stringent.

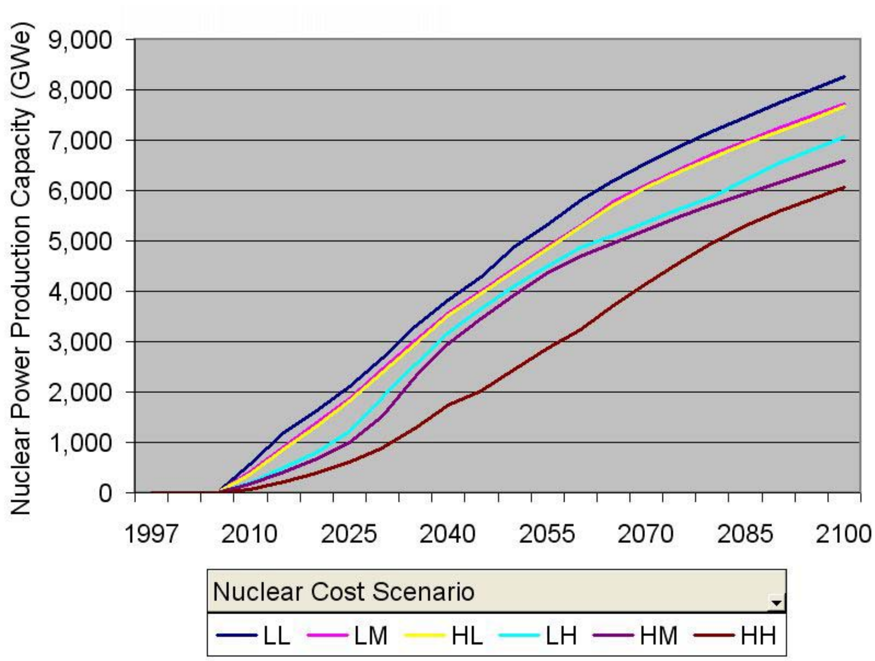

Figure 40. Worldwide Advanced Nuclear Capacity (in GWe), 550 ppm Scenario

An assessment of uranium resources was carried out to determine whether they could sustain the large development of nuclear power that is implied by our lowest nuclear cost scenario with a once-through fuel cycle. Such a development would involve the depletion of currently known deposits of conventional and phosphate uranium by the end of the century. Seawater uranium would therefore have to be extracted, which would raise significantly the price of uranium ore. However, given the large resources in seawater uranium, no nuclear fuel shortage would occur before the end of the century.

Impact of Nuclear Power on the Costs of Climate Policies

The cost of nuclear power has a very significant impact on the initial marginal emission abatement cost: the initial carbon price decreases from $50/tC if advanced nuclear technologies are not available to $2.6/tC in the low nuclear cost scenario. Two effects account for this reduction: first, the development of carbon-free nuclear power in the reference case decreases the required level of emission reduction when a policy is implemented; second, for a given level of emission reduction, inexpensive nuclear power provides an economical way of reducing these emissions.

The overall costs of climate policies, evaluated here in terms of consumption losses, are also highly dependent on the nuclear power costs, especially in the short term. The cost of a 550ppm policy is for example reduced by 83% in 2030 and by 49% in 2050 if nuclear power costs go from scenario HH to scenario LL. Using a 4% discount rate, this cost reduction amounts to a 36% decrease in the Net Present Value of the consumption loss over time. The cost of advanced nuclear technologies can therefore be regarded as one of the main drivers of the future costs of climate policies.

These reductions in the climate policy costs can be used to assess the total economic benefits of having low nuclear costs. Inexpensive nuclear power involves two kinds of benefits: first, it decreases the cost of electricity when no climate policy is implemented, which enables the reference consumption to grow; second, it decreases the costs of climate policies. Adding these two effects, one can assess the total benefits of switching from HH nuclear costs to LL nuclear costs (Figure 41): the payoffs of lowering nuclear costs would be very significant, and could offset the cost of R&D and of subsidies to overcome first-of-a-kind costs.

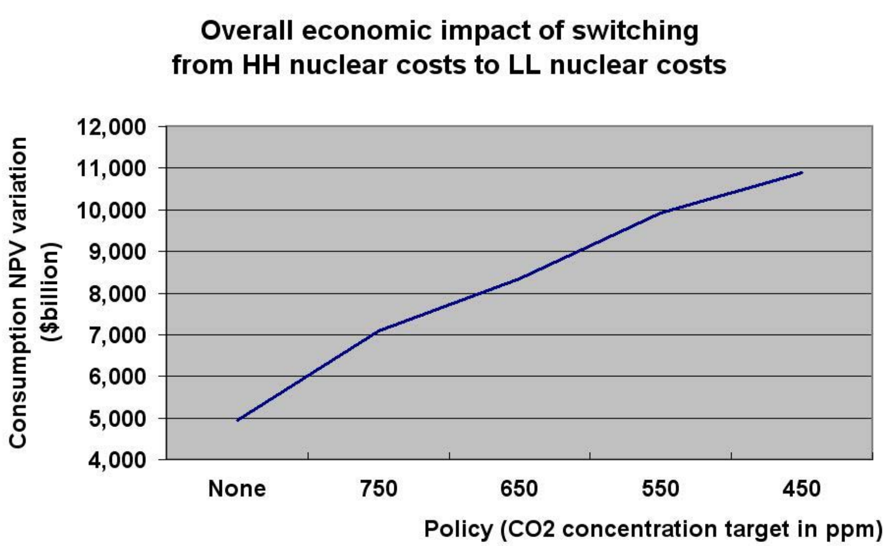

Figure 41. Willingness to Pay to Switch from Scenario HH to Scenario LL, as a Function of the Climate Policy Target

Environmental Benefits of a Development of Nuclear Power

Nuclear power, which is nearly carbon-free, can contribute to a decrease in the emissions of greenhouse gases. In particular, the development of competitive nuclear power could partly mitigate climate change even if no climate policy were implemented. As shown on Figure 42, the lower the cost of nuclear power, the higher the nuclear market share, and therefore the lower the greenhouse gas emissions. CO_2 emissions in 2050 would thus decrease by 32% from the scenario without advanced nuclear technologies to a scenario with very competitive nuclear power (LL).

The development of nuclear power associated with the most competitive nuclear scenario (LL) is even equivalent, until 2045, to implementing a 650ppm policy in which advanced nuclear technologies are not available. If climate policies cannot be implemented in the short run on an international scale – for example because of the difficulty in reaching an international agreement – expanding nuclear power worldwide could constitute a second-best option, at least for the next 30 years. If competitive advanced nuclear technologies are available, the optimal solution would however involve the implementation of a climate policy with stronger emissions reductions in the short term, and smaller ones in the longer term.

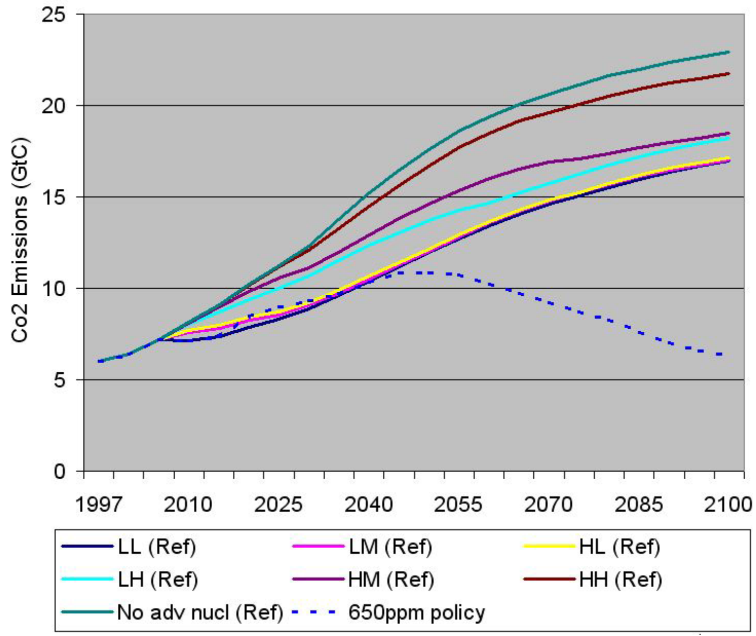

Figure 42. CO_2 Emissions, Reference Scenarios & 650ppm Policy

(in Billions of Metric Tons of Carbon)

The impact of a development of nuclear power would be fairly small with regard to pollution reduction, except for NO_x and SO_2 emissions, which would be reduced by respectively 14% and 24% in 2050 from the scenario without advanced nuclear power to an LL nuclear cost scenario.

Economic Value of the Political Decision to Keep the Nuclear Option Open

When deciding whether to expand, maintain or ban nuclear power, policymakers should weigh the economic and environmental benefits of nuclear power against their valuation of the corresponding disadvantages such as proliferation, waste or safety issues.

The benefits of nuclear power were here assessed in monetary terms by internalizing the environmental benefits through a climate policy, and by estimating the consumption loss due to a ban of nuclear power. Using a 4% discount rate, the cost of foregoing advanced nuclear technologies corresponds to the consumption NPV loss shown on Figure 43. This cost depends on the nuclear cost scenario (the less expensive the nuclear power, the higher the cost of foregoing it), and on the stringency of the climate policy (the tighter the carbon constraint, the higher the economic losses avoided by relying on nuclear power).

Quantitatively, the cost of foregoing advanced nuclear technologies ranges from 0.11% of the total consumption NPV in the HH nuclear cost scenario without climate policy, to 1.53% in the LL scenario with a 450ppm policy. In NPV terms, it ranges between $1,300 billion and $17,600 billion in net present value terms. Whether these significant economic benefits offset the disadvantages of nuclear power is a political question that should be addressed through a political deliberation process.

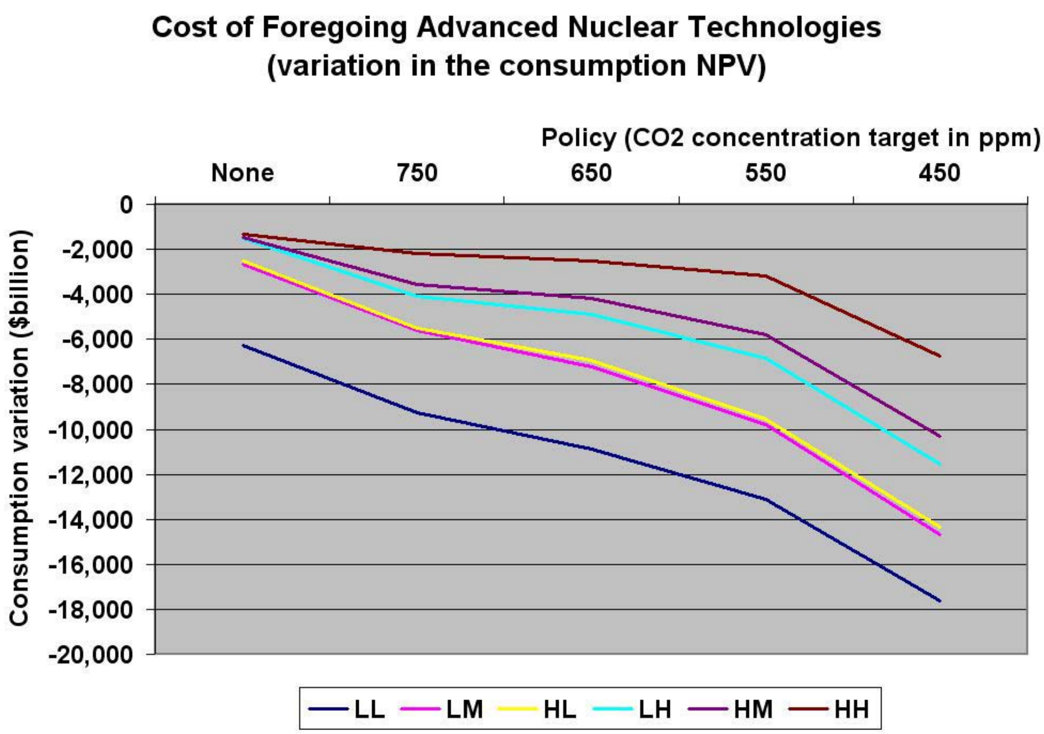

Figure 43. Cost of Foregoing Advanced Nuclear Technologies, in Terms of Consumption NPV Loss

<u>Recommendations for Future Work</u>

This analysis of the interaction between climate policies and the development of nuclear power could be improved and expanded in many respects. First, the nuclear power cost assessment was carried out using economic studies that were bound to be uncertain given the lack of recent data regarding nuclear costs. The accuracy of this cost assessment could therefore be improved over time by relying on actual data when they become available, as nuclear plants are built. This would in particular reduce the cost uncertainty, and allow the use of a narrower range of cost scenarios.

Furthermore, the economic sector representing advanced nuclear technologies was designed to model Generation III nuclear fission plants using a once-through fuel cycle, on which the thesis was focused. A broader and refined analysis of the potential for nuclear power could include other nuclear technologies, as data become available. In particular, modular nuclear reactors, Generation IV nuclear plants, and even nuclear fusion could be integrated in future versions of the model.

Since this analysis is based on the EPPA model, it would also benefit from improvements in the overall structure of the model. On-going work includes the development of a forward-looking version of the model, the augmentation of tax data, a better representation of intermittent sources, a greater sector detail to reflect explicit sectoral changes in consumption, improved geographic detail in emissions projections, and a more advanced representation of the feedback from climate change into the economy and the corresponding greenhouse gas emissions (Paltsev et al., 2005).

The impact of climate policies on the development of nuclear power was assessed on the example of cap-and-trade policies with international trading, assuming that the emissions reductions with advanced nuclear technologies would be similar to the reductions without these technologies. In a more refined analysis, the levels of emission reductions could be adjusted over time in the different nuclear cost scenarios, in order for the emission reduction timing to be economically optimal. Other types of climate policies, such as carbon taxes, could also be studied in detail.

Advanced nuclear technologies were also shown to decrease significantly the costs of climate policies, which implies significant incentives to lower nuclear costs, assuming that the current nuclear costs are high. A next step could be to analyze how to actually use this willingness to pay in order to lower nuclear costs.

Finally, the last part concluded that the benefits of keeping the nuclear option open should be weighed against potentially significant drawbacks such as proliferation, waste and safety issues. It provided an estimate of the benefits of nuclear power, in both the environmental and economic fields, but did not prejudge of how these benefits would compare to the downsides of nuclear power. In order for policymakers to make a decision based on more complete information, comparable assessments should therefore be carried out on the drawbacks of nuclear power.

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