World Nuclear Association Annual Symposium
3-5 September 2003 - London

Long-Term Cost Targets for Nuclear Energy

H-H. Rogner and A. McDonald

Abstract

In 2000 the International Atomic Energy Agency (IAEA) began the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) to help guide nuclear R&D strategies targeted on anticipated mid-century energy system needs. One part of INPRO seeks to develop cost targets for new designs to be competitive in mid-century markets.

The starting point was the 40 scenarios of the Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change. This paper summarizes four of the SRES scenarios, one from each of the four SRES scenario families. It discusses their implications for nuclear energy, including cost targets, and develops for each an "aggressive nuclear" variant. The aggressive nuclear variants estimate the potential market for nuclear energy if, by improving faster than assumed by the SRES authors, nuclear energy can make inroads into vulnerable market shares projected for its competitors. In addition to projected demands for nuclear generated electricity, hydrogen and heat, the aggressive variants include prospective demand for nuclear desalination and use in upgrading fossil fuels. The paper then presents learning rates and implied cost targets consistent with the aggressive nuclear variants of the SRES scenarios.

One provocative initial result is that many of the scenarios with substantial nuclear expansion do *not* seem to require big reductions in nuclear investment costs. One interpretation discussed at the end of the paper highlights the difference between cost reductions consistent with long-term energy system optimization based on perfect foresight, and cost reductions necessary to attract private investment in today's "deregulating" and uncertain energy markets.

Introduction

The IAEA started INPRO in 2000 with the overall objectives of ensuring that nuclear energy is available to help meet the energy needs of the twenty-first century and to contribute to sustainable development, engaging both technology holders and technology users, and promoting innovations in nuclear reactors and fuel cycles to meet expected future requirements in terms of economics, safety, waste management, environmental impacts, proliferation resistance and public acceptance. In June of this year it published a final report on Phase-IA defining "user requirements" in the six areas listed above and outlining a method for applying these user requirements to specific innovative nuclear designs. In Phase--IB, interested IAEA Member States will assess innovative designs of their choosing using the requirements and assessment method developed in Phase-IA.

This paper concerns one sub-objective of INPRO – the development of cost targets for new designs to be competitive in mid-century markets. The first step is to describe what the mid-century energy market might look like – the major competitors for nuclear energy, what products are in demand, how much of each, where growth is greatest, and so forth. The mechanism for systematically describing the future market is scenario building. Because we do not know the future precisely, we need several scenarios to reflect our uncertainty.

The starting point is the scenarios in the Special Report on Emissions Scenarios (SRES) of the Intergovernmental Panel on Climate Change[1]. Given their international authorship and comprehensive review by governments and scientific experts, the SRES scenarios are the state of the art in long-term energy scenarios.

SRES developed four narrative storylines, each representing a different coherent set of demographic, social, economic, technological, and environmental developments. For each storyline, several different quantifications, or scenarios, were then developed by six different international modeling teams. The result is 40 scenarios grouped in four "families" (A1, A2, B1, and B2) corresponding to the four narrative storylines. The four families are shown schematically in *Figure 1*. Economic objectives dominate in the "A" storylines at the top of the Figure, while environmental objectives dominate in the "B" storylines. The "1" storylines on the left emphasize globalization, while the "2" storylines are better characterized by regionalism. The following summaries are almost verbatim from the SRES report.

- The A1 storyline and scenario family describe a future world of very rapid economic growth, low population growth, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income.
- The A2 storyline and scenario family describe a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.
- The B1 storyline and scenario family describe a convergent world with the same low population growth as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic,

social, and environmental challenges, including improved equity, but without additional climate initiatives.
- The B2 storyline and scenario family describe a world in which the emphasis is on local solutions to economic, social, and environmental challenges. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the storyline is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

For each of the A2, B1, and B2 storylines this paper uses a single scenario representative of central tendencies within the scenario family. The primary energy mix for each is shown in *Figure 2*. For the A1 storyline, SRES projections showed that greenhouse gas emissions (the principal focus of SRES) vary greatly depending on the technologies assumed to progress most quickly. We have chosen the A1T Scenario, which assumes that advances in non-fossil technologies – renewables, nuclear, and high-efficiency conservation technologies – make them most cost-competitive.

The A1T emission trajectory for carbon is consistent with stabilizing the atmospheric carbon concentration at about 560 parts per million by volume (ppmv), and the emission trajectory for the B1 Scenario is consistent with stabilization at less than 500 ppmv. Thus, although both these scenarios explicitly exclude any policies specifically focused on limiting global warming, they do include policies to reduce other environmental impacts and to accelerate technological change, which lead to carbon emission levels that could be consistent with the objectives of the UN Framework Convention on Climate Change (UNFCCC). In contrast, the A2 and B2 Scenarios project higher carbon emissions at levels currently considered inconsistent with the UNFCCC objectives.

Nuclear energy in the SRES A1T, A2, B1, and B2 Scenarios

Figure 3 summarizes the nuclear projections in the SRES quantifications using the MESSAGE model of the International Institute for Applied Systems Analysis.[1] Each quartet of bars shows projected nuclear production in a given year for the four scenarios, with A1T on the left, then A2, then B1, and then B2 on the right. Each bar is divided into four segments corresponding to the four regions into which the SRES analysis divides the world. The dark segments at the bottom include all countries belonging to the OECD as of 1990. The next segments (REF) are countries undergoing economic reform. Next is “Asia,” which includes all developing countries in Asia. The top light segments cover the rest of the world (ROW) and include all developing countries in Africa, Latin America, and the Middle East.

---

[1] In the remainder of this paper, references to SRES results or assumptions refer specifically to the MESSAGE quantifications of the four scenarios in Figure 1.

The use of nuclear energy rises most rapidly in the A1T Scenario to more than 14 times its current level in 2050. Initially the expansion is driven by the OECD, but after 2040 expansion is greatest in Asia. Nuclear energy then peaks around 2070 and 2080 and is declining by the end of the century. The pattern is similar in the B1 Scenario, but at a much reduced level. Nuclear use in 2050 is slightly less than five times the current level. The pattern is very different in the A2 and B2 Scenarios. Expansion is slower than in the A1T Scenario, but it is steady and continuous. By 2050 nuclear use is almost six times its current level, and by 2100 it has passed the level in the A1T Scenario and is still growing.

“Aggressive nuclear” variations on the SRES scenarios

In terms of market perspectives for nuclear power, the SRES results should be viewed not as tight constraints, but as indications of opportunities. And the important question is how quickly must the industry innovate, i.e. improve costs and competitiveness, to capture future market shares significantly bigger than those based on the performance assumptions of SRES’ authors. To develop such cost improvement targets, we start by estimating just how big the potential nuclear market might be beyond what is shown in *Figure 3*. The assumptions underlying our estimates are described in this section. The results are shown in *Figure 4*.

Electricity

Any inroads by nuclear energy into the markets held by its competitors (as calculated in SRES) would begin in those parts of competitors’ market shares that are most expensive. Consider first competition from fossil-fired electricity generation. In the SRES scenarios fossil reserves and resources are divided into distinct cost categories. SRES calculates consumption in each category for each region and scenario. In general, consumption early in a scenario concentrates on lower cost categories and, as these are depleted, moves to higher cost categories in later parts of the scenario. In detail, the patterns are more complex, incorporating as they do regional differences in resources and infrastructural inertia – i.e. new plants, mines, transportation systems, and processing facilities do not replace old ones overnight, but are phased in at different rates in different regions. The situation is further complicated through inter-regional energy trade.

We assume that even aggressive nuclear improvements would be unlikely to displace electricity produced by coal and natural gas in the least expensive cost categories. Electricity from these categories is simply too cheap an option. But the higher-cost categories are more vulnerable to inroads from nuclear improvements that are faster than those assumed in SRES. We therefore assume that aggressive nuclear improvements would allow nuclear power to capture half of the market share (in each region in each scenario) that corresponds to electricity from the high-cost coal and natural gas resource categories. For oil, the remaining fossil fuel, there is no significant market share for nuclear power to capture, as oil-fired electricity drops quickly to zero in all scenarios.

Biomass and waste are not divided into cost categories in SRES like coal and natural gas. But the same principle should hold – even aggressive nuclear improvements would be unlikely to dislodge the cheapest biomass and waste from the electricity market, but should make in-roads at the expensive end of the biomass/waste market share. Since SRES estimates the total potential availability of biomass and waste, we assume that any use that exceeds 60% of this total potential would fall into the high-cost, vulnerable category.

SRES divides hydroelectricity into a high-cost category and a low-cost category. Only the high-cost category is considered vulnerable to inroads by nuclear energy. In the OCED and REF regions, we assume that nuclear energy could capture 50% of the high-cost hydroelectricity calculated by SRES. In the Asia and ROW regions, where nuclear energy faces greater infrastructural challenges even in the event of aggressive improvements, we assume that it could only capture 33% of the high-cost hydroelectricity calculated by SRES.

Solar electricity is divided in the SRES scenarios into three categories based on whether it is generated by centralized solar thermal plants, centralized photovoltaic plants, or decentralized on-site production (mostly from small photovoltaic systems). Only the two centralized categories are considered vulnerable to displacement by nuclear energy. We assume nuclear energy captures 50% of their market as calculated by SRES.

For wind and geothermal, SRES includes no cost categories. Based on the expectation that, with aggressive improvements, nuclear energy could displace a share of the more expensive end of the wind/geothermal market share, we assume that 25% (half of half) of the complete wind/geothermal electricity shares calculated by SRES is assumed vulnerable to nuclear inroads.

Hydrogen

Hydrogen in the SRES scenarios can be produced in six ways. For the first three, hydrogen is produced directly from carbon fuels – coal, natural gas, and biomass. The fourth option is electrolysis. And the fifth and sixth are thermochemical production from high-temperature nuclear and solar cycles. Of the six, the first three are the cheapest, and are assumed to be less vulnerable to inroads from nuclear energy. Any nuclear inroads into electrolytic hydrogen production are already accounted for in the assumptions above about nuclear power's potential displacement of competitors' contributions to the overall electricity mix. Thus, the only potential additional hydrogen market share to capture is that from thermochemical solar hydrogen production. Assuming again that the more expensive end of solar's market share is most vulnerable to displacement, nuclear hydrogen production displaces any solar hydrogen production in excess of 60% of the total solar potential estimated by SRES.

Heat and desalination

Additional applications of nuclear energy included in *Figure 4* are district heat (i.e. centralized heat generation) and heat for upgrading unconventional oil, for liquefying and gasifying coal, for producing synfuels from coal, and for desalinating seawater to increase freshwater supplies.

District heat supplies are included as a separate category in the SRES calculations, but they are not broken down into different cost categories. Paralleling the logic applied to wind and geothermal electricity generation above – that nuclear energy could displace a share of the more expensive end of the market – we assume in the calculations for *Figure 4* that nuclear district heat could capture 25% (half of half) of the total district heat use calculated by SRES.

Oil resources in SRES, like coal and gas resources, are divided in cost categories. Oil resources in the four highest-cost categories (out of eight) are all unconventional. In SRES the heat needed to upgrade oil in these categories comes from the oil itself, and thus shows up in the calculations as a conversion loss. Similarly, in coal gasification and liquefaction, and in synfuels production from coal, the necessary heat comes from the coal and shows up as a conversion loss. The assumption used for *Figure 4* is that aggressive nuclear improvements would allow nuclear energy to supply heat for these purposes equal to 50% of the conversion losses calculated by SRES.

The SRES scenarios do not elaborate on future water demand and supply. However, recent studies indicate that fresh water demand may well exceed sustainable supply in the near-term future[2-5]. Indeed, in areas of North Africa, the Middle East, and certain parts of Asia, this is already the case now. For the purposes of *Figure 4* we estimated overall water demand based on the demographic developments underlying the SRES scenarios, a daily diet of at least 2700 kcal per person per day, an average water demand of households and industry of 400m^3 per person per year, and rates of productivity in improving water use derived from the SRES storylines. Regional water availability was taken from a variety of sources[2-5]. A sustainable share of 40% of total water availability was assumed for all regions, as was a 25% potential share of nuclear power in the future water desalination market.

Innovation needs or technology learning

The potential markets for nuclear power estimated in the previous section are enormous, prompting immediate questions about the technology's future performance requirements, resource requirements, and proliferation resistance. In this paper we address the first of these.

The basic economic principle guiding nuclear RD&D strategists is that future nuclear power plants must prove to be attractive investments. This principle provides a constantly moving target, given that experience, nuclear technology, and competing alternative technologies are continuously improving. We therefore focus on rates of improvement, specifically "learning rates", rather than on fixed cost targets at specific dates.

The concept of technological learning was first introduced over 60 years ago. Simply put, a technology's performance improves as experience with the technology accumulates. The concept can be used with a variety of different indicators of technological performance and experience, but we will focus on specific capital costs as the performance indicator and total cumulative installed capacity as the experience indicator. The learning rate is defined as the percentage reduction in specific investment costs associated with a doubling of total cumulative installed capacity. The cost reduction is a function of the cumulative investment or production that actually takes place, and not a function of time.

The version of the MESSAGE model[6] that was used to derive the cost-optimal energy supply mix for the four selected SRES scenarios does not use learning rates. Rather the cost data input for the SRES scenarios assume decreases in technological costs as a function of *time*, not as an explicit function of experience (cumulative capacity). However, because cumulative capacity and time increase together in each scenario, costs that decrease with time also decrease with increases in cumulative capacity. Plotting such cost reductions as a function of installed capacity for each SRES scenario makes it possible to determine the learning rates implicit in the scenarios for various energy technologies.

Learning rates and nuclear cost improvements

An analysis has been carried out of the impact of different assumed learning rates for nuclear technology on the contributions of nuclear power and nuclear-based hydrogen production in the SRES scenarios. The analysis used a modified version of MESSAGE, labelled MESSAGE-ETL, that incorporates technology cost decreases as a function of experience rather than time, both for nuclear and for competing energy technologies such as solar power, other renewable technologies, and fossil energy technologies.

The results are summarized in *Table 1*. This shows, first, the implicit nuclear learning rates for the original four SRES scenarios. Second, it shows the higher nuclear learning rates necessary to generate the faster and more extensive nuclear build-up trajectories corresponding to the four "aggressive nuclear improvement" scenarios described in Section 3. The rates for the "aggressive nuclear improvement" variants are broadly consistent with historically observed rates for energy technologies[7].

*Table 1***:** Learning rates as implied by the four selected SRES scenarios and as required to match the "aggressive nuclear improvement" variations on these scenarios.

Scenario	**Implicit learning rate in original SRES scenario**	**Learning rate to match "aggressive nuclear improvement" variant**
A1T	4-5%	7%[2]
A2	0-1%	6%
B1	3-4%	10%
B2	0-1%	8%

---

[2] The learning rate for A1T scenario was derived from a one-region version of MESSAGE while the other scenarios use multi-region versions. One weakness of the one-region model is that all resources around the world are equally available to meet all energy demands, no matter where they arise. Thus, when the A1T Scenario is re-analyzed with a multi-region version and resources cannot flow instantly around the world, we expect that a higher nuclear learning rate will be needed for energy supplies to meet energy demands.

Turning learning rates into cost targets

Given a specified learning rate and a trajectory for capacity expansion over time, one can calculate the implied costs for each scenario as a function of time. *Figure 5* shows the results for capital costs (overnight costs plus interest during construction, per kilowatt electric) in 2050 for all eight scenarios discussed above. The suffix "-N" identifies the aggressive nuclear variants of the four original SRES scenarios. The range in the year 2000 is also from the SRES scenarios. The bar labeled "NTR" shows the range of current costs presented in the IAEA's *Nuclear Technology Review 2002*[8] based on data from the European Commission and the OECD[9, 10], and the bar labelled "NTDG" shows the range for near-term (2010) nuclear competitiveness estimated by the U.S. Near Term Deployment Group[11]. Note that the NTDG bar *does not* include interest during construction, but that all the other bars *do* include interest during construction. The interest rate used in the NTR figures is 10%. For the SRES scenarios it is 5%.

The MESSAGE model recognizes that in any given year, both the operating fleet of reactors, and any new reactors installed in that year, include a mix of technologies. The most expensive reactor among the new additions is probably cheaper than the most expensive reactor among the operating fleet, which could be several decades old. The bars in *Figure 5* show the range from the least expensive nuclear technology added in 2050 to the most expensive nuclear technology available in 2050, i.e. the range in which nuclear power plants are found by the model to be attractive investments. In the A1T and B1 Scenarios (and in the base year 2000) the top of the bar corresponds to high-temperature reactors capable of co-generating electricity and hydrogen.

Interpretation

Should RD&D strategists consider the results in *Figure 5* as cost targets for competitive nuclear designs in 2050? Not yet. Although these results are indeed the cost ranges in which the scenarios find nuclear technologies to be attractive investments relative to competing alternatives, we believe they need further work before they can serve as good targets for new designs. However, they already appear to support the case for near-term government subsidies of new nuclear power plants.

Before looking at what more needs to be done before results in *Figure 5* can serve as cost targets for new nuclear designs, we should recall how far we have come. The starting point was scenarios because they are the best mechanism for systematically incorporating a host of uncertain factors when estimating the capital and operating cost levels likely to make an innovative nuclear reactor an attractive investment in 2050. Such factors include how much populations grow around the world; how much economies grow and change; how lifestyles evolve and how that is reflected in changing market demands and changing safety, environmental and non-proliferation constraints; how extensive various energy resources prove to be; how quickly alternative technologies advance; and how quickly ideas, money, people and technologies move around the world. Scenarios incorporate all these – and more – consistently and systematically.

We therefore chose the best pedigreed independent set of scenarios available, those in the IPCC's Special Report on Emissions Scenarios (SRES), and extracted the relevant capital costs for nuclear technologies that those scenarios consider attractive investments in 2050. Those costs are shown by the bars labelled A1T, B1, A2, and B2 in *Figure 5*. Throughout the analysis, we emphasized the concept of technological learning measured by learning rates in order to focus on the need for continuous learning and improvement if a future technology is to be consistently competitive.

The nuclear costs in the SRES scenarios for 2050 (the A1T, B1, A2 and B2 bars in *Figure 5*) are, however, not as low as we expected. Below are two possible explanations related to idealizations incorporated in the MESSAGE model. An additional reason is that the cost ranges in *Figure 5* are those for which nuclear power is attractive based on fossil fuel prices in 2050, not 2003. Although the SRES scenarios do not deplete fossil resources as quickly as in standard applications of the Hubbert curve, due mainly to the unconventional fossil resources in the scenarios, depletion definitely takes place. Fossil fuels extracted in 2050 therefore come from higher cost categories than the cheaper fossil fuels against which nuclear energy is competing today. Other things being equal, this means that nuclear costs would not have to be as low in 2050 to be competitive as they must be today.

Of the two explanations related to idealizations in MESSAGE, the first is that the model optimises total energy system costs through 2100 using a discount rate of 5%. The current front-loaded cost structure of nuclear technologies (and renewable technologies for that matter), with their high initial capital costs and low long-term costs, is therefore less of a disadvantage in the scenarios than it would be for an investor in a liberalised energy market who faces higher financing charges than 5% and needs a rapid return on his investment. Thus MESSAGE is likely to still "buy" nuclear technologies (and renewable technologies) with high capital costs even when a private investor in a liberalised market might not. We recognize that not all prospective investors will be private companies seeking quick returns in fully liberalised markets. Many are likely to be governments that can focus on longer term returns, and for whom low discount rates are appropriate. But if the objective is a design attractive to private investors in liberalised markets, the cost targets should probably be lower than those extracted directly from the SRES scenarios.

A second related consideration is that in MESSAGE, investments are essentially risk free and benefit from the model's "perfect foresight". Given the investment risks that exist in actual markets, both for private investors and governments, costs may need to be lower than shown in *Figure 5* for nuclear technologies to still be attractive investments once investment risks are taken into account.

Although these comments are directed to the four original SRES scenarios, they also apply to the four aggressive nuclear variants. In addition, in the case of the aggressive nuclear variant of the A1T Scenario (i.e. A1T-N), as noted above, the costs in *Figure 5* were calculated using an initial one-region version of MESSAGE-ETL. When the scenario is re-analysed with a multi-region version of

MESSAGE-ETL, the result is likely to be a higher nuclear learning rate than the 7% shown in *Table 1*, and correspondingly lower costs.

As for near-term policy implications, one way to interpret the higher than expected numbers in *Figure 5* (at least for the A1T, B1, B2, and A2 Scenarios) is that the incentives of today's "deregulating" and uncertain energy markets will not lead to the best (least-cost) long-term evolution of the energy system. If the A1T, B1, A2, and B2 cost ranges in *Figure 5* are too high to attract nuclear investments (at the levels in the scenarios) in today's "deregulating" and uncertain energy markets, that means investment that should be going into nuclear energy is inefficiently going elsewhere – probably to natural gas and, where gas is less available, to coal. This would hardly be the first case of market incentives motivating investments that, while they make perfect sense from the perspective of the individual investor, are not the best in terms of the greater national or international interest. If one accepts that the long-term evolution of the energy system is something where broader national or international interests might sometimes trump the sanctity of investor independence, then there is a case for governments intervening in markets to bring the incentives perceived by investors more into line with those broader national or international interests. In practical terms this means government subsidies for new nuclear plants to prompt expansion, even based on relatively high capital-cost nuclear designs. Where governments are direct investors, the results in *Figure 5* suggest they could justifiably invest in relatively high-capital-cost nuclear plants, even when these are not always the least-cost option available.

Governments also have an interest in the maintenance and preservation of nuclear expertise. The best assurance of such expertise is a growing nuclear sector that expands experience and attracts talent. Although MESSAGE assumes that unused skills never get rusty, and new talent will still flock to even stagnant technologies, reality is different. Government subsidies to assure nuclear expansion in the long-term national interest may in fact be a more cost-effective way to maintain expertise than allowing nuclear stagnation and then spending on compensatory programs to assure expertise.

In interpreting the higher than expected numbers for the A1T, B1, A2, and B2 Scenarios as support for government subsidies and investment to help new nuclear power plants over the up-front cost hump that discourages today's private investors, we note that a comparable analysis of renewables in the scenarios would likely provide similar support for subsidies for renewable technologies, which also have an up-front cost hump.

Future Work

As noted above, future work will focus on adjusting the results in *Figure 5* to provide useful guidance to nuclear RD&D strategists operating, not in the somewhat idealized world of the MESSAGE model, but in our more familiar world without perfect foresight, with risks and uncertainty, and with pressure for rapid returns on energy investments.

The capital costs in *Figure 5* also need to be complemented with similar results for electricity production costs, which will include more explicitly the impact of fuel costs of nuclear cost targets.

REFERENCES

[1] IPCC (Intergovernmental Panel on Climate Change). *Special Report on Emission Scenarios*. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 2000. (http://www.grida.no/climate/ipcc/emission/index.htm).

[2] M. Falkenmark. *Meeting Water Requirements of an Expanding World*. Phil. Trans. R. Soc. Lond. B352: 929-36, 1997.

[3] Peter H. Gleick. *The World's Water 2000-2001: The Biennial Report on Freshwater Resources*. Island Press, Washington, D.C., 2000.

[4] D. Seckler, U. Amarasinghe, D. Molden, R. de Silva, and R. Barker. *World Water Demand and Supply, 1990 to 2025: Scenarios and Issues*. Research Report 19, International Water Management Institute, Colombo, Sri Lanka, 1998.

[5] WRI (World Resources Institute). *World Resources 1998-99*. Oxford University Press, Oxford, UK, 1998.

[6] S. Messner and M. Strubbeger. *User's guide for MESSAGE III*. WP-95-69, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1995.

[7] Alan McDonald and Leo Schrattenholzer. *Learning rates for energy technologies*, Energy Policy 29, pp. 255-261, 2001.

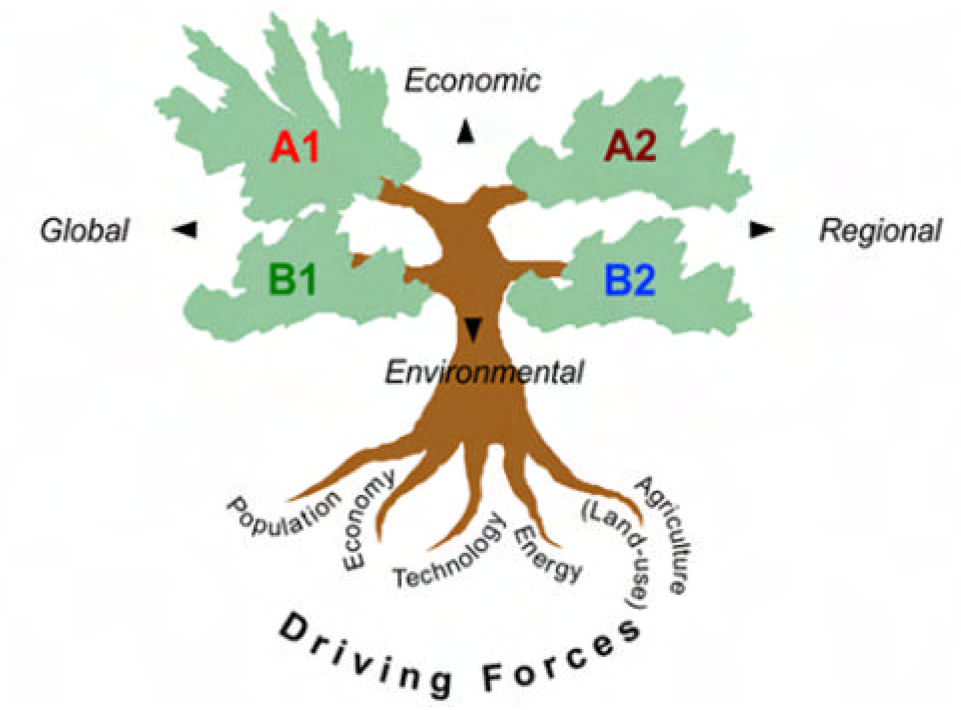
[8] IAEA (International Atomic Energy Agency). *Nuclear Technology Review 2002*. IAEA, Vienna, Austria, 2002.

[9] EC (European Commission). *ExternE 1998, Externalities of Energy: New Results*, Directorate General XII, Science Research and Development, L-2920 Luxembourg, 1998.

[10] OECD (Organisation for Economic Cooperation And Development). *Projected Costs of Generating Electricity*: *Update 1998*. OECD, International Energy Agency (IEA) and Nuclear Energy Agency (NEA), Paris, France, 1998.

[11] USDOE (United States Department of Energy). *A Roadmap to Deploy New Nuclear Power Plants in the United States by 2010, Volume II, Main Report,* prepared for the United States Department of Energy, Office of Nuclear Energy, Science and Technology and its Nuclear Energy Research Advisory Committee, Subcommittee on Generation IV Technology Planning, 31October, 2001, Washington, D.C.

Figure 1. Schematic illustration of the four SRES storyline families.



Source: IPCC, 2000

Figure 2. Primary energy use in four SRES scenarios.

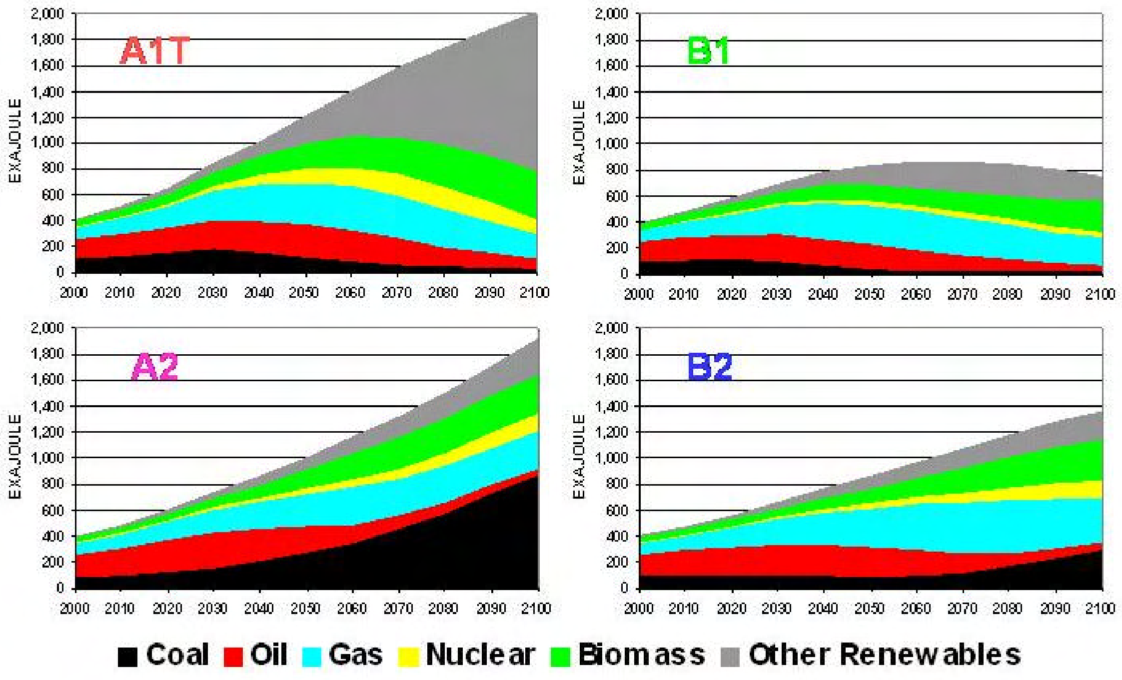


Figure 3. Projected use of nuclear energy in four SRES scenarios.

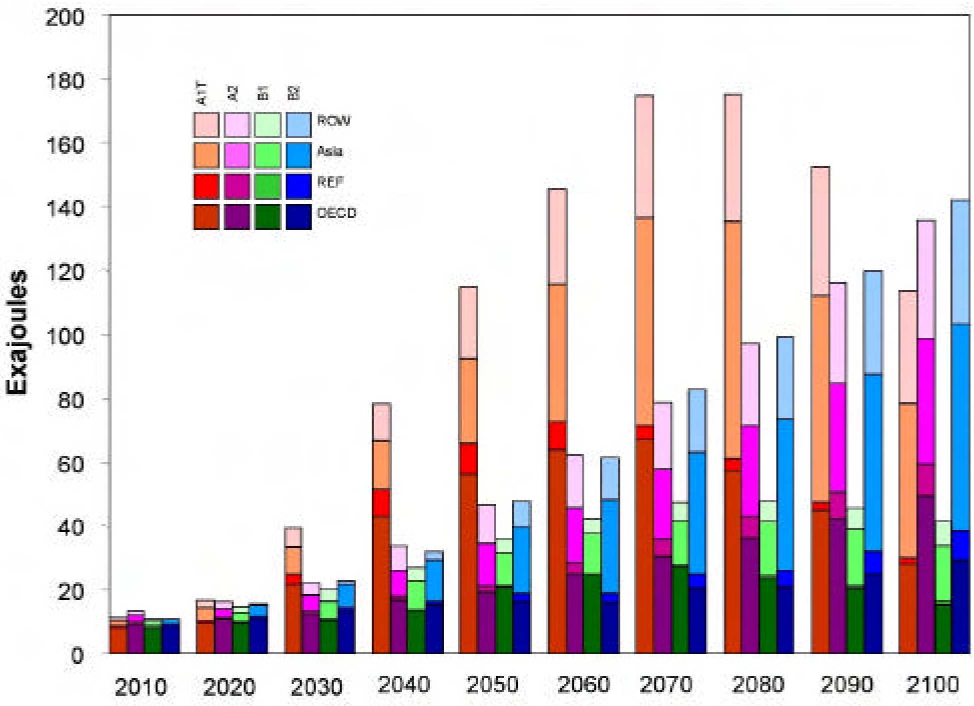


Figure 4: Projected use of nuclear energy in "aggressive nuclear" variations of the four SRES scenarios. The bottom three categories in each panel (electricity, hydrogen, and heat) show projected nuclear use in the original four SRES scenarios. Their collective trajectories match those in Figure 3. The top five categories show the additional nuclear market potential based on the assumptions in Section 3.

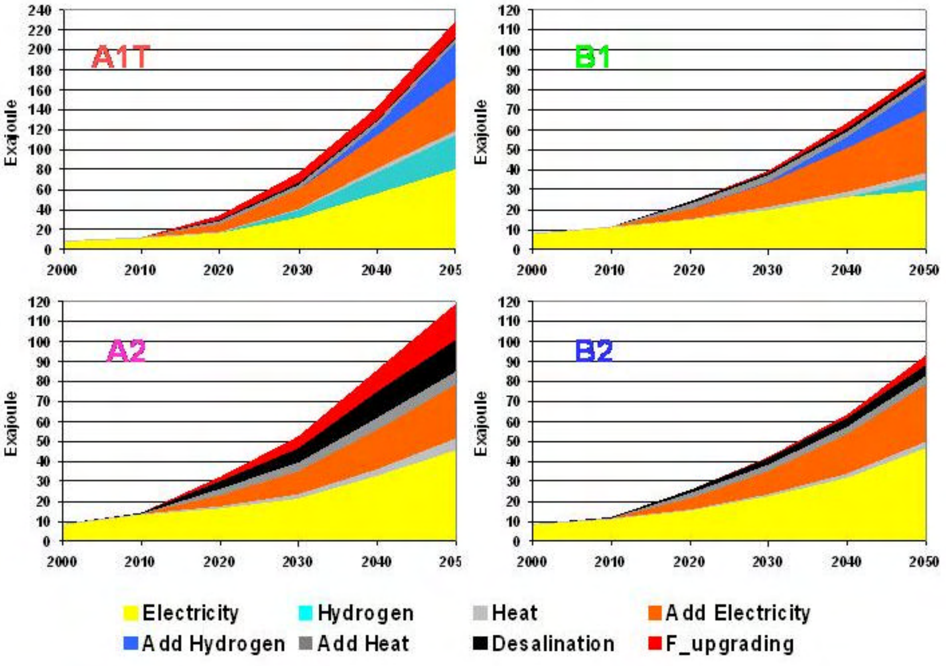


Figure 5: Projected ranges for specific capital costs in 2050 for nuclear power plants in eight scenarios.