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Nuclear power: Understanding the economic risks and uncertainties

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ABSTRACT

This paper identifies the fundamental elements and critical research tasks of a comprehensive analysis of the costs and benefits of nuclear power relative to investments in alternative baseload technologies. The proposed framework seeks to: (i) identify the set of expected parameter values under which nuclear power becomes cost competitive relative to alternative generating technologies; (ii) identify the main risk drivers and quantify their impacts on the costs of nuclear power; (iii) estimate the nuclear power option value; (iv) assess the nexus between electricity market structure and the commercial attractiveness of nuclear power; (v) evaluate the economics of smaller sized nuclear reactors; (vi) identify options for strengthening the institutional underpinnings of the international safeguards regime; and (vii) evaluate the proliferation resistance of new generation reactors and fuel cycles.

1. Motivation and context

Volatile fuel prices, concerns about the security of energy supplies, and global climate change are coinciding to strengthen the case for building new nuclear power generation capacity. By 2030, global electricity demand is projected to more than double to over 30,000 TWh annually. More than 70% of the increased energy demand will come from developing countries, led by China and India. Providing sufficient energy to meet the needs of a growing world population with rising living standards will be a challenge. Doing it without substantially exacerbating the already disquieting risks of climate change will be an especially daunting task.

There is an emerging consensus that there is no obvious "silver bullet" for addressing the global energy challenge—the solution will be comprised of a variety of technologies on both the supply and demand side of the energy system (Pacala and Socolow, 2004; Holdren, 2006; EC (European Commission), 2007; Richels et al., 2007). In addition to energy efficiency and low-carbon renewable options, two technologies that could do much of the heavy lifting in the future are carbon capture and sequestration (CCS) and nuclear power. However, the views on nuclear power and its potential role in meeting the projected large absolute increase in global energy demand, while mitigating the risks of serious climate disruption, are highly divergent. Part of the continuing controversy is due to the large risks and uncertainties underlying the cost elements of nuclear power. These risks and uncertainties are reflected in the wide range of cost estimates. The cost overruns and schedule delays of Finland's new Olkiluoto plant are rekindling old fears about nuclear power being far too complex and costly, and raising new questions about the viability of new nuclear plants, especially in deregulated electricity markets. Indeed, the costs of nuclear power stations (and large coal-fired power stations, particularly those with carbon capture and sequestration) remain uncertain. On the other hand, the fact that countries seem keen to build nuclear power stations suggests that their relative cost compared to low-carbon alternatives still seems attractive to at least some potential investors (David Newbery, private communication).

Proponents argue that in relation to the objectives of electricity supply security, resource efficiency, and mitigating the threat of climate change, nuclear power performs very well. Nuclear power: (a) represents a well-established technology for generating electricity that produces no carbon or other climate-relevant emissions; (b) is amenable to significant scaling-up and thus can provide large amounts of power; and (c) uses a natural resource (uranium), which is found at an abundance (2–3 parts per million) in the earth's crust—with advanced technologies, it could provide enough fuel to meet the world's electricity needs for several centuries. And, advances in nuclear reactor technology have substantially improved the underlying economics and safety profile of nuclear power. Skeptics claim that nuclear power is costly and technically complex. It involves the use of highly toxic materials that must be kept secure from attack or theft. Moreover, a viable technology for the permanent disposal or reprocessing of spent nuclear fuel has not yet been fully demonstrated. Finally, even in a carbon-constrained world, nuclear power may be less

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economically attractive than a host of decentralized energy efficiency and distributed generation technologies.

It is within this context that this paper identifies the fundamental elements and critical research tasks of a comprehensive analysis of costs and benefits of nuclear, relative to investments in alternative baseload technologies. In view of the continuing high degree of public concern surrounding nuclear power, this evaluation problem is of extreme importance. Moreover, because of the emerging centrality of climate change and security of supply in the energy policy debate, the need for an objective and well-focused cost–benefit analysis has been sharpened considerably. It should be noted that there have been numerous studies on the economics of nuclear power in recent years.[2] However, it is necessary to complement and extend these studies in a number of important areas. It is essential to: (i) develop an internationally agreed definition of the basic variables and standards for nuclear power plant costing and a uniform methodology for modeling the various sectors of the nuclear fuel cycle; (ii) employ a methodology that accounts more completely (than the traditional levelized cost approach) for the large and diverse set of risks characterizing investment in nuclear power; (iii) employ a comprehensive framework for assessing the external costs and benefits of nuclear power; and (iv) collect and utilize, to the largest extent possible, actual construction cost data rather than engineering estimates.

Studies and forecasts of future costs of nuclear generation vary widely. These differences arise in large part from the different assumptions that these studies make. Although much work has been done over the last four decades to standardize nuclear plant costing, there is still no internationally agreed definition of capital costs for nuclear power stations (DTI (Department of Trade and Industry), 2007). Especially in the context of an expanded global nuclear deployment, it is imperative to develop a uniform set of cost-engineering standards and a generalized costing model that is based on microeconomic principles. The Economic Modeling Working Group of the Generation IV International Forum has developed a set of cost-engineering standards (Economic Modeling Working Group (EMWG), 2007), but most analyses of nuclear power lack a basis in microeconomics.

Most of the studies estimating the potential costs of nuclear generation rely on non-transparent engineering cost calculations from industry sources rather than parameters based on actual experience. These cost figures should be viewed with some skepticism because vendors of nuclear power plants might have incentives to misrepresent their costs so as to maximize their chances of commercial success—e.g., as part of their commercial strategy they may choose to enter into early contracts as ''loss leaders'' (DTI, 2007). To mitigate these potential biases, we need to pay special attention to the actual construction experience from recently completed nuclear plants and place particular emphasis on the collection of actual data on the key variables determining the life-cycle costs of nuclear power. These data could be used to determine how variations in the planning regime, technology, and the operation of plants affect the life-cycle costs of nuclear generating technology.

Investment in electricity generation entails substantial and diverse market and non-market risks. Some of these risks have been augmented by market liberalization. The traditional ''levelized cost'' methodology used in previous studies does not properly take into account these risks and uncertainties when valuing different power generation technologies.[3] This calls for a probabilistic analysis to value power generation under uncertainty. An economic modeling process could be employed to identify the most influential uncertainties and risk drivers associated with nuclear power and the alternative technologies, and estimate probability distributions of net present value for different investments. Moreover, in order to compare nuclear power and the alternative technologies on a level-playing field, the cost–benefit–risk analysis should be generalized to fossil fuel and other technologies (Roques et al., 2006).

Uncertainties can reveal benefits, as well as costs. The focus of previous studies has mostly been on the downside risks of nuclear power. But the upside is also critical. For example, fossil price volatility favors nuclear power and renewable technologies. And international agreements to limit greenhouse gas (GHG) emissions are likely to represent considerable downside risk for coal-fired plants and a significant upside for nuclear power and renewables (Cain, 2006). In the face of volatile fossil fuel prices and significant uncertainties underlying the future price of carbon, non-fossil technologies have an ''option value''. This would require an integrated quantitative framework (taking into account fossil fuel, carbon, and electricity price risks) to evaluate the risk-return profiles of alternative generation technologies and to balance the risk-mitigating benefits of portfolios of mixed technologies against the costs of such portfolios. The option value of keeping open the choice between nuclear power and fossil fuel technologies could also be estimated in the context of such a framework (Rothwell, 2006).

Previous studies have largely overlooked the option value of nuclear power. Moreover, the incentives facing private investors with respect to fuel diversification might not be consistent with the socially optimal fuel mix (Roques et al., 2008). These studies have not analyzed the complementary policy measures that could be implemented to remedy such market failures. Especially in the face of tightening credit markets, there is a need to identify alternative institutional risk allocation mechanisms that might render capital intensive, but fuel-price risk free technologies more attractive to such investors.

While the present paper focuses on the economics of nuclear energy within the context of climate change and a carbon-constrained world, it should be borne in mind that the future prospects of nuclear power will ultimately depend on resolving the issues of safety of operations, safe management of radioactive waste, and measures to prevent the proliferation of weapons-usable materials, facilities, technology, or expertise (MIT, 2003). Still, in a deregulated global electricity marketplace, economics (including an appropriate accounting for the carbon implications of alternative energy sources and the costs of mitigating various risks) will arguably be the most important determinant of nuclear energy's role in the future global energy mix.

The paper is organized as follows. Section 1: defines the key components of nuclear power costs; describes the data challenges; highlights the need for a generalized methodology for modeling the various sectors of the nuclear fuels cycle; describes recent methodological advances in the assessment of externalities; identifies appropriate methodologies for the economic valuation of nuclear power investments under uncertainty; analyzes the diversification value of nuclear power (the social benefits of keeping the nuclear power option open); and describes the emerging importance of small-size reactors in the context of a global nuclear deployment. Section 2: focuses on the institutional

[2] These include: DTI (2007), Greenpeace International (2007), The Keystone Center (2007), IEA/NEA (2005), OXERA (2005), Thomas (2005), Canadian Energy Research Institute (2004), Royal Academy of Engineers (2004), University of Chicago (2004), MIT (2003), and Scully Capital (2002).

[3] The real levelized cost of a project is equivalent to the constant dollar price of electricity that would be required over the life of the plant to cover all operating expenses, interest and repayment obligations on project debt, and taxes plus an acceptable return to equity investors over the economic life of the project.

and technical challenges and options for developing proliferation-resistant nuclear power; describes the extrinsic barriers to proliferation; assesses the potential contribution of international energy parks and a hub-and-spoke nuclear architecture; and highlights the proliferation resistance of new generation reactors and fuel cycles. Section 4 provides a brief summary and articulates the need for an integrated framework.

2. Nuclear power generation: cost–benefit analysis under uncertainty

We propose a framework to analyze a diverse set of market and non-market risks and uncertainties underlying nuclear power and the other baseload (coal and natural gas) generating technologies.[4] This framework would enable us to assess the economic viability of nuclear power under a range of scenarios reflecting different assumptions relating to plant construction costs, costs of uranium and alternative fossil fuels and their real rates of escalation over time, and carbon prices. Thus, we seek to examine issues that are statistically quantifiable and analyze the impacts of scenario risks (e.g., new carbon prices with uncertain magnitudes and timing) and paradigm risks (e.g., shifts in the governance structure of electricity markets, or significant changes in the status of alternative generating technologies).

New nuclear generating capacity would give rise to direct costs as well as a range of external costs and benefits. These would call for the valuation of the following:

- environmental benefits—reduced GHG emissions to be gained from adding nuclear rather than coal- or gas-fired generating capacity;
- fuel mix diversification value of nuclear power as a hedge against uncertain fossil fuel and carbon prices;
- costs of radioactive waste disposal;
- risks associated with radioactivity release from all fuel cycle activity;
- risks of proliferation from the nuclear fuel cycle; and
- financial liabilities arising from the back-end activities of the nuclear fuel cycle—e.g., decommissioning and waste management.

It must be stated at the outset that it is difficult to quantify the costs and risks related to nuclear safety and especially to nuclear proliferation. It should also be noted that the original risk analysis of nuclear power might have underestimated the true probability of reactor meltdown. And while modern reactors are claimed to achieve a very low risk of serious accidents, this needs to be assessed as it is dependent on "best practices" in construction and operation. Therefore, all developments in the literature on the probabilistic risk assessment of nuclear safety and proliferation need to be carefully reviewed, as well as the estimates and approaches of existing credible studies.

2.1. Components of nuclear power costs and levelized costs of alternative baseload generation technologies

One of the fundamental problems underlying the debate on the potential role of nuclear power in meeting the future global energy needs relates to the continuing lack of consensus on what will be the costs of new nuclear generating plants (Joskow, 2007; Joskow and Parsons, 2009).

The costs of nuclear power comprise of four major components (Joskow, 2006):

- *Capital or construction costs*—are those incurred during the planning, preparation and construction of a new nuclear power station;
- *Operations and maintenance (O&M)*—relate to administration, management, support and upkeep of a power station (labor, material and supplies, capital upgrades and additions, spares, insurance, security, planned maintenance and contractor services, licensing and regulatory fees, and corporate overhead costs);
- *Fuel costs*—reflect the cost of fuel for the power station; and
- *Back-end costs*—are those related to the decommissioning and dismantling of nuclear facilities at the end of their operating life and the long-term management and disposal of radioactive waste.

Investment costs represent approximately 60% of the total cost of nuclear power while O&M and fuel account for 20% each (OECD/NEA, 2003). The O&M component includes expenses related to health and environmental protection and accumulation of funds for spent-fuel management and final waste disposal and for eventual plant decommissioning. It also includes the cost for insurance coverage against accidents. Thus several potential externalities are internalized in O&M costs.

Proposition 1. *The economics of nuclear power depend critically on the construction or capital costs, the speed of build (length of the pre-construction period and the time it takes to construct the plant), the long-term real discount rate, and to a lesser extent on operations and maintenance, fuel, and back-end (waste disposal and decommissioning) costs.*[5]

Most of the recent studies that have evaluated the life-cycle levelized costs of nuclear power were based on vendor projections and as such they should be critically reviewed. Given how fierce the debate on nuclear power has been, it would be important to obtain the views of a diverse set of market participants, academic experts, and industry analysts on the reasonableness of these construction cost estimates.[6] While the range of costs based on past studies should be carefully examined, the main focus should be on: (a) standardizing nuclear power plant costing and (b) collecting market data based on projects completed in recent years and projects under development/implementation—such as the Olkiluoto in Finland, Flamaville in France, and those in India, China, Japan, and South Korea. See Du and Parsons (2009). Thus, to the largest extent possible, actual data (and not just engineering and other estimates) should be collected on several primary variables that determine the expected life-cycle costs of nuclear power plants.[7]

[4] Here, we use Frank Knight's distinction between risk and uncertainty, where "risk" involves randomness with knowable probabilities, and "uncertainty" refers to randomness with unknowable probabilities. See Knight (1921).

[5] Given that it is not possible to have real costs for future developments and the fact that it is necessary to incorporate uncertainty in the calculations when using historical data from different countries, it might be easier to simply include uncertainty in the costs supplied by vendors to account for the fact that they have a commercial interest in promoting their equipment and projects.

[6] The debate on nuclear power costs has been characterized by a significant degree of confirmation bias. Historically, the nuclear industry had the tendency of putting forward very optimistic construction cost estimates. In the United States, for example, the final costs of plants that commenced commercial operations in the late 1970s were in some cases several times greater than their initial cost estimates. Opponents of nuclear power, on the other hand, can be wildly pessimistic. It is a challenge to identify experts with unbiased views. Still, some of the previous studies, especially those carried out by academic institutions (e.g., MIT (2003)), could not be questioned for their integrity.

[7] It should be pointed out that actual data is only a proxy for what real costs will be as the projects differ in many respects.

Some of the variables needed for the economic analysis of nuclear power – e.g., construction time and operating performance (nameplate capacity, average plant load and availability factors) – are available for most nuclear plants, including those in India and China; for a discussion of these data see Rothwell (1998). Construction cost and operating cost data, on the other hand, are not available in most countries. However, detailed cost data are available for each reactor within the entire commercial US nuclear fleet (Hultman et al., 2007). Moreover, labor data is available for some nuclear facilities and can be compared with labor data for similar facilities world-wide. Also, fuel costs can be inferred from (a) the reactor technology, (b) models of enrichment and fuel fabrication costs (assuming exogenous uranium prices), and (c) the length of the refueling outage—see Rothwell (2009a, 2010).

If actual construction cost data continues to be unavailable, then an alternative strategy might be to: (a) rely on country announcements about the total cost of new nuclear plants and try to back-out construction costs; (b) seek to obtain information from vendor bids or vendor engineering estimates for the next generation reactors; and (c) try to estimate construction costs in a specific country by utilizing data from countries where these costs are available and appropriately adjusting such data—break down construction costs into local (e.g., labor or concrete) and international supply components (e.g., reactor components, steel), utilize labor productivity and labor cost indices to adjust labor costs, adjust material costs with domestic price indices, etc.

Still, there are several factors that make forecasting nuclear plant construction costs difficult. First, new nuclear plants require a large amount of on-site engineering, which accounts for a significant portion of total construction cost (Thomas, 2005). It is notoriously difficult to manage and control the costs of large projects involving complex on-site engineering. While major equipment items (turbine generators, the steam generators, and the reactor vessel) can be purchased on "turnkey terms", it would difficult for the entire nuclear plant to be sold on turnkey terms precisely because of the lack of confidence on the part of vendors that they can control all aspects of the total construction costs. Even if turnkey terms are quoted or were to be offered, they must be viewed with skepticism. In any case, turnkey contracts are commercially sensitive and many of their details remain confidential.

Second, the most reliable indicator of future costs has often been past costs. Unfortunately, the countries with the most recent nuclear construction experience generally do not require their utilities to provide properly audited constructions costs. Moreover, for political and nationalistic reasons they often present very optimistic cost estimates. These countries often announce the total cost of new nuclear plants. Any attempt to back-out the construction component from total plant costs will inevitably encounter significant methodological challenges especially given the lack of uniform cost-engineering standards and the concomitant uncertainty related to the financial costs that may or may not be included in the total cost figures. Third, the prices quoted by plant vendors, utilities with a stake in nuclear power, and various promotional bodies, are likely to also be unreliable. Vendors of nuclear power stations, in particular, have incentives to present biased construction cost estimates for the sake of wining contracts and maximizing their chances of commercial success (DTI, 2007).

Still, uncertainties in estimating construction costs do not preclude a comprehensive cost–benefit analysis of nuclear power. They do mean, however, that any economic assessment must reflect the uncertainty using sensitivity analysis, probabilistic scenario analysis, and Monte Carlo simulation, and should take a prudent approach when reaching conclusions.

While available data from both developed and developing countries should be used, particular emphasis could be placed on the observed values of these variables and the cost drivers realized in Asian countries (China, India, and South Korea) where nuclear plants have been most recently constructed. China and India are building new nuclear plants and information on their cost, time to build, and financing would be a natural starting place and a comparison with the plants under construction in Finland and France would be instructive.[8] However, because of potentially significant input (material and labor) pricing distortions, great caution needs to be exercised in using the data from China. China plant costs are roughly 40% lower than OECD averages. Furthermore, the prices appear to be unusually stable compared to that in OECD countries that have experienced considerable price increases (25–30%, on average over the past 3 years). China's lower plant costs may reflect exchange rate controls (a long standing policy of pegging the Yuan to the dollar at a fixed rate and strictly regulating imports and the allocation of foreign exchange) and domestic pricing distortions.[9] Recognizing these sources of bias, the Chinese data could be normalized by considering alternative scenarios of convergence of China's labor costs, domestic material costs, etc., to OECD levels. The ultimate goal is to create an economic model that generalizes all of the recent cost studies so as to make it possible to combine available plant-specific data from specific developing countries with international cost and price information.

In particular, it will be important to analyze the recent on-site engineering, construction management, quality control, and speed of build experience in the Asian countries and contrast that with the emerging experience from other developing countries. Also, it will be important to identify the factors that contributed to the very low load factors achieved by nuclear plants in some developing countries, especially during their early years of operation (e.g., just 25% achieved by Angra-1 in Brazil during the first 15 years of its operation) and the impressive capacity factors realized in recent years, e.g., 96.5% for South Korean power reactors in 2005.

Thus it would be important to collect data, assess forward-looking estimates and other forecasts, and analyze:

- Construction or capital costs for new reactors
  - (i) overnight costs
  - (ii) shares of overnight capital costs in total levelized cost of electricity of nuclear plants
  - (iii) reactor designs and capital cost scenarios
  - (iv) construction time: to get information on time to completion of nuclear projects in as many developing countries as possible, because a major factor in the cost uncertainty is construction delays due to safety issues and general complexity of the technology (understanding what factors allow certain projects to move forward to completion faster would provide valuable input to ensuring nuclear power is cost competitive with fossil fuel technologies; in addition, the time to completion of project could be linked to information on capacity factors to determine if there is a positive or negative relationship between speed of build and reliability)
- alternative fuel costs
- operations and maintenance charges
- insurance and liability
- "back end" costs for waste and decommissioning

[8] For developments in the Chinese nuclear power program, see Rothwell (2003)—in particular, see Table 9.1, for nuclear power plant construction cost.

[9] China fixed its exchange rate at 8.28 Yuan to the dollar from 1994 to 2005, and has only allowed a small, tightly controlled, appreciation since then.

- capacity factors
- long-term real discount rate
- cost of carbon.

Research Task 1: *Identify the set of expected parameter values under which nuclear power becomes cost competitive as a component in a multifaceted solution together with other forms of electricity generation in developing countries. These parameters relate to plant construction costs, life-cycle plant capacity factors, costs of uranium and alternative fossil fuels and their real rates of escalation over time, non-fuel operation and maintenance expenses, carbon taxes, and the economic life of the representative nuclear plant.*[10]

The levelized life-cycle cost might be usefully employed as the metric for evaluating nuclear power relative to investments in alternative baseload technologies. The real levelized cost could be computed using discounted cash flow analysis (EMWG, 2007).

As noted in Rothwell (2007), two sets of standards have emerged for nuclear power plant costing: (a) the International Atomic Energy Agency's Economic *Evaluation of Bids for Nuclear Power Plants* (1976, 1999) and (b) EMWG (2007). Employing microeconomic principles to translate these cost guidelines into estimation of industry production functions and cost structures would be an important step towards a rigorous and analytically defensible cost–benefit analysis of nuclear power. It would facilitate the generalization of the different guidelines into one set of consistent standards that should then clarify the differences in the cost estimates obtained by the various studies and how these studies of nuclear energy costs relate to each other. Moreover, the estimated cost structures would also provide the analytic basis for tracing and interpreting the international supply curves for the various products and services of the nuclear fuel cycle.

Rothwell (2009c, 2010), introduces a methodology for modeling the various sectors of the nuclear fuel cycle. For each sector, a generalized production function of the form

$$Q = Q(K,F,L,M)$$

is specified, where Q is the annual output, K is the total capital investment, F is the fuel or energy input, L is the number of employees, and M represents materials used in the corresponding nuclear process. In the context of this framework, four cost inputs and a single output are estimated for each facility type, which are then used to: calculate the total cost TC of producing Q, and the levelized cost AC; test for economies of scale (returns to scale in K and L) and estimate MES (minimum efficient scale). Such a framework could be usefully employed to analyze, among others, the decision of a non-fuel cycle state to enter a specific sector of the nuclear fuel cycle (e.g., uranium enrichment). In its simplest form, this would entail a comparison of the sector's estimated MES to the size of the entrant's facility.

To apply this methodology to the various sectors of the nuclear fuel cycle following Rothwell (2009c, 2010), it will be necessary to

- obtain data on existing and prospective facilities in each sector from different countries;
- employ these data to estimate the levelized average costs, economies of scale, and minimum efficient scale;
- use the fixed and variable components of the cost function to calculate each sector's required capital and labor inputs;
- analyze the cost characteristics of incumbent operating entities and new entrants;
- calibrate the model's parameters so that the estimated costs approximate those of other studies;
- analyze the characteristics of the international supply curve; and
- determine the scope for public intervention in each sector given the economic characteristics and technological conditions of its production.

2.2. Assessment of externalities

A basic objective of cost–benefit analysis is to measure all the costs and benefits associated with a given energy supply option. Thus, full-cost accounting that quantifies and ultimate provides a monetary valuation of externalities is necessary to promote power investment decisions that are truly least cost. Economists have long advocated making explicit the magnitude of direct environmental costs borne by society from electricity generation. However, at least until recently, the monetary valuation of externalities played only a limited role in actual energy policy decision-making (NEEDS, 2006a). The lack of a commonly accepted methodology for state-of-the-art assessment of external costs has been in part responsible for their low rate of diffusion in the comparative assessment of alternative electricity generating technologies. In recent years, significant progress has been made in remedying this deficiency. Several major projects – most notably a series of studies supported by the European Commission, called ExternE (Externalities of Energy) – have sought to develop powerful analytic tools for evaluating the negative environmental impacts of electricity generation. It should also be noted that with rising concerns about global warming, pressures for the integration of environmental impacts and externality considerations in energy policy making have been escalating sharply. Indeed, the capacity of a given technological option to mitigate climate change is rapidly becoming a dominant paradigm in the comparative appraisal of competing energy supply chains.

An appropriate methodology for evaluating the externalities associated with electricity generation comprises of four essential elements:

- identifying all stages of the energy chain;
- providing information on the material and energy flows and environmental burdens of each stage;
- evaluating the health and environmental impacts of these burdens; and
- defining a mechanism for estimating the costs of the various impacts.

The ExternE project has developed a methodology for assessing all relevant external effects and transforming impacts that are expressed in different units into a common metric—monetary value.[11] It comprises of a form of life-cycle analysis (LCA) which covers the first two components listed above; and an impact pathway analysis (IPA) which addresses the other two elements (OECD/NEA, 2003).[12]

[10] Some of these parameters are reasonably deterministic while others will require simulation.

[11] ExternE, launched in 1991 by the European Commission in collaboration with the US Department of Energy (which subsequently dropped out), was the first research project to put plausible financial figures on the environmental burdens arising from the different electricity generation chains.

[12] The term "impact pathway" relates to the sequence of events linking a "burden" to an "impact" and subsequent valuation.

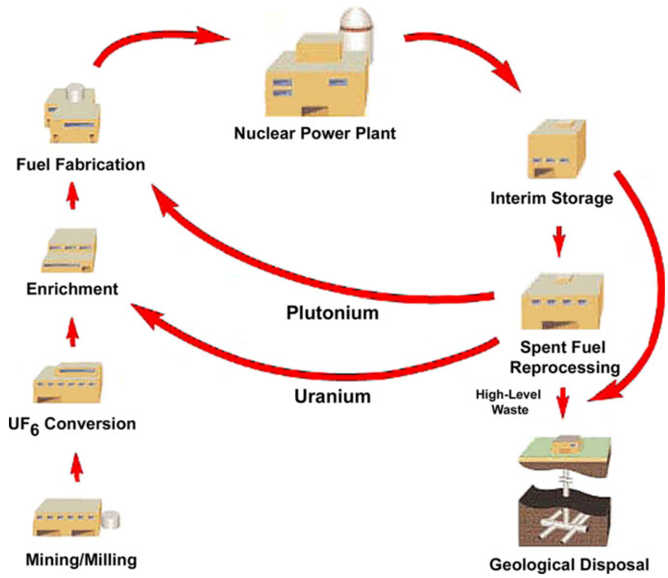


Fig. 1. Elements of a nuclear power system..
Source: NEEDS (2007a)

The nuclear fuel cycle can be broken into 8 separate stages (Fig. 1; NEEDS, 2007a). These include:

- mining and milling—uranium is mined, the lumps of ore (containing approximately 1% uranium) are crushed and milled to a fine powder which through a series of chemical processing steps is converted into uranium oxide (U_3O_8) in the form of yellowcake;
- conversion—through several chemical transformations, uranium oxide is converted into uranium hexafluoride (UF_6);
- enrichment—the proportion of the highly fissionable U-235 isotope is increased from its natural level of 0.7% to around 4%;
- fuel fabrication—the enriched UF_6 is converted to uranium dioxide (UO_2) powder and then pressed into pellets that are inserted into thin zirconium or stainless steel tubes to form fuel rods;
- electricity generation;
- interim spent fuel storage—spent fuel assemblies taken from the reactor core are stored in special pools, usually located at the plant site, to allow their heat and radioactivity to decrease;
- reprocessing of spent fuel[13]—uranium and plutonium are separated from the waste products; and
- high-level waste disposal—spent fuel which has not been reprocessed is encapsulated in corrosion-resistant metals (or after reprocessing the remaining 3% of high-level radioactive wastes is sealed in stainless steel canisters) that can be buried in deep underground rock structures.

It should be noted that spent fuel reprocessing is omitted from the cycle in most countries. Also, the impacts of construction, decommissioning and dismantling of nuclear facilities are typically included in the electricity generation stage (ExternE, 1995; NEEDS, 2007a).

The LCA methodology requires an inventory of all relevant environmental burdens and impacts. However, the current state of knowledge still contains a number of gaps and uncertainties. Thus, in practical terms, it is not possible to consider the whole range of burdens and impacts. There is a need for prioritization of the different impacts in terms of their magnitude, social, economic, and environmental relevance. This disregard of several externalities requires careful attention in any future research strategy. The following priority impacts were considered in the ExternE project (ExternE, 2005):

- environmental impacts—caused by substances or energy (radiation, heat, noise) released into the environmental media (air, soil and water);
- accidents—rare unwanted events in contrast to normal operation; and
- global warming impacts—caused by greenhouse gas emissions.

The impact pathway approach is used to quantify the different impacts associated with each environmental burden (or "stressor"). IPA seeks to model the casual chain of interactions from the emission of a pollutant into the environmental media to the impacts on various receptors (people, ecosystems, etc.).[14] Welfare losses from these impacts are transformed into monetary values (NEEDS, 2009). Thus, IPA's key steps can be grouped as follows:

- emissions—technology characterization and the amount of pollutants emitted per kWh on a site specific basis;
- dispersion—modeling the dispersion and transformation of pollutants over their full range and estimation of the increase in ambient concentrations;
- physical impacts identification—calculation of cumulative exposure and assessment of impacts utilizing an exposure-response function; and
- cost—monetization of impacts.

Environmental burdens occur in several stages of the nuclear power chain. Although both radioactive and non-radioactive substances are discharged, of particular importance are the impacts from the radionuclides that are released into the environmental media. Thus the priority pathways are those related to the radiological impacts on human health. The impacts assessed are those caused by routine emissions (atmospheric, liquid, and solid wastes) occurring during normal operations of the facilities in the fuel cycle. Since the releases from severe accidents involve far more complex issues, they are treated as a distinct category.[15] The assessment of each pathway is undertaken for every radionuclide and the total population dose is calculated by summing the population doses related to each radionuclide and pathway.[16] This aggregate dose value is used to

[13] The spent fuel contains approximately 96% of the initial uranium oxide mass, 1% plutonium (Pu) produced while the fuel was in the reactor, and 3% various waste products.

[14] IPA is much more complex than the standard inventory analysis of these stressors. Both the total impact and the relative contribution of stressors will vary by their geographic location. Thus, the contributions to local and regional effects cannot simply be aggregated throughout the electricity generation chains (Darras, 2001).

[15] There is no generally accepted definition of what constitutes a severe accident. Hirschberg et al. (1998) consider an accident to be severe if it entails one or more of the following: (i) at least 5 fatalities; (ii) at least 10 injured; (iii) at least 200 evacuees; (iv) extensive ban on food consumption; (v) release of hydrocarbons in excess of 10,000 tons; (vi) forced clean-up of an area of land or water in excess of 25 km^2; economic loss of at least $US 5 million. See also Hirschberg et al. (2004a).

[16] The scope of the assessment is divided into a matrix of space and time. Thus the temporal and geographic distribution of impacts is reflected in the IPA approach. Impacts occurring within one year, such as injuries from occupational accidents, are considered immediate or short-term. Medium-term impacts are those occurring within a lifetime (less than 100 years). Long-term impacts, such as releases of radionuclides from waste disposal sites, are those occurring beyond 100 years. The geographic scale, based on a radial grid, is as follows: local (0–100 km), regional (100–1000 km), global (> 1000 km).

estimate the impacts to human health on the basis of an exposure-response function. These physical impacts are further aggregated by monetization. The monetary valuation of the physical impacts (e.g., number of cased of cancer) is based on economic models, often using willingness-to-pay methods to estimate the costs of non-fatal health impacts; and the statistical value of life for the monetary valuation of fatalities (ExternE, 1995; NEEDS, 2007b).

One area of significant concern is the risk of reactor accidents in nuclear power plants. Indeed, two accidents have indelibly marked the history of nuclear power, leaving impressions in the public mind that, many years later, still affect reactions to this form of energy: the 1979 accident at the Three Mile Island nuclear power plant (in Pennsylvania, the United States) and the 1986 accident at Chernobyl (in Ukraine). Thus, the evaluation of the consequences of a severe nuclear accident should be a key element of every assessment of the external costs of nuclear power. However, accidents represent one of the most challenging components of environmental assessment of the nuclear fuel cycle. There is no general consensus on the appropriate methodology for calculating the economic consequences of severe nuclear reactor accidents.[17] As a result, the estimates of past studies tended to diverge by several orders of magnitude (OECD/NEA, 2000).

The evaluation of external costs associated with severe reactor accidents usually requires a series of assumptions, including the choice of a scenario and the associated probabilities. Thus, some input from Probabilistic Safety Assessment (PSA) is needed. A PSA-based assessment of offsite consequences of a severe accident entails an analysis of the potential causes of the accident, the underlying probabilities of occurrence, and the associated expected radioactive releases and offsite consequences, including immediate health effects, delayed health effects, and economic damages (Hirschberg et al., 2003; OECD/NEA, 2003).[18]

Although the operation of nuclear plants does not give rise to any significant GHG emissions, the other stages of the nuclear power chain (especially enrichment) do give rise to some GHG emissions. Still, there is widespread agreement that the emissions from nuclear power generation are substantially lower (between one and two orders of magnitude) than those from fossil fuel energy chains and comparable to those from renewable options.[19] This environmental advantage constitutes a positive "global warming" externality for nuclear power, which until recently was not explicitly recognized in economic analyses.

Research Task 2: *Develop and employ a comprehensive approach for evaluating the external costs and benefits of nuclear power including those related to environmental burdens, severe accidents, and global warming.*

There are additional externalities (both positive and negative) associated with the nuclear power. These are generally more difficult to quantify and monetize. On the negative side, the risk of future releases (possibly over the next several thousand years) of radionuclides from stored spent fuel, the risk of release of radionuclides due to terrorist attack, and the risk of nuclear weapons proliferation.[20] On the positive side, energy security, research and development spin-off, balance of payments, and price stability.

2.3. *Comparative assessment of nuclear power and alternative electricity generation investments under uncertainty*

Economic competitiveness is an indispensable precondition for the successful deployment of any electricity generation technology. Utilities, especially profit-maximizing ones, make their various business decisions by comparing the costs of generating electricity from alternative energy sources and by determining how these alternatives fit with their current portfolio of technologies. The levelized cost metric is a powerful tool for assessing these alternative electricity generation technologies and evaluating their relative competitiveness in the context of an analytically coherent and transparent framework (Koplow, 2005). It has been an especially effective tool for investors and for overall economic analysis during the pre-liberalization era when long-term financing was assured, costs could be passed to consumers through regulated prices, technology was stable, and the merit order was predictable. Unfortunately, the levelized methodology is much less suited for an economic environment characterized by significant uncertainties because it cannot incorporate such uncertainties effectively.

The economic environment in which nuclear power investments will be considered by electricity producers has changed dramatically in recent years. Prior to the liberalization of electricity markets, electric utilities were able to pass on their prudently incurred investments costs to consumers. Moreover, most of these utilities were state-owned and could finance their investment needs with implicit or explicit government guarantees—thus facing little or no market risk. It is not that risks did not exist in the pre-liberalization environment but that those risks were merely transferred to consumers and/or taxpayers. Market liberalization is removing most of that risk shield. It has been shifting most of risks associated with constructions costs, operating performance, and changing economic conditions, as well as residual regulatory risks, from consumers to investors. Thus, in the context of a liberalized market environment, investment in power generation comprises a large and diverse set of risks. These business risks include (IEA/NEA, 2005):

- factors that influence the demand for electricity and impact the supply of capital and labor;
- regulatory controls (economic and non-economic) and political risks that generally affect revenues, costs, and financing conditions;
- price and volume risks in the electricity market;
- fuel price and supply risks; and
- risks arising from the financing of investment.

While these risks affect all generating technologies, they do so in different ways (Table 1). In liberalized electricity markets, investors evaluate the profitability of their investment taking into

[17] The basis for the comparative assessment of severe accident risks across the different electricity supply chains has improved substantially in recent years, especially with respect to the completeness of historical records, quality and consistency of information, and coverage of various types of damages (Hirschberg et al., 2001)

[18] There have been numerous PSA studies for different types of reactors in several countries. The estimated probabilities of core meltdown for pressurized water reactors range from 3.7E−06 per reactor.year for Biblis in Germany to 3.4E−04 per reactor.year for Zion in the United States (OECD/NEA, 2003).

[19] According to the Nuclear Energy Agency, GHG emissions (expressed in g CO2 equivalent) per unit of electricity generated from various full life-cycle electricity generation chains are: 1200 g CO_2-eq./kWh for lignite, 1007 g CO_2-eq./kWh for hard coal, 900 g CO_2-eq./kWh for the oil chain, 400 g CO_2-eq./kWh for natural gas, 8 g CO_2-eq./kWh for nuclear, 5 g CO_2-eq./kWh for hydro. 11 g CO_2-eq./kWh for onshore wind, 14 g CO_2-eq./kWh for offshore wind, 60 g CO_2-eq./kWh for PV, and 100 g CO_2-eq./kWh for wood cogeneration (OECD/NEA, 2007). These estimates are UCTE (Union for the Coordination of Transmission of Electricity) averages and are consistent with those provided by the IPCC (2007). However there are dissenting voices. See, for example, Van Leeuwen and Smith, 2005.

[20] Two points of the nuclear fuel cycle form especially sensitive links between civilian uses and weapons applications: uranium enrichment and spent fuel reprocessing.

Table 1
Qualitative comparison of generic features of generation technologies.
Source: IEA/NEA (2005).

Technology	Unit size	Lead time	Capital cost (kW)	Operating cost	Fuel prices	CO_2 emissions	Regulatory risk
CCGT	Medium	Short	Low	Low	High	Medium	Low
Coal	Large	Long	High	Medium	Medium	High	High
Nuclear	Very large	Long	High	Medium	Low	Nil	High
Hydro	Large	Long	Very high	Very low	Nil	Nil	High
Wind	Small	Short	High	Very low	Nil	Nil	Medium
Recip. engine	Small	Very short	Low	Low	High	Medium	Medium
Fuel cells	Small	Very short	Very high	Medium	High	Medium	Low
Photovoltaics	Very small	Very short	Very high	Very low	Nil	Nil	Low

Note: CO_2 emissions refer to emissions at the power plant only.

account the risk underlying the capital employed, i.e., the risk-adjusted rate of return. Investors will generally demand higher returns, the greater the business and financial risks that they perceive. Thus, even when levelized costs are equivalent and technologies are commercially proven, different risk profiles of different technologies can influence the choice of power generation mix, the range of technologies offered, and the strategies for their development and operation.

The levelized cost methodology is a very useful tool for making comparisons among alternative generation technologies. However, its main limitation is that it does not incorporate risks effectively. Thus, it needs to be complemented with methodologies that account more completely for the risks in future costs and revenues. To assess these underlying risks, different scenarios or sensitivities can be constructed and calculated. However, such calculations generally permit only a limited assessment of the risks involved, i.e., not all uncertainties can be characterized as risks.

Research Task 3: *Develop and employ a comprehensive approach for identifying the main risk drivers and quantifying their impacts on the costs of nuclear power and alternative generation technologies.*

The most comprehensive approach to take into account the wide range of risks and uncertainties is to use a probabilistic assessment. A number of approaches are available for making risk assessments. When there are only a few significant sources of risk, sensitivity analysis may be employed to assess the impacts of likely variations in the key parameter values—and thus to identify the most important parameters that are driving the risk (Spinney and Watkins, 1996). When there are multiple sequences of events that could contribute to risk, probabilistic scenario analysis and decision trees might be appropriate (Chapman and Ward, 1996; Oryang, 2002).[21] Scenario analysis and decision trees are techniques that help us assess the effects of discrete risk. They begin with the identification of a hazard and the development of a step-by-step scenario from some initiating event to the end point at which the hazard occurs (Ahl, 1996; North, 2006). Simulations, on the other hand, provide a way of examining the consequences of continuous risk. In the real world, there is a multiplicity of risks, which, in turn, can give rise to a large number of possible outcomes. In that case, simulation techniques would allow for a much more comprehensive description of the underlying risks. System Dynamics and Agent-Based Simulation models which link observable patterns of behavior to micro-level structures and decision-making processes for the exploration of possible future scenarios could be very useful (Borshchev and Filippov, 2004; Chappin et al., 2009). Following what has become a common practice in probabilistic risk assessment, the focus might also be on Monte Carlo simulation and related techniques that are generally capable of addressing many of the challenges of decision analysis under significant uncertainty (Spinney and Watkins, 1996).

The Monte Carlo simulation process is a stochastic technique that describes risk in model outputs by converting risk in inputs into probability distributions and simulating the output distribution through repeated sampling. Thus, Monte Carlo simulation techniques effectively estimate future outcomes as functions of multiple inputs that are characterized by large ranges and are expressed as probability distributions. These probability distributions can be assigned a variety of functional forms and, as such, they can provide a much more complete and detailed description of model outputs in comparison to decision analysis where only a relatively small number of discrete, point probabilities are typically employed. Monte Carlo simulation typically entails the following steps (Spinney and Watkins, 1996):

- identification of key uncertain model input variables relating to resource options and their operational environment;
- statistical description of the risk for these key inputs through the assignment of probability distributions;
- identification and statistical description of any relationships (covariance) among key inputs;
- multiple iteration, where sets of input assumptions are drawn from each specified variable's probability distributions; and
- description of key model outputs with probability distributions.

In recent years, input prices, in particular those related to fuel (gas, coal, oil), plant construction material (steel, cement, etc.), and other relevant parameters of the different generating technologies have been characterized by large uncertainties and exhibited substantial volatility. The Monte Carlo simulation process is ideally suited to model these quantifiable uncertainties. It can effectively estimate their impacts on the basic performance metrics of alternative generating technologies by calculating a Net Present Value (NPV) probability distribution through repeated sampling and simulation runs. Thus it represents a much more comprehensive and powerful framework than the traditional levelized cost methodology for analyzing the performance of these technologies in the context of liberalized electricity markets, where the distribution of risks has been continuously shifting. However, it should also be acknowledged that Monte Carlo simulation suffers from some potential deficiencies and pitfalls. Some of these limitations are described by Spinney

[21] The probabilistic scenario analysis is a methodology for quantitative risk assessment that has been used for over 60 years. For example, in the 1950s it was used to assess the what-if scenarios of nuclear proliferation.

and Watkins (1996):

- the estimation of both probabilities and the interrelationships among the key variables in Monte Carlo simulation can be difficult and can lead to very complex models that are difficult to interpret;
- to easily deploy Monte Carlo simulation, assumptions are made about the underlying probability distributions without frequently understanding their implications; and
- no explicit distinction is made between diversifiable and non-diversifiable (systematic) risks.

Although the above concerns seem to be as difficult to address with alternative probabilistic methods, nevertheless it is important to carefully evaluate and explore the potential use of alternative approaches to probabilistic risk assessment. Thus, in addition to Monte Carlo simulation, the appropriateness of sensitivity analysis, probabilistic scenario analysis, and decision trees should also be evaluated.

It has been suggested that the total (internal plus external) system cost can serve as integrated relative indicator of sustainability. As such, this total cost indicator would be an appropriate metric for the comparative assessment and balanced evaluation of alternative electricity systems because it reflects both their economic and environmental efficiency (Hirschberg and Jakob, 1999). However, issues like high-level radioactive wastes, hypothetical severe accidents, or proliferation make relatively minor contribution to the estimated external costs. And yet, the extent to which nuclear power will prove an acceptable and enduring option for meeting the future energy requirements in many regions of the world will depend in part upon the ability of the international community to deal with the radioactive waste problem and minimize the proliferation risks. Indeed, these issues continue to play a decisive role in defining the public's attitude toward nuclear power. Thus a single integrated indicator of sustainability is unlikely to provide sufficient guidance in the decision-making process (Hirschberg et al., 2004b).

The various generating technologies differ significantly in terms of their underlying technological, environmental, and economic characteristics. Decision-makers need to carefully balance the competing characteristics of the different options in order to make socially optimal choices.[22] Multi-Criteria Decision Analysis (MCDA) is an essential methodology that employs a diversified set of indicators and criteria for measuring the performance of alternatives, clarifies the trade-offs between competing attributes, and facilitates a transparent decision process by allowing a complete comparison of all available electricity supply options (Roth et al., 2009; NEEDS, 2006b).

MCDA allows for the explicit accounting of social factors that are difficult to monetize or whose monetization is not widely accepted. It combines the results of the analyses undertaken for economic, environmental, and social attributes with user preferences. Some form of a weighted, multi-attribute objective function is defined with individual weights reflecting the relative importance of the various evaluation criteria (economic, environmental, and social). Thus, there is an explicit accounting for such issues as the disposal of long-lived radioactive waste, aversion towards hypothetical severe accidents and proliferation (Hirschberg et al., 2000, 2006; OECD/NEA, 2007).

[22] Indeed, as Hirschberg (2003) notes, trade-offs between environmental, economic and social sustainability components are inevitable. They are influenced by value judgments. Emphasis on economic issues would tend to penalize renewables; emphasis on the environment would penalize fossil chains; and emphasis on social aspects would penalize nuclear.

Understanding the complex nature of the various electricity systems, as well as the factors that influence and shape their evolution over time, requires a modeling framework. One such framework that has been extensively employed over the past 20 years is the MARKAL/TIMES family of models. MARKAL/TIMES are technology rich, bottom-up, least-cost optimization models based on life-cycle costs of competing technologies. A menu of both existing and future technologies is input to the models. MARKAL/TIMES assess the importance of new energy technologies in meeting different policy goals, identify cost-effective responses to environmental constraints, and select the combination of technologies that minimize cumulative energy system costs. The different technologies compete against each other for market share (Hirschberg et al., 2004b).

2.4. *The diversification value of nuclear power—the social benefits of "keeping the nuclear option open"*

The world energy markets have experienced considerable strain in recent years. This market stress is mainly due to the tightening balance between supply and demand, and it is further exacerbated by the concentration of oil and natural gas reserves in politically unstable parts of the world and the threat of terrorism. Without adequate and timely mitigation, irreversible oil and natural gas shortages, as well as unexpected geopolitical events, could have unprecedented economic, social, and political costs.

If retreating glaciers, hotter summers, stronger hurricanes, and other recently observed extreme weather patterns are ominous harbingers of things to come, then the pressures to reduce GHG emissions will intensify. This may lead to the introduction of carbon-emission taxes, as well as a continuing escalation of such taxes.

Previous work on the optimal degree of generating diversity has identified two principal macroeconomic benefits of fuel diversification and technology-mix: (a) non-fossil fuel technologies reduce fossil price risk and help avoid costly economic losses and (b) a diverse system is intrinsically more robust to supply shocks and thus diversification benefits security of supply (Awerbuch and Berger, 2003; Stirling, 2001). In the face of the current disturbing trends in climate change caused by the anthropogenic emission of carbon dioxide and other greenhouse gases, diversification into generating technologies that do not emit such gases will have the added climate-change mitigation benefit.

For nuclear power, construction costs represent the most important component (roughly two-thirds) of total generating costs. As a result, the costs of nuclear generation are fairly insensitive to oil, gas and carbon prices. Nuclear power could, therefore, offer a hedge to an electric utility against the uncertainty and volatility and risk of oil, gas and carbon prices. This hedging and the flexibility to choose between nuclear power and other generating technologies as new information emerges about fossil fuel supply conditions and evidence accumulates on climate change, creates an option value for nuclear power (Graber and Rothwell, 2006; Rothwell, 2006, 2009a). This hedging value cannot be adequately taken into account in the context of the standard levelized life-cycle cost methodology. It requires a dynamic framework to fully capture the value of the flexibility of waiting for more information on the supply conditions of oil and gas and the policy towards carbon. Moreover, it should be noted that the levelized cost methodology typically analyzes and compares the different generating technologies on a standalone basis. Clearly, the best informed choice among these technologies would require taking into account the complementarities of their risk-return profiles (Roques et al., 2006).

There is now a well established literature analyzing the diversification value of nuclear power as it reduces an importing country's exposure to fuel price risk.[23] It should however be noted that the hedging value against fuel and carbon price risks is not specific to nuclear power, insofar as it can also be attributed to renewables. Therefore, analysis should be conducted in the broader context of carbon free technologies, and should not be restricted to nuclear power.

Research Task 4**:** *Estimate the nuclear option value*—i.e., *(a) the value associated with the opportunity to wait and obtain additional information on the supply conditions of fossil fuels and (b) the diversification value of investing in nuclear power as a hedge against electricity, fossil fuel, and carbon price risks. Also, analyze the scope for market-based policy interventions to align the incentives faced by private investors with respect to fuel diversification with the socially optimal fuel mix.*

Stochastic optimization techniques could be used to estimate the option value of keeping the nuclear option open for a utility confronted with uncertain fossil fuel, electricity, and carbon prices. Roques et al. (2008) propose the following steps:

1. The discounted cash flow model of the different generation technologies will be first implemented.
2. Historical time series of electricity, fuel, and CO_2 prices will be used to derive the volatility and cross-correlations of each of these parameters in a specific country market.
3. A Monte Carlo simulation will be run to compute the distribution of NPV of an investment in the different generating technologies—the fuel, electricity, and CO_2 prices will be represented by normally distributed random variables, whose cross-correlations and standard deviations will be calibrated using data from the historical time series.
4. An econometric regression of the simulations of the different technology returns will be run to determine the correlation of the returns of the different technologies.
5. Mean-Variance Portfolio (MVP) theory will be applied to compute the returns (expected NPV) and risks (standard deviation of NVP) of different portfolios of the generation technologies considered, using the correlation factors between technologies computed in the previous step.

2.5. *Economies of scale and the economics of smaller sized nuclear reactors*

What type of nuclear energy is likely to emerge under the expanded global deployment scenario? The power grids in many developing countries that could consider nuclear power are not large enough to support deployment of very large units. Power systems engineering dictates that no single unit should be larger than about 10% or at most 15% of system demand. This implies that the 1000 MW size unit, the smallest of the three reactor types currently being promoted actively in the international market, cannot be considered in systems with a peak demand lower that about 7000 MW (e.g., Albania, Bolivia, Georgia, Ghana, Honduras, Morocco). These considerations suggest that there is merit to analyzing the economics of smaller nuclear plants. (The IAEA defines as "small" those reactors with power < 300 MW.)

Large nuclear plants entail massive fixed (largely construction) costs that are mostly sunk. In increasingly liberalized electricity markets, investors, who must bear the bulk of the construction and other performance risks, will favor less capital-intensive and shorter construction lead-time investments. There is a clear paradigm shift in electricity markets, away from the large, centralized power stations and towards more decentralized, distributive generation systems that reduce the need for expensive regional or national electricity grids. New nuclear reactor designs may be necessary to adapt to changing commercial and social requirements. Thus, there may be considerable scope for small-size reactors, which would permit a more incremental investment than the large units of the past and provide a better match to the limited grid capacity of many developing countries (Rothwell, 2001; Schock et al., 2001).[24]

Proposition 2. *Smaller size reactors will be an important component of an expanded global nuclear power deployment.*

Research Task 5**:**

- *review the econometric evidence of economies of scale in nuclear power*
- *evaluate the countervailing factors that might potentially compensate for losses of economies of scale in small reactors*
  - (i) *scope for modularization, minimization of the initial investment, and economies of mass production*
  - (ii) *reduced on-site installation, operation (higher fuel burnup, fewer refueling shutdowns, increased automation and reduction in specialized staffing), and decommissioning costs*
  - (iii) *reduced site infrastructure requirements*
  - (iv) *reduced time of build.*

There is a need to collect data on and analyze the operating performance of small and medium-size reactors (especially from India where there are 15 small- and two mid-sized nuclear power reactors in commercial operation). Also, an investment choice model should be developed to measure the option value generated by the modularity of a project with a flexible sequence of small reactor plants, given the uncertain future competitive price of electricity (Gollier et al., 2005).

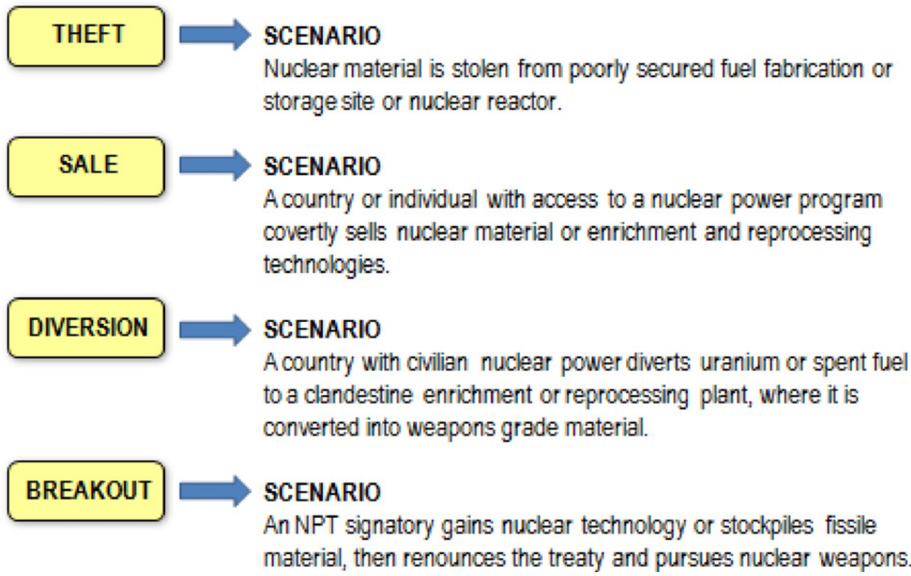
3. The search for proliferation-resistant nuclear power: technical and institutional options

All nuclear fuel cycles employ dual-use technologies that can be applied for both commercial and military. Whether nuclear power will realize its full potential in meeting the forecast large absolute increase in global energy demand will depend to a large extent upon the ability of the international community to control the concomitant proliferation risks. Indeed, a major global expansion of nuclear power, unless is accompanied by sufficient anti-proliferation safeguards, will inevitably increase the risk that fissile materials, equipment, technology, or expertise might be diverted or hijacked. This is because such an expansion could facilitate the acquisition of civilian nuclear technology by states whose ultimate objective is to develop nuclear weapons capability; or make it easier for terrorist groups to obtain nuclear assets. Moreover, these underlying proliferation risks would be further exacerbated if nuclear expansion caused a serious tightening of uranium supplies, which in turn would necessitate an increased deployment of reprocessing and recycling technologies. Thus, proliferation could ultimately prove to be the Achilles

[23] Under a global, large-scale deployment of nuclear power, there will be increased pressure on uranium resources and a greater likelihood that the uranium producing countries will start behaving strategically. Clearly, under such a scenario there will be increased fuel price risk. However, for nuclear power, construction accounts for most (around 2/3) of the costs, whereas for gas-fired generation fuel is the largest (over 2/3) component. Thus, nuclear power will reduce the sensitivity of electricity generation costs to fuel price variations.

[24] It should be noted that limited grid capacity is not a problem unique to developing countries. Lack of grid capacity has been a major obstacle to the development of a single European electricity market.

Box 1–Pathways: from nuclear power to nuclear weapons.*Source*: APS (2005).



heel of the nuclear renaissance that is predicted by some industry observers. And consequently, it is imperative to adopt the requisite measures for enhancing the proliferation resistance of nuclear power (APS (American Physical Society), 2005).

Two points of the nuclear fuel cycle form the sensitive links between civilian uses and weapons applications: uranium enrichment and spent fuel reprocessing.

- ***Uranium enrichment***: Uranium enrichment raises the low content of fissile uranium in the natural uranium mined from deposits from 0.7% to 3–4% (and now, with longer fuel cycles, up to 5%)—the level needed for the nuclear chain reaction in the core. To produce nuclear explosives, the enrichment level must be 90% or more. The process for these two distinct applications is the same, with multiple stages in parallel and in series, though more time is required for the higher enrichment. Two factors inhibited the spread of enrichment technologies until the 1980s: the secrecy that shrouded the process and the prohibitive costs of the diffusion method used in the first few decades of nuclear development. The introduction of the centrifuge enrichment process and the advent of the laser raised the potential for proliferation of enrichment technologies. See Rothwell (2009c).
- ***Spent fuel reprocessing***: Reprocessing of spent fuel is a chemical process that separates spent fuel from remaining (unspent) low-enriched uranium, fission products produced in the fission process, and more importantly, the new material that is produced in the fuel—plutonium-239, which is fissionable. Plutonium-239 is generated from the absorption of neutrons in non-fissile but fertile uranium-238, which accounts for 96.5–97.5% of uranium in the fuel (the rest is uranium-235). Plutonium-239, which does not exist in nature, is fissile and can be used in reactors to produce power or in explosive devices—in fact, a plutonium device is more expedient than one made of uranium-235. See Rothwell (2009b).

Box 1 identifies a multiplicity of pathways linking civilian nuclear programs to nuclear weapons development or acquisition. In almost all nuclear states, nuclear weapons were developed in dedicated military programs with very little, if any, input from civilian energy activities (Bunn, 2001). In recent years, on the other hand, there has been a heightened concern about civilian nuclear technology and materials being diverted, sold, stolen, or used as a subterfuge for developing nuclear weapons capability (APS, 2005).

Proliferation resistance refers to the characteristics of a nuclear system that make more difficult, transparent, or time consuming, the diversion or clandestine manufacture of nuclear material, or the misuse of declared facilities and technology, for the express purpose of acquiring or developing nuclear weapons (IAEA (International Atomic Energy Agency), 2004a). Technical (*intrinsic*) barriers to proliferation comprise those essential elements of the nuclear fuel cycle that inhibit, impede, or deter the diversion of materials, facilities, or technologies from civilian to military uses. For example, since low enriched uranium (LEU) fuel cannot be used in nuclear weapons, it represents an intrinsic barrier to proliferation. Institutional (*extrinsic*) barriers, on the other hand, focus on the implementation details of an existing mechanism or regime such as the international safeguards system by the International Atomic Energy Agency (IAEA). As such, they can complement the intrinsic barriers and compensate for their weaknesses. Proliferation resistance is achieved through a combination of technical and institutional elements of the nuclear energy system. Both elements are important and neither should be considered adequate by itself. Indeed, any sustainable resolution of the energy security/non-proliferation dilemma will require institutional as well as fundamental technological innovations (Feiveson, 2001a).

As in most other areas of the nuclear power debate, there is a significant divergence of views regarding the magnitude of the various proliferation risks and the robustness of barriers to proliferation (Box 2). Since the effectiveness of the non-proliferation regime is fundamental to the public's support for nuclear energy, it would be very important to (a) undertake a comprehensive cost–benefit analysis of alternative intrinsic barriers to proliferation; (b) evaluate the different options for strengthening the international safeguards regime to mitigate the increased proliferation risks under an expanded global nuclear

Box 2–Proliferation resistance: neither side of the nuclear debate much interested. *Source*: Bunn (2005).

- **Pro-nuclear view**:
  - Existing safeguards provide sufficient protection against use of civilian nuclear energy for weapons—no country has ever used safeguarded nuclear material to make a bomb
  - Proliferation is a political issue, not a technical one—countries that are determined to get nuclear weapons will eventually do so, regardless of technology of civilian nuclear energy system
- **Antinuclear view**:
  - *All* nuclear energy systems pose proliferation risks—relying on enrichment, producing plutonium (or at least producing neutrons that could be used to produce plutonium)
  - These dangers cannot be substantially reduced without abandoning nuclear energy

deployment; and (c) assess the impacts of measures improving proliferation resistance to the underlying economics of nuclear power (Bunn, 2005).

Proposition 3. *A robust global expansion of civilian nuclear power will significantly increase proliferation risks unless the current non-proliferation regime is substantially strengthened by technical and institutional measures and its international safeguards system adequately meets the new challenges associated with a geographic spread and an increase in the number of nuclear facilities.*

Thus, it is important to address the fundamental question whether an effective combination of technological advances and institutional measures could offer an adequate level of proliferation resistance in the context of a robust nuclear future. Or, alternatively, whether the risks associated with expanded nuclear deployment are quasi-irreducible even under an effective implementation of proliferation-resistant concepts that are currently available or are now being explored (Feiveson, 2003).

3.1. Extrinsic barriers to proliferation

Over the past 35 years, IAEA's safeguards system under the Nuclear Non-Proliferation Treaty (NPT) has proven fairly effective in restraining the diversion of fuel-cycle materials and facilities from civilian to military uses.[25] Indeed, the adoption of institutional measures to mitigate proliferation risks has played a key, if not dominant, anti-proliferation role. Consequently, there is an emerging consensus that most of the progress made towards improving proliferation resistance can be attributed to the increased authority accorded to the IAEA to detect clandestine facilities and undeclared operations within declared facilities. This includes the statutory authority provided through the "Additional Protocol" to the existing agreements governing IAEA's safeguards system.[26] The results from any intrinsic assessment should, therefore, be considered as input to determining the needs for improving extrinsic or institutional measures, i.e., an input defining the required extrinsic barriers for specific reactor and fuel-cycle systems under applicable political constraints or international standards (IAEA, 2004b).

If there is a considerable expansion of nuclear power throughout the world, a large number of currently non-nuclear-weapon states will acquire nuclear materials and facilities as well as the technology and expertise. In that case, it will likely become necessary for IAEA's monitoring and inspection activities to be calibrated roughly by the number of facilities in non-nuclear-weapon states. Thus, a robust nuclear future will likely require a significant expansion of the agency's safeguards system (Feiveson, 2003).

Moreover, under a robust global nuclear power expansion program, there will be increasing pressures on countries to deploy reprocessing and recycling technologies. This will happen for two main reasons. First, a large-scale deployment based on a once-through fuel cycle will require substantial quantities of uranium. How long will the global uranium resources be sufficient to support such deployment is a critical policy issue. Present data on the total identified amount of conventional uranium stock (which can be mined for less than $US130/kg) suggest that it is sufficient for several decades.[27] However, expanded utilization could lead to more costly extraction from low-concentration terrestrial ore deposits and seawater, and a more tightly balanced uranium market that will be prone to higher and more volatile prices (Cabrera-Palmer and Rothwell, 2008).[28] Higher prices will generate irresistible pressures for more efficient resource utilization, i.e., to reprocess and recycle. Second, expanded deployment based on a once-through fuel cycle will lead to a substantial increase in the quantity of waste materials requiring permanent disposal. Closed cycles have a distinct advantage with respect to long-term waste disposal, because long-lived actinides can be separated from the fission products and transmuted in a reactor (MIT, 2003).

Reprocessing and recycling have clear advantages in terms of resource utilization and spent fuel disposal. However, they can give rise to plutonium that is weapons-usable, whether by unsophisticated proliferators or by states seeking nuclear weapons capability. Thus, they will require strong process safeguards against misuse, diversion, or theft. The primary challenge will be to adequately account and control weapons-usable material during normal operations of the nuclear energy system; and to monitor, detect and prevent process modification or facilities diversion to produce or acquire such material (USDOE, 1997).

Research Task 6:

- analyze options for strengthening the institutional underpinnings of the IAEA safeguards regime;

[25] International Safeguards are a set of activities that the IAEA uses to verify that a country is adhering to international commitments not to use its nuclear program for nuclear weapons purposes. The safeguards system is based on regularly verifying the accuracy and completeness of a country's declarations to the IAEA concerning nuclear-related activities and seeking to assure that no undeclared nuclear materials or activities exist within the country. In total, presently more than 900 declared facilities in 71 countries are "safeguarded" and subject to inspection [p. 7, APS (2005)].

[26] The Additional Protocol is a legal document granting the IAEA complementary inspection authority to that provided in underlying safeguards agreements. A principal aim is to enable the IAEA inspectorate to provide assurance about both declared and possible undeclared activities. Under the Protocol, the IAEA is granted expanded rights of access to information and sites, as well as additional authority to use the most advanced technologies during the verification process (http://www.iaea.org/Publications/Factsheets/English/sg_overview.html).

[27] Even if the additional undiscovered uranium resources are taken into account, the once-through fuel cycle would not meet conditions of intermediate sustainability (Rothwell and van der Zwaan, 2003).

[28] Especially if, given the concentration of uranium resources, coordination emerges in that market (Rothwell, 1980).

- identify technological options that are likely to be most effective in enhancing extrinsic barriers to proliferation and making it easier to administer international safeguard; and
- identify economic incentives to strengthen the non-proliferation regime.

To reconcile a robust nuclear future with non-proliferation, it is important to analyze the scope for: (a) expanding IAEA's authority to carry out inspections beyond declared facilities to suspected illicit facilities and (b) implementing more effective and efficient safeguards measures by moving IAEA's safeguards regime towards continuous material protection, control and accounting through the application of advanced information, monitoring and containment technologies. This reassessment of IAEA's institutional architecture and mandate could be complemented with an analysis of cutting-edge information technology applications that enhance monitoring capability, including advanced sensor/telemetry, integration of sensors and data-monitoring systems that provide real-time video and measurements, and store information; and technologies that permit faster analysis of information collected through remote and on-site monitoring systems. The technological underpinnings of this monitoring and inspections regime could be further strengthened by the application of enhanced material-tagging measures, including tracers in material that continuously signal its location without interfering with plant operations; technologies that remotely confirm the location and integrity of spent-fuel assembly; and detecting high enriched uranium from enrichment plants (CGSR (Center for Global Security Research), 2000).

In addition to institutional and technological innovations, the non-proliferation regime could also be strengthened with economic incentives to motivate compliance. Thus, it will be important to analyze, among others, the potential role of tying carbon-emission permits and credits to a nation's agreement to refrain from constructing indigenous fuel cycle facilities or to dismantle any existing reprocessing infrastructure; and the subsidized provision of nuclear reactors and other components of the nuclear energy system to the recipient country's complying with IAEA safeguards and permitting comprehensive inspections of its nuclear facilities.

3.2. International energy parks—a hub-and-spoke nuclear architecture

One potential way of mitigating the proliferation risks of expanded nuclear deployment might be through the adoption of hub-and-spoke configurations that restrict all sensitive activities (such as isotope separation of uranium or reprocessing of spent fuel) to large, international/regional energy parks that would export fuel, hydrogen, and even small (40–50 MW) sealed reactors to client states (Kursunoglu and Mintz, 2001; Feiveson, 2001a). These reactors would be assembled and fueled at the central nuclear park, sealed (so that individual fuel assemblies could not be removed) and delivered as a unit to the power plant cites of client countries. At the end of their core life (say 15–20 years) the reactors would be returned to the central park unopened. Thus, during the 15–20 years of operation there would be no refueling and consequently the client countries would need no fuel fabrication facilities and management capabilities. To the extent that such modular reactors would operate almost autonomously, the hub-and-spoke architecture could reduce substantially the rationale and opportunities for countries to develop nuclear research laboratories and train technical specialists and scientists whose know-how could later be diverted to weapons activities (Feiveson et al., 2008). However, little economic analysis has been done on energy parks.

Although international energy parks and the hub-and-spoke nuclear architecture are technically feasible, they could prove politically difficult to implement. Countries might reasonably view these arrangements as threatening their sovereignty and encroaching upon their so energy independence. Moreover, the hub-and-spoke system would normally require the spoke countries to accept restrictions on their nuclear activities that might not be similarly imposed on the larger countries hosting the international or regional nuclear parks. Inevitably, such restriction will be viewed as being discriminatory, unless all countries (including the advanced industrial countries) were willing to accept a high degree of international control over their nuclear energy programs.

The analysis of options to reconfigure the developing world's energy supply architecture to exploit the innate features of nuclear power might include (Wade, 2005): a hierarchical hub-and-spoke energy supply architecture with regional energy parks handling both front- and back-end fuel cycle services; and reactor and plant designs that will enable incremental, time-phased market penetration to match the energy demand in the geographic areas circumscribed by the spokes and will efficiently mesh with existing energy distribution infrastructures.

Overcoming the political obstacles to regionalizing nuclear energy will require the identification and adoption of innovative institutional measures. It would be important to assess the scope for the following: creating regional energy parks owned by consortia of client countries that have had a fair amount of success in regional cooperation and economic integration; providing the recipient (spoke) countries with guaranteed (legally binding) access to services from the regional energy park in exchange for their foregoing building an indigenous fuel cycle infrastructure; and creating regional regulatory authorities and regimes for governing the regional nuclear energy infrastructure.

3.3. Proliferation resistance of new generation reactors and fuel cycles

Over the past three decades several attempts have been made to develop alternative nuclear technologies and cycles with greater resistance to proliferation. These efforts have focused on

- advanced reactor designs and/or new fuels that allow high burnup and produce less plutonium than current reactors (such as, for example, the pebble-bed high-temperature gas-cooled reactor);
- co-location of sensitive activities and processes with nuclear power plants; and
- reprocessing technologies that do not separate the plutonium from other actinides.

Analyses of various reactor cycles have shown that all have some potential for diversion, i.e., there is no proliferation-proof nuclear power cycle. Still, the development of higher burnup fuels, non-fertile fuels, or uranium-thorium fuels offer some promise. Moreover, reactor concepts that do not require refueling (with 15–20 years core life), especially under a hub-and-spoke architecture, would enhance proliferation resistance. Small Innovative Reactors (SIRs) have special attributes that make them more proliferation resistant than the larger, conventional nuclear reactors. These attributes include infrequent refueling, restricted access to nuclear fuel, and elimination of the host country needs or rationale to construct facilities that could be diverted from civilian to military purposes and ultimately used for clandestine production of nuclear material (Feiveson, 2001b; Greenspan and Brown, 2001). Another advantage of the SIRs is that they can be constructed on a shorter time scale and track actual capacity needs more closely—an important consideration, especially in the context of developing countries with small power markets (Stewart et al., 2002).

Proposition 4. *There is significant scope for improving intrinsic barriers to proliferation through high-burnup fuels (including uranium and thorium), non-fertile fuels, closed fuel cycles, high-temperature gas-cooled reactors, and small reactors.*

Existing methodologies do not permit definitive, quantitative assessments of proliferation resistance—objective quantitative measures are not obvious. In particular, it is extremely difficult to obtain meaningful, quantitative metrics by considering single technologies. Moreover, a generally accepted methodology has proven difficult to develop because both quantitative and qualitative factors contribute to proliferation resistance (CGSR, 2000). Multi-attribute qualitative (and any available quantitative) methodologies could be used to assess the progress made to date in enhancing intrinsic barriers in the context of (Hassberger, 2001):

- Light Water Reactors
  - Extending burnup to reduce plutonium quantity and quality
  - Thorium cycles to further reduce plutonium quantity and quality
- High-Temperature Gas-cooled Reactors
  - Low fissile loadings, very high burnup, and low plutonium production
- Fast Reactors
  - Recycle-in-place systems that eliminate reprocessing
  - Ultra long-life fuels
- Small Reactor Systems
  - Fueled-for-life cores, eliminating all on-site fuel handling
- Advanced Generation IV Systems
  - Integrating safeguard technologies that can continuously monitor and impede any misuse
- Advanced Recycle Systems
  - Eliminating separable weapons-useable materials for both closed and transmuted fuel cycles.

4. Summary—need for an integrated framework

A comprehensive analysis of the life-cycle costs and benefits of nuclear power must address a variety of complex issues related to the: components of nuclear power costs; assessment of important negative and positive externalities associated with the nuclear fuel cycle; large uncertainties characterizing construction costs and most of the key system parameters; and lack of actual construction cost and operating data. There is a need for an integrated framework that incorporates all these elements into the cost–benefit analysis.

4.1. Microeconomics of nuclear systems: Rothwell's methodology

One of the most critical differences among the diverse studies on the economics of nuclear power is related to the variables used for estimating capital costs. There is no an internationally agreed definition of the basic variables and standards for nuclear power plant costing. Different costs assessments make varying assumptions that render direct comparisons among them very difficult. Any credible cost–benefit analysis of nuclear power will need to reconcile these different studies. For this we propose to employ Rothwell's cost structure and market analysis methodology for modeling each sector of the nuclear fuel cycle Rothwell (2009c, 2010).

4.2. Assessing the externalities of nuclear power

No study of nuclear power can resolve the question whether the economics stack up if it does not explicitly address the negative externalities of nuclear power—i.e., those related to residual health and environmental impacts of routine emissions occurring during normal operations, risk of radioactive releases from severe accidents, risk of future releases of radionuclides from stored spend fuel, and proliferation. Due to growing concerns about climate disruption, the global warming (positive) externality of nuclear power needs to be carefully evaluated. A form of life-cycle analysis can be combined with an impact pathway analysis to assess all relevant external effects and monetize their impacts.

4.3. Incorporating risk and uncertainty

Investment in nuclear power and other generating technologies entails a large and diverse set of risks that cannot be captured by the standard levelized cost methodology. Rothwell's modeling of each sector of the nuclear fuel cycle can be complemented with Monte Carlo simulation to more fully represent the large uncertainties characterizing the "real" values of key variables. However, it must be acknowledged that the scope of what is being proposed is rather limited compared to the full spectrum of risks and uncertainties characterizing the nuclear fuel cycle.

4.4. Option value of nuclear power

Nuclear generation costs are fairly insensitive to oil, gas and carbon prices. Construction costs, particularly those related to steel and concrete, generally increase with rising fossil fuel prices. However, this reflects a sunk cost that once incurred has no further impact on running costs. Real option valuation methodologies and a modeling approach combining Mean-Variance Portfolio theory with Monte Carlo simulation can be employed to properly value the fact that nuclear costs are largely uncorrelated with oil, gas and carbon prices and to analyze the incentives for fuel-mix diversification in liberalized electricity markets. Also, real options analysis can be applied to estimate the option value of nuclear power that arises from the flexibility to wait and choose between further investment in the nuclear plant and other generating technologies as new information emerges about energy market conditions.

4.5. Smaller sized reactors

The electricity markets of many developing countries are too small to support investments in standard, large-scale nuclear plants. In addition to addressing the question of whether smaller sized reactors are economically viable, it would be important to estimate the value of modularity using real options theory.

4.6. Comparative assessment of alternative electricity supply options

The total (internal plus external) system cost can serve as an aggregated measure of sustainability. However, monetization is not universally accepted and social factors may be monetized only to a limited extent. Multi-Criteria Decision Analysis could be used as a complementary evaluation approach in the comparative assessment of alternative electricity systems. Moreover, large optimization energy-economic models (such as the MARKAL/TIMES family of models) can be used to analyze the competition between the various supply options taking into account externalities and the large uncertainties that characterize key parameters of these systems.

4.7. Sources of data

There is widespread agreement that the best predictors for the future costs of nuclear plants are based on actual experience rather than detailed engineering cost models and estimates. The relevant data need to be identified in the context of the microeconomic analysis mentioned above. In recent years most new nuclear build took place in developing countries. Despite differences in accounting methods and the volatility in exchange rates, actual construction data from countries like China and India would nevertheless be extremely valuable to the economic analysis of nuclear power. This is because of the past unreliability of engineering cost estimates and the inherent biases of estimates provided by vendors of nuclear power stations. Thus, the main effort should be directed towards collecting actual construction data. However, it should also be noted that there is little actual construction cost and operational experience related to the new generation of advance nuclear reactors.

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