FUTURE REGIONAL NUCLEAR FUEL CYCLE COOPERATION IN EAST ASIA: ENERGY SECURITY COSTS AND BENEFITS

Report of the
EAST ASIA SCIENCE AND SECURITY PROJECT
Prepared for
The John T. and Catherine T. MacArthur Foundation

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Executive Summary

Over the past two decades, economic growth in East Asia—and particularly in China, the Republic of Korea (ROK), Vietnam, Taiwan, and Indonesia—has rapidly increased regional energy, and especially, electricity needs. As a recent, eye-opening example of these increased needs, China added more than 100 GW of generating capacity—equivalent to 150 percent of the total generation capacity in the ROK as of 2007—in the year 2006 alone, with the vast bulk of that added capacity being coal-fired, with attendant concerns regarding the global climate impacts of steadily increasing coal consumption. Even more striking than growth in primary energy use—and indeed one of its main drivers—has been the increase in electricity generation (and consumption) in the region.

With the lessons of the "energy crises" of the 1970s in mind, several of the countries of East Asia—starting with Japan, and continuing with the ROK, Taiwan, and China—have sought to diversify their energy sources and bolster their energy supply security by developing nuclear power. Several other East Asian nations are currently discussing adopting nuclear power as well. At the same time, global security concerns related to terrorism and to the nuclear weapons activities of North Korea, Pakistan, and India, as well as the (nominally peaceful) uranium enrichment program pursued by Iran, have focused international concern on the potential for nuclear proliferation associated with nuclear power. In addition, old concerns regarding the management of nuclear spent fuel and other wastes remain, at best, only partially addressed.

One means of addressing proliferation concerns, reducing environmental and safety risks of nuclear power, and possibly of reducing the costs of nuclear energy to the countries of the region, is regional cooperation on nuclear fuel activities. A number of proposals for regional cooperation on safety, enrichment, spent-fuel and waste management, and other issues have been offered over the years, some from within the region, and some from outside the region. The net impact, however, of regional nuclear cooperation on the energy security—expressed broadly to include supply security, economic impacts, environmental security, and security related to social and military risks—requires a more detailed look at how cooperation on nuclear power might be organized and operated. In the East Asia Science and Security (EASS) Project, Nautilus Institute and its collaborating teams in nine countries of the region have been working together to define several different scenarios for nuclear fuel cycle cooperation in East Asia, and to evaluate those scenarios under different sets of assumptions regarding the development of nuclear power in the region. This Draft Report to the MacArthur Foundation provides a discussion of the background of the project, as well as results of the EASS analyses undertaken to date. In the coming years, we expect to further elaborate and refine these analyses, and also to broaden our review of the impacts of nuclear power in East Asia to look at the interactions between climate change issues and nuclear power.

Given the constraints on nuclear fuel activities in East Asian countries that are (or could potentially be) major users of nuclear power, regional fuel cycle activities have been attractive to policymakers. Domestic and international political constraints on construction and operation of enrichment and reprocessing facilities, and, especially, domestic constraints on the siting and operation of spent fuel management facilities, have spurred international discussions on nuclear collaborations. Over the last two decades, a number of regional nuclear fuel cycle proposals have been discussed, including the Global Nuclear Energy Partnership (GNEP) proposed by the

United States during the George W. Bush administration (and recently discontinued by the Obama administration), but also including less ambitious proposals for shared enrichment and/or spent fuel management and/or nuclear safety and fuel management safeguards. Specific proposals have included "ASIATOM", an "Asian Nuclear Safety Centre", and an "East Asian Collaboration for Intermediate Storage", among others. These and other options are summarized briefly in Chapter 4 of this Report.

The goals of the EASS activities described in this Report are as follows:

- Develop, in consultation with national expert teams, a set of detailed, internally-consistent nuclear energy/nuclear fuel-cycle paths for each of the countries of East Asia that have (or may have within the next few decades) nuclear power plants (Japan, the Republic of Korea, the DPRK, the Far Eastern region of Russia, China, Taiwan, Vietnam, Indonesia, and Australia).
- Develop regional nuclear energy/fuel-cycle paths/scenarios that explore advanced technical and organizational concepts of improved regional spent fuel security based on regional cooperation. These scenarios include the evaluation of various schemes to produce enriched uranium within the region on a "non-proliferation preferential" basis, and spent fuel management/reprocessing options for regional cooperation in East Asia within "reference" and "maximum" nuclear power capacity development paths. Paths development includes elaboration of alternative maximum nuclear energy paths reflecting regional cooperation to address nuclear fuel-cycle policy imperatives. Paths variants include different nuclear materials recycling regimes.
- Evaluate the generation of different types of nuclear wastes, and the national and regional costs for waste management, through the application of tools and information produced during the EASS project and by other researchers in the field

The EASS project builds on the extensive quantitative, qualitative research and analysis undertaken under Nautilus' Asian Energy Security (AES) project (and its predecessor efforts such as the East Asia Energy Futures project) to investigate alternative future nuclear power and fuel-cycle development paths, and to develop realistic policy options for developing implementable projects to reduce the proliferation potential of nuclear power systems in the region (and, by extension, globally). Analytically, the overall approach taken in the study to date has been to estimate future electricity demand by country, then use EASS energy paths ("BAU", "Minimum Nuclear" and "Maximum Nuclear") to develop different requirements for/implied SF production from nuclear energy use by country. In parallel, we have developed several different initial "generic scenarios" of regional enrichment/spent-fuel management, and are using them to examine the cost, technical/physical outputs, and other energy security (see text box below) implications of those scenarios.

This Interim Report focuses on early results of the EASS project's analysis of four cooperation "scenarios" for nuclear fuel enrichment and for spent fuel management. The scenarios, and some (but hardly all) of the key policy issues they suggest, are as follows:

1. "**National Enrichment, National Reprocessing**": In this scenario the major current nuclear energy users in East Asia (Japan, China, and the ROK), and perhaps others as well, each pursue their own enrichment and reprocessing programs. Disposal of high-level nuclear wastes from reprocessing would be up to each individual country, with attendant political and

social issues in each nation. Security would be up to the individual country, and as a result, transparency in the actions of each country is not a given.

2. "**Regional Center(s)**": This scenario features the use of one or more regional centers for enrichment and reprocessing/waste management, drawn upon and shared by all of the nuclear energy users of the region. We avoid identifying particular country hosts for the facilities, but China and Russia are obvious candidates.
3. "**Fuel Stockpile/Market Reprocessing**": Here, the countries of the region purchase natural and enriched uranium internationally, but cooperate to create a fuel stockpile that the nations of the region can draw upon under specified market conditions. Reprocessing services are purchased from international sources, such as France's AREVA or from Russia, while some spent fuel continues to be stored in nations where nuclear generation is used.
4. "**Market Enrichment/Dry Cask Storage**": In this, likely the cheapest of the four scenarios for participants, countries in the region (with the possible exception of China) would continue to purchase enrichment services from international suppliers such as URENCO in Europe, the USEC in North America, and Russia. All spent fuel, after cooling in ponds at reactor sites, would be put into dry cask storage either at reactor sites or at intermediate storage facilities.

Below we present a brief summary of study findings.

Nuclear Paths by Country

Table EX-1 summarizes the nuclear capacity included for each the three nuclear capacity expansion paths (Business as Usual, Maximum Nuclear, and Minimum Nuclear) for each country for the years 2010, 2030, and 2050. Key results by country are as follows:

- **Japan**, with relatively little additional space for reactors and a declining population, shows slow growth in reactor capacity from 2010 to 2050 in the BAU case—adding about 33 percent more capacity over 40 years, and only modestly more rapid growth in the MAX case. The MIN case, which amounts to a nuclear phase-out as reactors reach the end of their operating lifetimes, represents a significant departure for Japan, virtually eliminating its nuclear fleet by 2050.
- In the **ROK**, Additional reactor space is also limited, but more and larger reactors are added to existing sites in the BAU case, resulting in a near-doubling of 2010 capacity by 2050, and in the MAX case, where capacity increases by a factor of nearly 2.5 (though new sites would probably be needed in the MAX case). I the MIN case, existing reactors are retired without life extension and not replaced, resulting in a reduction in capacity of more than 50% by 2050.
- For **China**, all three capacity expansion paths show explosive growth in nuclear capacity through 2030. Growth continues in the BAU path after 2030, though at a lower rate as the Chinese economy matures and population begins to decline, In the MAX path, the growth rate of capacity also declines somewhat after 2030, but nearly 100 GW are still added in between 2030 and 2050, nearly twice as much as is added in the BAU case. In the MIN case, capacity additions essentially cease after 2030 (and growth to 2030 is less than in the other paths), with older reactors retired as they reach the ends of their operating lifetimes.

- The **Russian Far East** add some capacity between about 2020 and 2050 in the BAU case to its very small existing reactors in the far north. This capacity is mostly to serve export markets and/or to provide power for producing export commodities such as aluminum. In the MAX case, future capacity is approximately twice that in the BAU case, reflecting a stronger market for RFE power exports. In the MIN case, only one new (larger) reactor is added in the RFE by 2030, and no more thereafter.
- In **Taiwan**, as in Japan and the ROK, limited space for new reactors and a declining population limit the extent to which nuclear capacity can increase. In the BAU case, capacity increases by 2 GW, as a result of adding reactors now under construction, but remains at the resulting 7 GW level through 2050. In the MAX case, larger reactors are added at existing sites when older reactors are decommissioned, pushing capacity to 11 GW by 2050. In the MIN case, older reactors are not replaced, resulting in Taiwan’s capacity falling to 3 GW by 2050.
- In the BAU case, the **DPRK** is assumed to reach an agreement with other parties regarding its nuclear weapons program in the next few years, and as a result completes (or, more likely, works with the ROK to complete) by 2030 the reactors at Simpo begun under the KEDO project. In the MAX case, a additional 4 GW of capacity is added in the years around 2030, for a total of 6 GW. In the MIN case, the DPRK does not develop nuclear power.
- For **Indonesia, Vietnam**, and **Australia**, which do not have and are not yet building nuclear power capacity, the BAU case includes first reactors that come on line between 2020 and 2030, with Vietnam’s program being much more aggressive than in the other two nations. The MAX path includes greater use of nuclear power for each nation by both 2030 and 2050. In the MIN path, none of these nations ultimately adopt nuclear power.

Table EX-1: Regional Nuclear Generation Capacity, Summary of BAU, MAX, and MIN Paths

	Total Nuclear Capacity Net of Decommissioned Units (GWe)								
	RAU (Reference) Case			Maximum Nuclear Case			Minimum Nuclear Case		
Nation	2010	2030	2050	2010	2030	2050	2010	2030	2050
Japan	47	62	64	47	68	69	47	20	2
ROK	19	33	35	19	42	47	19	18	9
China	10	120	170	10	161	257	10	93	84
RFE	0	3	6	0	6	11	0	1	1
Taiwan	5	7	7	5	9	11	5	3	3
DPRK	-	2	2	-	6	6	-	-	-
Indonesia	-	2	6	-	4	13	-	-	-
Vietnam	-	10	20	-	15	30	-	-	-
Australia	-	2	6	-	7	20	-	-	-
TOTAL	81	241	316	81	318	464	81	134	97

Summary of Regional Scenario Results

The results of the regional scenario evaluation summarized above (and detailed in Chapter 5) indicates that Scenario 4, which focuses on at-reactor dry cask storage and coordinated fuel stockpiling, but largely avoids reprocessing and mixed-oxide fuel (MOx, that is, reactor fuel that uses a mixture of plutonium reprocessed from spent fuel and uranium and as its fissile material) use, results in lower fuel-cycle costs, and offers benefits in terms of social-cultural and military security. These results are consistent with (and, indeed, draw ideas and parameters from) broader studies by other research groups, including, for example, the joint work by the Harvard University Project on Managing the Atom and the University of Tokyo Project on Sociotechnics of Nuclear Energy.

That said, there are definite trade-offs between scenarios. Scenario 1, by using much more domestic enrichment and reprocessing than the other scenarios, arguably improves energy supply security for individual nations, but results in higher technological risk due to national reliance on one or a small number of enrichment and reprocessing plants, rather than the larger number of plants that constitute the international market. Scenario 1 would also raise significant proliferation concerns (not the least of which would be the DPRK's reaction to ROK enrichment and reprocessing). Scenario 1 also results in the build-up of stockpiles of plutonium (Pu) in each of the nations pursuing reprocessing. Though the magnitude of the plutonium stockpiles, and the rate at which they are used, varies considerably by nuclear path and scenario, the quantities accrued, ranging from about 130 to about 270 tonnes of Pu at a maximum in Scenarios 1 through 3 in the years around 2040, are sufficient for tens of thousands of nuclear weapons, meaning that the misplacement or diversion of a very small portion of the stockpile becomes a serious proliferation issue, and thus requires significant security measures in each country where plutonium is produced or stored. Scenario 4, without additional reprocessing, maintains a stockpile of about 70 tonnes of Pu from about 2010 on. This still represents a serious proliferation risk, but does not add to existing stockpiles or create stockpile in new places.

Scenarios 1 through 3, which include reprocessing, result, as noted above, in higher annual costs-about $5 billion per year higher in 2050 relative to Scenario 4, over the entire region (see Figure EX-1). Scenarios 1 through 3 reduce the amount of spent fuel to be managed substantially—by 50 percent or more over the period from 2000 through 2050, relative to Scenario 4—but imply additional production of 7000 to 7600 cubic meters of high-level waste that must be managed instead (versus about 300 cubic meters in Scenario 4). This in addition to medium- and low-level wastes from reprocessing, and wastes from MOx fuel fabrication that must be managed in significant quantities in Scenarios 1 through 3, but not in Scenario 4. Scenarios 1 through 3 offer a modest reduction—less than10 percent in for the BAU nuclear capacity paths case—in the amount of natural uranium required region-wide, and in attendant needs for enriched uranium and enrichment services. This reduction is not very significant from a cost perspective unless uranium costs rise much, much higher in the next four decades. Reductions in the quantities of electricity and fuel used for uranium mining and milling, as well as production of depleted uranium, are generally somewhat lower under Scenarios 1 through 3 than under Scenario 4, though results for Scenario 1 differ from Scenarios 2 and 3 because of the emphasis on sourcing uranium from domestic mines in the region. Figure EX-2 shows aggregated front-end (fuel preparation) and back-end (spent fuel management) costs by Scenario and for each of the three nuclear capacity paths for the region.

Figure EX-1: Summary of Fuel-cycle Costs by Scenario, BAU Capacity Expansion Path

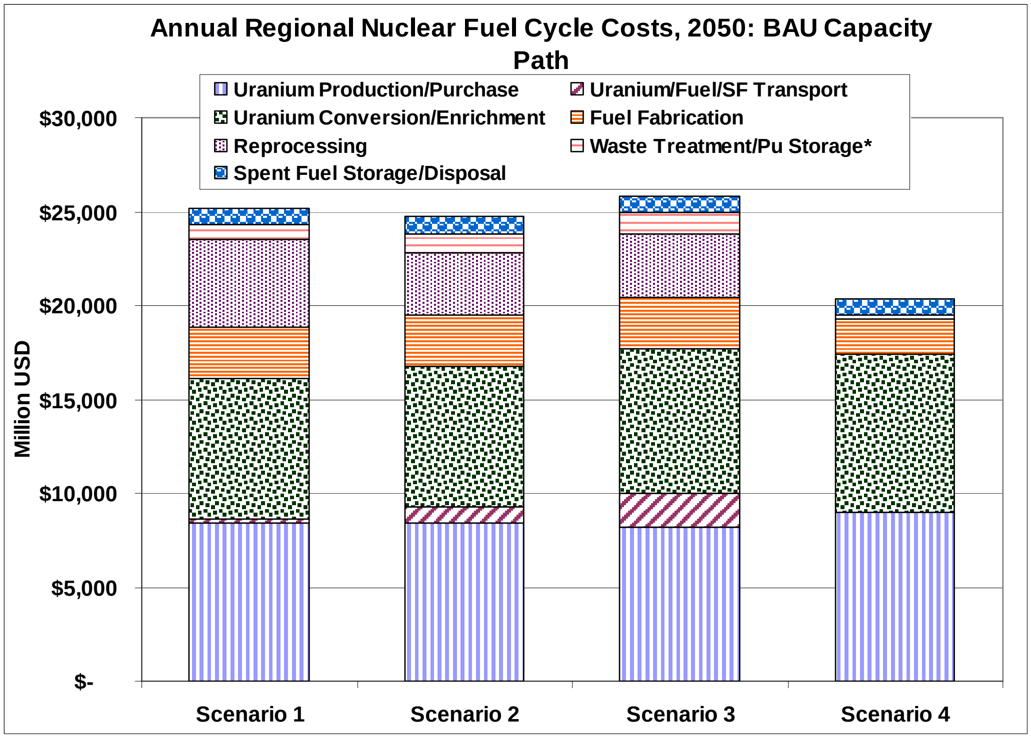
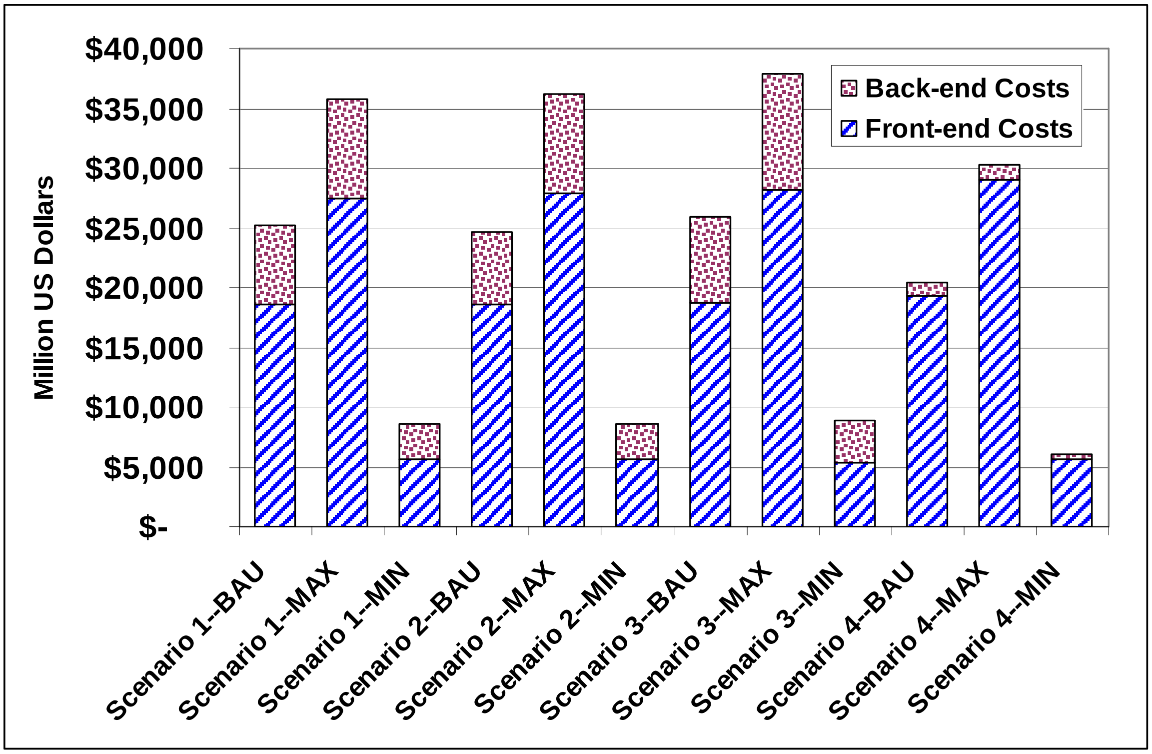


Figure EX-2: Summary of Year 2050 Annual Costs by Scenario and by Nuclear Capacity Expansion Path



Scenarios 2 and 3, though they include reprocessing, place more of the sensitive materials and technologies in the nuclear fuel cycle in regional and international facilities, and as a consequence, are likely to be superior to Scenario 1 in terms of reducing proliferation opportunities, reducing security costs, and increasing the transparency of (and thus international trust in) fuel cycle activities. The costs of Scenarios 2 and 3 shown in this analysis are not significantly different, overall, from those of Scenario 1, but a more detailed evaluation of the relative costs of nuclear facilities (particularly, enrichment and reprocessing facilities) in different countries, when available, might result in some differentiation in the costs of these three scenarios. Scenarios 2 and 3 result in significantly more transport of nuclear materials—particularly spent fuel, enriched fuel, MOx fuel, and possibly high-level wastes around the globe, likely by ship, than Scenario 1, though there would be somewhat more transport of those materials inside the nations of East Asia in Scenario 1.

Nuclear power will certainly continue to play a significant role in the economies of the countries of the East Asia and Pacific region for decades to come. The extent of that role, however, and how the various cost, safety, environmental, and proliferation-risk issues surrounding nuclear power will be addressed on the national and regional levels is not at all certain, and will depend on policy choices made in the next decade or two. The analysis summarized above and presented in detail in this report indicates that different policy choices today, particularly with regard to cooperation between nations on nuclear fuel cycle issues, can lead to very different outcomes regarding the shape of the nuclear energy sector—and of related international security arrangements—over time.

Acknowledgements

The authors of this report gratefully acknowledge the support of the MacArthur Foundation for the East Asia Science and Security (EASS) project. In addition, over the past decade, much-appreciated support for Nautilus research that has built the foundation for and contributed to the work described in this report has come from the Alton Jones Foundation, the United States Department of Energy, the Ploughshares Foundation, and others. A number of colleagues in the EASS project, including Professor Li Bin of Tsinghua University, have contributed to discussions of potential nuclear fuel cycle cooperation in the region. The authors also wish to acknowledge the hard work of our many colleagues from around the East Asia and Pacific region that constitute the Country Teams in the EASS project. The work of these Country Teams, including some participants who have been collaborating with Nautilus for more than a decade, have been instrumental in enabling the project, through their careful and patient work, cooperative, friendly, and open attitudes, varied points of view, and generous spirits, to provide what we believe is a uniquely detailed and considered collaborative analysis. A listing of the members of the Country Teams who have contributed to this report follows (most affiliations listed remain current, but some are as of approximately 2008-2009, and have changed).

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1. Introduction—Nuclear Power and the Nuclear Fuel Cycle in East Asia

Over the past two decades, economic growth in East Asia—and particularly in China, the Republic of Korea (ROK), Vietnam, Taiwan, and Indonesia—has rapidly increased regional energy, and especially, electricity needs. As a recent, eye-opening example of these increased needs, China added more than 100 GW of generating capacity—equivalent to 150 percent of the total generation capacity in the ROK as of 2007—in the year 2006 alone, with the vast bulk of that added capacity being coal-fired, with attendant concerns regarding the global climate impacts of steadily increasing coal consumption. Even more striking than growth in primary energy use—and indeed one of its main drivers—has been the increase in electricity generation (and consumption) in the region.

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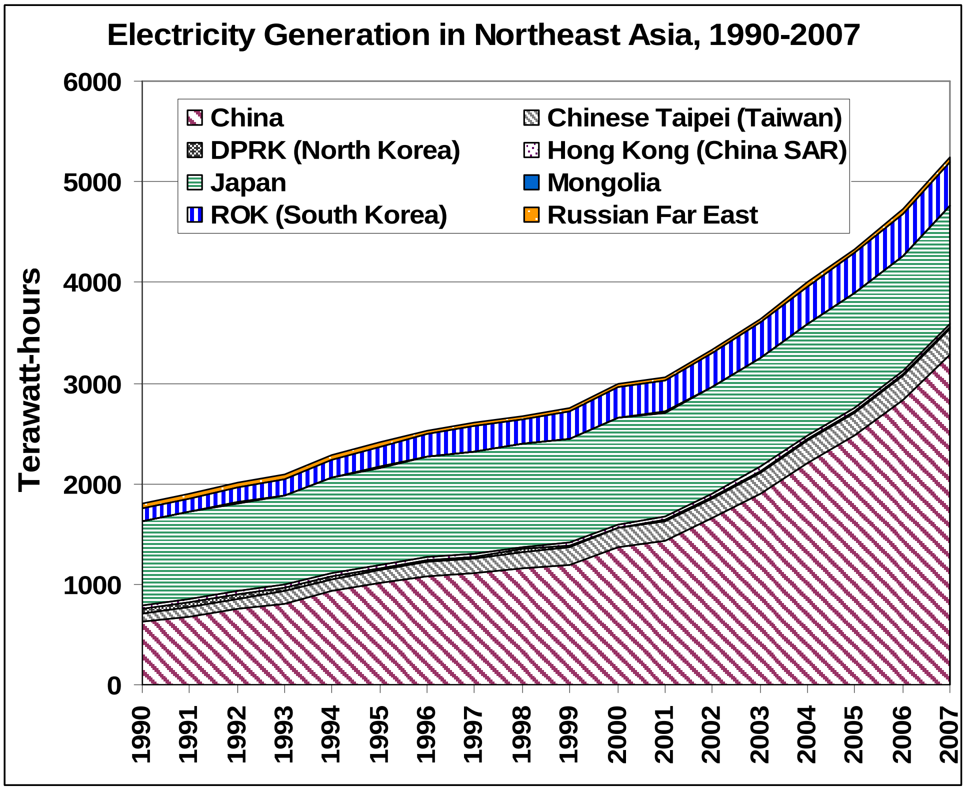
1.1. Nuclear Power and Energy Security in East Asia

Recent growth in electricity generation and use in East Asia has been remarkable. As an example, Figure 1 shows total electricity generation in the Northeast Asia region nearly tripled between 1990 and 2007, with generation in China increasing by a factor of five, generation in Taiwan increasing by a factor of nearly three, and generation in the ROK increasing by a factor of 3.7. Even though electricity production in Japan—which in 1990 had the highest generation in the region—grew by only 37 percent (an average of less than two percent annually), the fraction of global generation accounted for by the Northeast Asia region grew from just over 15 percent in 1990 to over 26 percent in 2007, even as electricity generation in the rest of the world grew at an average rate of 2.2 percent annually.

Figure 1-1: Electricity Generation in Northeast Asia, 1990-2007



Sources: Data from BP (2008) for all countries except the DPRK (von Hippel and Hayes, 2007), Mongolia (USDOE/EIA, 2008a), and RFE (estimated from Gulidov and Ognev, 2007). Generation figures shown are for gross generation (that is, including in-plant electricity use), except for Mongolia and the RFE.

Against this backdrop of growth in electricity needs—existing "business as usual" projections call for continuing strong increases in electricity use in the countries of East Asia (with the possible exception of Japan)—many of the countries of the region face significant energy resource constraints. The industrialized economies of Taiwan, the ROK, and Japan import over 90 percent of their energy needs. Vietnam and Indonesia, though they have been net energy exporters for several decades, are at or near the point where they will become net importers. China, though endowed with large reserves of coal and significant oil and gas reserves, is obliged to meet the energy needs of an increasingly affluent 1.3 billion people, and the economy that sustains them. As a result, China is increasingly an energy importer as well. The sparsely settled Russian Far East has a vast resource endowment—including hydraulic energy, coal, oil, and natural gas—that could potentially be harnessed for export to its neighbors.

A combination of severe climatic conditions, politics, and huge financial requirements for the infrastructure needed to accomplish oil, gas, and power exports have slowed development of these resource sharing schemes. Even massive international pipelines and powerlines, however, will only make a modest contribution to the energy needs of Russia's energy-hungry neighbors (see von Hippel and Hayes, 2008b).

The resource constraints faced by most of the nations of the region, together with the technical allure of nuclear power, have made East Asia a world center for nuclear energy development, and—news reports of a global nuclear renaissance notwithstanding—one of the few areas of the world where significant numbers of nuclear power plants are being added. Nations have chosen nuclear power because they wish to diversify their energy portfolios away from fossil fuels (especially oil) and thus improve their energy supply security, because nuclear power provides a stable sources of baseload power with low air pollutant emissions (particularly compared with coal), and for the less practical but still significant reason that being a member of the nuclear energy "club" is seen as offering a certain level of status in the international community.

1.2. The Nuclear Fuel Cycle in East Asia

Here we provide a brief discussion of current and possible future nuclear energy and nuclear fuel cycle activities and discussions underway in each of the countries of East Asia (plus Australia). Additional detail on the nuclear fuel cycle in each country is (or will be) provided in Chapter 2 of this report.

- **Australia** has some small reactors used for testing and education, but no commercial-scale reactor program. Development of nuclear power in Australia has been discussed a number of times in recent decades, but is not favored by the current government. Australia is, however, a major producer and exporter of uranium.
- **China** has been a nuclear weapons state since the 1960s, but did not develop a nuclear power program until the 1990s. At present, however, China is adding nuclear capacity faster than any other nation, with eleven reactors in service, 12 under construction, and construction on an additional dozen units due to start this year (World Nuclear Association, 2009). China has uranium enrichment capability, some uranium resources, and is developing a centralized spent fuel storage facility. A pilot scale facility to reprocess spent fuel to separate out plutonium and uranium has been constructed, and was due to go on line in 2008.
- The **Democratic People's Republic of Korea (DPRK)** had until recently a small (approximately 25 MW thermal) gas-cooled nuclear reactor fueled with natural (unenriched) uranium, with a reprocessing capability that was used to separate plutonium for use is the DPRK's nuclear weapons development program. The DPRK has been negotiating with the international community over its nuclear weapons program since the early 1990s, and seeks to acquire Light Water Reactor (LWR) technology for use in meeting its domestic electricity needs. A pair of LWR units that were under construction by the ROK (with some DPRK workers) at Simpo in the DPRK, as part of the 1994 "Agreed Framework", were only partially completed, with no nuclear materials on site, at the time the project was suspended in 2005-2006. The DPRK has some uranium resources.

- **Indonesia** has some domestic uranium resources. Though it has no commercial nuclear industry at present, development of nuclear power has been discussed, and a first reactor is nominally planned for operation in about 2020.
- **Japan** was the first country in East Asia to acquire nuclear power, beginning with a small gas-cooled reactor in the late 1960s, and continuing with different LWR designs in the 1970s. Japan now generates nearly a third of its electricity with nuclear reactors. Japan started "hot testing" of a large reprocessing plant at Rokkasho in 2006. Japan Nuclear Fuel Ltd, Rokkasho's operator, recently announced that commercial operation of the Rokkasho plant, originally scheduled for early 2008, will be delayed until October, 2010[1]. A smaller reprocessing facility at Tokai-mura operated for nearly 30 years. Japan has no domestic uranium resources, but has uranium enrichment capability, though it contracts with other countries for most of its enrichment services (and some reprocessing).
- The first commercial reactor in the **Republic of Korea** went on-line in the late 1970s, and the ROK now has 20 power reactors operating. The ROK has a limited number of sites for additional units. Enriched fuel for the ROK's reactors is acquired from international suppliers, and the ROK does not currently have a reprocessing capability, though reprocessing has been discussed as an option.
- Though the **Russian Federation** as a whole has an extensive nuclear power program, is a nuclear weapons state, has uranium resources, and operates both enrichment and reprocessing facilities, the **Russian Far East (RFE)** region has only one very small (48 MWe) operating power reactor. Development of commercial reactors on the 1 GWe scale has been under discussion in the RFE for many years, in part to serve local electricity users, but also for power exports to the ROK and China, but construction of new plants has not yet taken place.
- **Taiwan**, has six operating commercial nuclear reactors, the first of which went into service in 1978. About 20 percent of Taiwan's electricity is generated by these nuclear units. An additional two reactor units are nominally under construction for many years, but construction has been stalled for some time by political and other consideration. Taiwan lacks uranium resources, and depends on international sources for enrichment services.
- Like Indonesia, **Vietnam** has been discussing the possibility of developing a nuclear power program, and plans to operate its first reactor starting in about 2020. Vietnam has some uranium resources.

1.3. Nuclear Technology Cooperation in East Asia

Cooperation on nuclear technology in Northeast Asia could include cooperation on development of new, safer and more cost-effective generation technologies, cooperation on provision of nuclear fuel enrichment services, cooperation on nuclear waste and nuclear materials handling and disposal, or all three.

The light water reactor (LWR) technology used widely in Japan, the Republic of Korea, and Taiwan, as well as in China, is by now over half a century old (the first commercial reactor

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[1] World Nuclear News (2009), "Rokkasho reprocessing plant delayed again". Dated 8 September, 2009, and available as http://www.world-nuclear-news.org/WR-Rokkasho_reprocessing_plant_delayed_again-0809094.html.

was commissioned in the United States in 1958, and research reactors using LWR technology date from earlier in the 1950s; ANL, 1996), and is well characterized. Additional LWR installations are planned for these countries, though in each country (with the exception of China), few promising sites remain, and the social and political considerations to be faced in finding sites for new reactors are considerable. Except possibly on a bilateral basis (specifically, siting of new LWR plants in the DPRK with power to be used by both the DPRK and the ROK), it seems that there are limited prospects for regional collaboration to on the use of LWR technology, though China, the ROK and other countries continue to make incremental improvements in reactor capacity and other attributes. The possible exception is collaboration, through a regional organization, to establish and maintain regional standards for LWR reactor safety. This type of collaboration is unlikely to have any energy impacts, and would have modest costs, but would be expected to offer benefits in the form of lowering regional risks of reactor operation, and of increasing confidence and cooperation among the nuclear power establishments of the countries of the region. It remains an open question, however, whether this sort of organization would be more attractive to the countries of the region, or more effective in achieving its goals, than the current International Atomic Energy Agency (IAEA) is for the countries of the region.

Another possible area of cooperation in the nuclear energy area is for enrichment of natural uranium to produce low-enriched uranium for reactor fuel. Countries of the region could, for example, share enrichment facilities, thereby helping to achieve economies of scale, and presumably, through regional oversight, reducing the possibility that nuclear materials are diverted for nuclear weapons purposes. Several of the countries in the region that now operate nuclear reactors currently purchase enrichment services from outside the region.

The countries of the region with an interest in ongoing development of nuclear power could collaborate on research leading toward "next-generation" reactor designs. Next-generation nuclear reactor designs are generally described as being smaller in size and output, and thus more easily placed and sized to specific applications (grids), less vulnerable to accidents that would release radioactivity, more efficient, and (possibly) less expensive. This collaboration could be in the form of a regional consortium, funded by governments and/or private sector companies from each participating nation, and staffed by scientists and engineers from all nations. Practically, it is highly unlikely that a commercially-viable, tested "next generation" reactor will be available for significant use by 2030, so the impacts of such a regional "next generation nuclear power consortium" would not be evident for several decades. Japan and the ROK are both participants in the US-led "Generation IV International Forum" (GIF), which collaborates on research into next-generation nuclear technologies.

Another potential area for regional collaboration in the nuclear power area is collaboration and coordination in the management of nuclear waste from nuclear power programs. Such an initiative could take a number of forms and have goals ranging from the setting of regional standards for the storage, disposition, and transport of nuclear wastes (including high-level wastes, low-level wastes, spent fuel, and wastes from fuel reprocessing, if any), to the development of shared spent-fuel reprocessing capabilities[2], to the development and

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[2] Reprocessing, in summary, involves taking nuclear fuel elements used in the reactor (after a cooling period of five or more years in spent fuel pools at reactor sites), removing the fuel cladding, isolating the plutonium produced from uranium in the fuel elements during the nuclear reaction, mixing the plutonium with fresh uranium, and producing new fuel elements to use the resulting "Mixed Oxide" fuel in reactors.

operation of a regional repository for nuclear wastes (or even a regional agreement to develop a waste repository outside the region). Such an organization would allow a measure of regional control over nuclear waste issues, providing quality control and transparency in waste disposal transactions. The countries/companies using the waste repository would provide financial transfers to the host country or countries. Of course, it is highly likely that significant technical, financial, and environmental concerns regarding the siting and operation of a regional waste storage facility will be identified, and very significant political/institutional issues will also need to be addressed before any such facility can be developed.

This Interim Report focuses on early results of the EASS project's analysis of cooperation "scenarios" for nuclear fuel enrichment and for spent fuel management.

1.4. Future Alternative for the Nuclear Fuel Cycle in East Asia

Given the constraints on nuclear fuel activities in East Asian countries that are (or could potentially be) major users of nuclear power, regional fuel cycle activities have been attractive to policymakers. Domestic and international political constraints on construction and operation of enrichment and reprocessing facilities, and, especially, domestic constraints on the siting and operation of spent fuel management facilities, have spurred international discussions on nuclear collaborations. Over the last two decades, a number of regional nuclear fuel cycle proposals have been discussed, including the Global Nuclear Energy Partnership (GNEP) proposed by the United States during the George W. Bush administration (and recently discontinued by the Obama administration), but also including less ambitious proposals for shared enrichment and/or spent fuel management and/or nuclear safety and fuel management safeguards. Specific proposals have included "ASIATOM", an "Asian Nuclear Safety Centre", and an "East Asian Collaboration for Intermediate Storage", among others. These and other options are summarized briefly in Chapter 4 of this Interim Report.

1.5. Evaluating Regional Nuclear Fuel Cycle Options for East Asia

1.5.1. Goal of this Study

The goals of the EASS activities described in this Interim Report are as follows:

- Develop, in consultation with national expert teams, a set of detailed, internally-consistent nuclear energy/nuclear fuel-cycle paths for each of the countries of East Asia that have (or may have within the next few decades) nuclear power plants (Japan, the Republic of Korea, the DPRK, the Far Eastern region of Russia, China, Taiwan, Vietnam, Indonesia, and Australia).
- Develop regional nuclear energy/fuel-cycle paths/scenarios that explore advanced technical and organizational concepts of improved regional spent fuel security based on regional cooperation. These scenarios include the evaluation of various schemes to produce enriched uranium within the region on a "non-proliferation preferential" basis, and spent fuel management/reprocessing options for regional cooperation in East Asia within "reference" and "maximum" nuclear power capacity development paths. Paths development includes elaboration of alternative maximum nuclear energy paths reflecting regional cooperation to address nuclear fuel-cycle policy imperatives. Paths variants include different nuclear materials recycling regimes.

- Evaluate the generation of different types of nuclear wastes, and the national and regional costs for waste management, through the application of tools and information produced during the EASS project and by other researchers in the field

1.5.2. Study Methods and Goals

The EASS project builds on the extensive quantitative, qualitative research and analysis undertaken under Nautilus' Asian Energy Security (AES) project (and its predecessor efforts such as the East Asia Energy Futures project) to investigate alternative future nuclear power and fuel-cycle development paths, and to develop realistic policy options for developing implementable projects to reduce the proliferation potential of nuclear power systems in the region (and, by extension, globally). As with past AES work, a core Nautilus team, backed by, and collaborating with national expert teams, conduct the research and analysis using already-compiled national energy supply-demand databases for each country. The teams are working to further elaborate, detail, and develop variants of existing nuclear fuel-cycle pathways, which are embedded in national energy pathways to ensure the realism of the nuclear pathways. Most of this quantitative and qualitative analytical work is carried out through intensive long-distance collaboration between Nautilus team members and our national counterparts, supplemented this year by travel by Nautilus staff to the project countries for intensive work sessions. The project also includes, as a key element, an annual training and regional framework review workshop that brings together all of the National teams.

Analytically, the overall approach taken in the study to date has been to estimate future electricity demand by country, then use EASS energy paths ("BAU", "Minimum Nuclear" and "Maximum Nuclear") to develop different requirements for/implied SF production from nuclear energy use by country. In parallel, we have developed several different initial "generic scenarios" of regional enrichment/spent-fuel management, and are using them to examine the cost, technical/physical outputs, and other energy security (see text box below) implications of those scenarios.

A Broad Definition of Energy Security

In the EASS (and AES) projects, Nautilus and its colleagues use a definition of "energy security" that is more inclusive than the common usage of the term (Suzuki et al, 1998, von Hippel 2004, von Hippel et al, 2009). Many of the existing definitions of energy security begin, and usually end with a focus on maintaining supplies of energy, particularly oil. This focus has as its cornerstones reducing vulnerability to foreign threats or pressures, preventing a supply crisis from occurring, and minimizing the economic and military impact of a supply crisis once it has occurred. National energy policies today are being challenged on multiple fronts. The substance of these challenges needs to be incorporated into a new concept of energy security. Current National and international energy policies have been facing many new challenges, and have at their disposal new tools, that need to be considered as key components of new energy security concepts. At least five key components—environment, technology, demand side management, social and cultural factors, and post-Cold War international relations—are central additions to the traditional supply-side point of view.

Considering the addition of these concepts, we offer this new definition of Energy Security.

> A nation-state is energy secure to the degree that fuel and energy services are available to ensure: a) survival of the nation, b) protection of national welfare, and c) minimization of risks associated with supply and use of fuel and energy services. The six dimensions of energy security include **energy supply**, **economic**, **technological**, **environmental**, **social and cultural**, and **military/security** dimensions. Energy policies must address the domestic and international (regional and global) implications of each of these dimensions.

What distinguishes this energy security definition is its emphasis on the imperative to consider extra-territorial implications of the provision of energy and energy services while recognizing the complexity of actualizing (and measuring) national energy security. The definition is also designed to include emerging concepts of environmental security, which include the effects of the state of the environment on human security and military security, and the effects of security institutions on the environment and on prospects for international environmental cooperation.

1.6. "Road Map" of Study

The remainder of this report is organized as described below. In this Interim Report, some of these sections are present in outline form only, and will be elaborated as research continues.

- **Chapter 2** presents overviews of current and recent nuclear power and nuclear fuel cycle activities by country, focusing on the current status of the sector, including nuclear generation capacity status and near-term plans, summaries of other nuclear fuel cycle activities, and descriptions of current nuclear policies.

- **Chapter 3** presents EASS future nuclear energy paths by country, including estimates of future generation capacity and energy production for each of the energy paths considered. This Interim Report focuses on the Business as Usual, Minimum Nuclear, and Maximum Nuclear paths for each nation.
- Regional nuclear fuel cycle options are discussed in **Chapter 4** of this interim report. Chapter 4 provides brief descriptions of previous proposals for regional cooperation that have been offered by various groups and individuals within and outside of the East Asia region, then describes the four “scenarios” considered to date by EASS researchers.
- **Chapter 5** presents the results, to date, of the evaluation of the scenarios for nuclear fuel cycle options. These results will ultimately include material flows, costs, qualitative and quantitative (as applicable) descriptions of other energy security costs and benefits, and a description of some of the political constraints on each scenario.
- **Chapter 6** provides a discussion of study conclusions, and expected next steps in the project.
- The final chapter of this report, **Chapter 7**, though still in outline form as of this writing, will analyze and review the implications of the findings of this study for maintenance of safeguards on the handling of nuclear materials, and safeguards preventing nuclear weapons proliferation, in the countries of the region.

2. Nuclear Power and Nuclear Fuel Cycle Activities by Country: Status, Plans, and Policies

In this chapter we provide brief descriptions of the nuclear sector in the region on a country-by country basis, as background to the discussion of future nuclear power paths and regional fuel-cycle issues and scenarios. Brief descriptions of near-term nuclear capacity expansion policies are provided.

2.1. Introduction

East Asia and the Pacific includes three nuclear weapons states—one a recent addition to the list, three major economies that are nearly completely dependent on energy imports and for whom nuclear energy plays a key role, a nuclear materials supplier nation currently without commercial reactors of its own, and at least two populous and fast-developing nations with stated plans to pursue nuclear energy. In the remainder of this Chapter, we provide a survey of the status of nuclear power and nuclear fuel cycle activities in the countries of the region. Table 2-1 provides a summary of the status of major nuclear fuel-cycle activities in each country covered by this report, as well as a listing of the sections of this chapter in which descriptions of the countries' nuclear activities can be found.

Table 2-1: Summary of Nuclear Energy Activities in East Asia/Pacific Countries, and Guide to this Chapter

Country	Section	Nuclear Generation	Front-end Fuel Cycle Activities	Back-end Fuel Cycle Activities
Japan	**2.2**	Mature nuclear industry (~47 GWe as of 2010) with continuing slow growth	No significant mining, milling. Some domestic enrichment, but most enrichment services imported	Significant experience with reprocessing, including commercial-scale facility now in testing; interim spent-fuel storage facility
ROK	**2.3**	Mature nuclear industry, ~18 GWe at 4 sites as of 2010	No significant U resources, enrichment services imported, but some domestic fuel fabrication	Very limited tests with reprocessing; at-reactor spent fuel storage thus far
DPRK	**2.4**	Had small (5 MWe equivalent) reactor for heat and Pu production, now partly decommissioned; Policy to acquire LWRs	At least modest Uranium resources and history of U mining; some production exported; no enrichment as yet	Reprocessing of Pu for weapons use. Arrangements/plans for spent fuel management unknown
China	**2.5**	Relatively new but rapidly-growing nuclear power industry; ~9 GWe as of 2010	Domestic enrichment and U mining/milling, but not sufficient for large reactor fleet.	Nuclear weapons state. Small reprocessing facility; plans for spent fuel storage facilities.
Russian Far East	**2.6**	One small plant (48 MWe) in far North of RFE (RF has large reactor fleet); plans for larger (1 GWe scale) units for power export	Domestic enrichment and U mining/milling (but not in RFE)	Nuclear weapons state. Russia has reprocessing facilities, spent fuel storage facilities (but not in RFE)
Australia	**2.7**	No existing reactors above research scale; has had plans to build power reactors, but currently very uncertain	Significant U mining/milling capacity, major U exporter; no enrichment	No back-end facilities
Taiwan	**2.8**	~5 GWe at 3 sites, plant at 4th site under construction	No U resources, no enrichment—imports enrichment services	Current spent-fuel storage at reactor, no reprocessing
Indonesia	**2.9**	No current commercial reactors, but full-scale reactors planned	Some U resources, but no production; no enrichment	Consideration of back-end facilities in early stages
Vietnam	**2.10**	No current commercial reactors, but full-scale reactors planned	Some U resources, but no production; no enrichment	Consideration of back-end facilities in early stages

2.2. Nuclear Power and Nuclear Fuel Cycle Activities in Japan

2.2.1. Introduction

Japan was the first country in East Asia to acquire nuclear power, beginning with a small gas-cooled reactor in the late 1960s, and continuing with different LWR designs in the 1970s. Following the energy crises (oil price spikes) of the 1970s, Japan became more committed to nuclear power as a way of diversifying its energy imports. Japan now generates nearly a third of its electricity with nuclear reactors, and is the only nation with uranium enrichment and spent-fuel reprocessing capability that does not also have nuclear weapons.

2.2.2. History, Current Status, and Near-term Plans

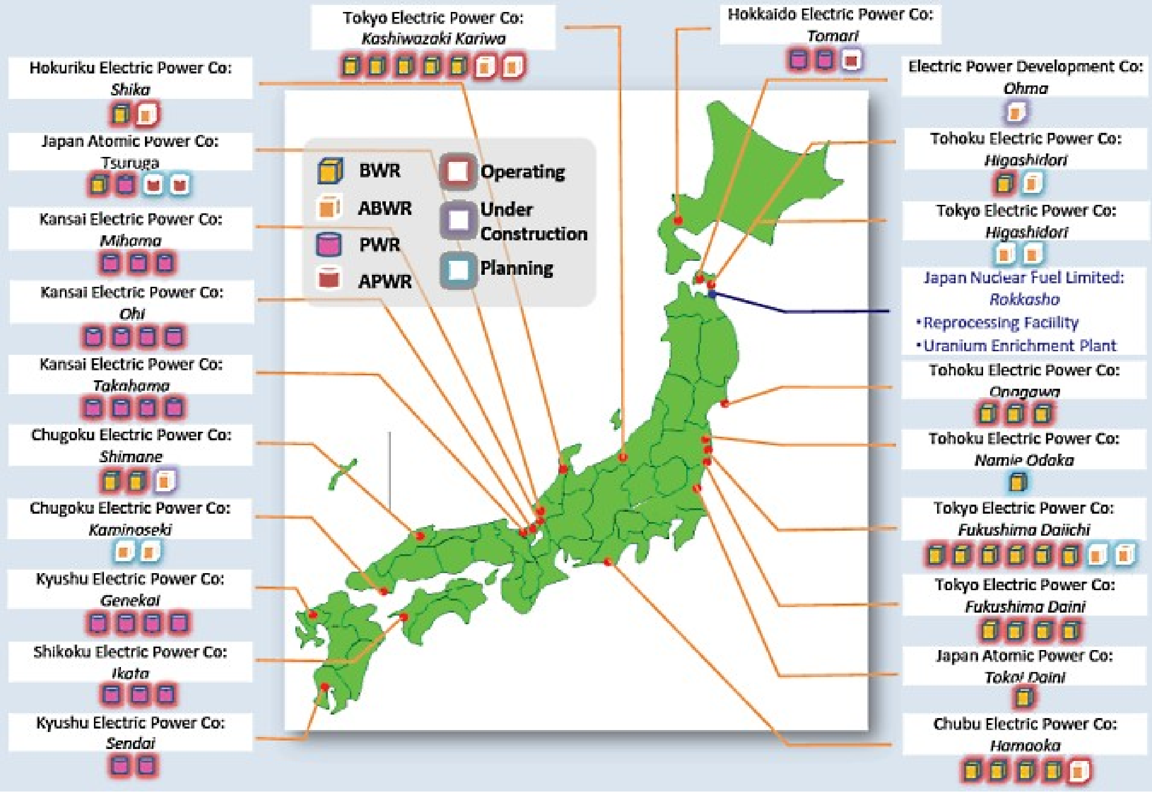
Since the first commercial nuclear power plant was put into operation in 1966, a total of 54 NPPs, including 30 boiling water reactors (BWRs) and 24 PWRs, with an electric power generation capacity of 47.1 GWe (net basis), had been built and commissioned in Japan as of the end of March 2009. Japan's nuclear reactors currently supply over 30% of its total national electricity generation (in GWh). Table 2-2 shows the current status and the long-term nuclear power supply plan in Japan through the year 2016 (Kang, 2006; World Nuclear Association 2009). The locations of NPPs in Japan, and their current operational or development status, as of April, 2009, are shown in Figure 2-1 (Kang, 2006).

Table 2-2: Current Status of Nuclear Power in Japan, Existing and Planned Units

Site	Unit	Type	Capacity (MWe)	Utility	Operation
Tomari	Tomari-1	PWR	550	Hokkaido	June 1989
	Tomari-2	PWR	550		April 1991
	Tomari-3	PWR	912		March 2009.
Onagawa	Onagawa-1	BWR	498	Tohoku	June 1984
	Onagawa-2	BWR	796		July 1995
	Onagawa-3	BWR	798		January 2002
Higashidori	Higashidori-1	BWR	1067	Tohoku	March 2005
	Higashidori-2	ABWR	1385		2018 (planned)
Namie-odaka	Namie-odaka-1	BWR	1385	Tohoku	2016 (planned)
Higashidori	Higashidori-1	ABWR	1385	TEPCO	2016 (planned)
	Higashidori-2	ABWR	1385		2017 (planned)
Fukushima I	Fukushima I-1	BWR	439	TEPCO	Mar. 1971
	Fukushima I-2	BWR	760		Jul. 1974
	Fukushima I-3	BWR	760		Mar. 1976
	Fukushima I-4	BWR	760		Oct. 1978
	Fukushima I-5	BWR	760		Apr. 1979
	Fukushima I-6	BWR	1067		Oct. 1979
	Fukushima I-7	ABWR	1380		2014 (planned)
	Fukushima I-8	ABWR	1380		2015 (planned)
Fukushima II	Fukushima I-1	BWR	1067	TEPCO	Apr. 1982
	Fukushima I-2	BWR	1067		Feb. 1984
	Fukushima I-3	BWR	1067		Jun. 1985
	Fukushima I-4	BWR	1067		Aug. 1987

Kashiwazaki-Kariwa	K-K-1	BWR	1067	TEPCO	Sept. 1985
	K-K-2	BWR	1067		Sept. 1990
	K-K-3	BWR	1067		Aug. 1993
	K-K-4	BWR	1067		Aug. 1994
	K-K-5	BWR	1067		Apr. 1995
	K-K-6	ABWR	1315		Nov. 1996
	K-K-7	ABWR	1315		Jul. 1997
Hamaoka	Hamaoka-1	BWR	515	Chubu	Mar. 1976
	Hamaoka-2	BWR	806		Nov. 1978
	Hamaoka-3	BWR	1056		Aug. 1987
	Hamaoka-4	BWR	1092		Sept. 1993
	Hamaoka-5	ABWR	1380		Jan. 2005
Shika	Shika-1	BWR	505	Chubu	Jul. 1993
	Shika-2	BWR	1358		March 2006
Mihama	Mihama-1	PWR	320	Kansai	Nov. 1970
	Mihama-2	PWR	470		Jul. 1972
	Mihama-3	PWR	780		Dec. 1976
Takahama	Takahama-1	PWR	780	Kansai	Nov. 1974
	Takahama-2	PWR	780		Nov. 1975
	Takahama-3	PWR	830		Jan. 1985
	Takahama-4	PWR	830		Jun. 1985
Ohi	Ohi-1	PWR	1120	Kansai	Mar. 1979
	Ohi-2	PWR	1120		Dec. 1979
	Ohi-3	PWR	1127		Dec. 1991
	Ohi-4	PWR	1127		Feb. 1993
Shimane	Shimane-1	BWR	439	Chugoku	Mar. 1974
	Shimane-2	BWR	789		Feb. 1989
	Shimane-3	ABWR	1373		Under const.
Kaminoseki	Kaminoseki-1	ABWR	1373	Chugoku	2015 (planned)
	Kaminoseki-2	ABWR	1373		2018 (planned)
Itaka	Itaka-1	PWR	538	Shikoku	Sept. 1977
	Itaka-2	PWR	538		Mar. 1982
	Itaka-3	PWR	846		Dec. 1994
Genkai	Genkai-1	PWR	529	Kyushu	Oct. 1975
	Genkai-2	PWR	529		Mar. 1981
	Genkai-3	PWR	1127		Mar. 1994
	Genkai-4	PWR	1127		Jul. 1997
Sendai	Sendai-1	PWR	846	Kyushu	Jul. 1984
	Sendai-2	PWR	846		Nov. 1985
Tsuruga	Tsuruga-1	BWR	341	JAPC	Mar. 1970
	Tsuruga-2	PWR	1115		Feb. 1987
	Tsuruga-3	APWR	1538		2016 (planned)
	Tsuruga-4	APWR	1538		2017 (planned)
Tokai	Tokai-2	BWR	1056	JAPC	Nov. 1978
Ohma	Ohma	ABWR	1383	EPDC	Under const.
Monju	Monju	Prototype FBR	246	JAEA	Operated 1994-95, awaiting restart

Figure 2-1: Current status of operation and construction of NPPs in Japan (from World Nuclear Association, 2009)



2.2.3. Nuclear Fuel Cycle Activities in Japan—Enrichment and Fuel Fabrication

Japan has no significant domestic uranium resources, but has uranium enrichment capability, though it contracts with other countries (in Europe and the United States) for most of its enrichment. Japan's enrichment and fuel fabrication facilities are described by the World Nuclear Association (2009) as follows:

> "Japan has been progressively developing a complete domestic nuclear fuel cycle industry, based on imported uranium.
>
> "JAEA operates a small uranium refining and conversion plant, as well as a small centrifuge enrichment demonstration plant, at Ningyo Toge, Okayama prefecture.
>
> "While most enrichment services are still imported, Japan Nuclear Fuel Ltd (JNFL) operates a commercial enrichment plant at Rokkasho. This began operation in 1992 using indigenous technology and has seven cascades each of 150,000 SWU/yr, though only two are operating. Its eventual capacity is planned to be 1.5 million SWU/yr. it is now testing a lead cascade of its new Shingata design, and expects to re-equip the plant with this. JNFL's shareholders are the power utilities.
>
> "A new enrichment plant in Japan using Russian centrifuge technology is planned under an agreement between Rosatom and Toshiba.

> “Japan has 6400 tonnes of uranium recovered from reprocessing and stored in France and the UK, where the reprocessing was carried out. In 2007 it was agreed that Russia's Atomenergoprom would enrich this for the Japanese utilities who own it.”

2.2.4. Nuclear Fuel Cycle Activities in Japan—Spent Fuel Management and Advanced Reactor Designs

Japan was scheduled to start commercial operation of a large reprocessing plant at Rokkasho, with a capacity of 800 tonnes of heavy metal (tHM) per year, in 2008, following more than two years of testing, but a recent announcement by plant operator Japan Nuclear Fuel Ltd has pushed the projected date of commercial operation back to October 2010 “to allow for cleaning and inspections of the vitrification facility”[3]. A smaller reprocessing facility at Tokai-mura operated for nearly 30 years. Japan also contracts with companies in other nations, notably the UK and France, for nuclear services (enrichment and some reprocessing). The Monju experimental fast breeder reactor (246 gross MWe) was operated from 1994 through 1995, but has been shut down since, though it is listed as “awaiting restart”.

2.3. Nuclear Power and Nuclear Fuel Cycle Activities in the Republic of Korea

2.3.1. Introduction

Like Japan, the Republic of Korea’s meager fossil fuel resource endowment has obliged it to import fuels to meet nearly all of its energy needs. Nuclear research in the ROK began in the early 1960s, with reactor construction beginning in the 1970s. The ROK’s first 10 reactor units were imported from the North America and Europe, but more recent units have been ROK designs based on US (Combustion Engineering/Westinghouse) LWR designs. The ROK continues to develop nuclear power, but not (yet) a full nuclear fuel cycle.

2.3.2. History and Current Status

Since the first commercial nuclear power plant (NPP) in the ROK was placed into operation in 1978, a total of 20 NPPs, including 16 pressurized water reactors (PWRs) and 4 CANDU reactors[4], with a total electric power generation capacity of 17.7 GWe, have been constructed and placed in operation (as of April 2009). Eight PWRs are planned to be deployed by 2016, based on a long-term electricity plan for the Republic of Korea titled "The 3rd Basic Plan for Long-Term Electricity Supply and Demand (2006-2020)", published by the ROK Ministry of Commerce, Industry & Energy in December 2006 (MOCIE, 2006), with a further four units planned for the 2018 to 2021 timeframe. The current status of nuclear power generation, as well as the long-term nuclear power supply plan for the ROK through the year 2021, are provided in Table 2-3 (Kang, 2006). As of end of 2004, nuclear generation accounted for 28% of total electricity generation capacity in the ROK, and supplied 39% of total electricity generation. Nuclear generation capacity is expected to grow to 26.6 GWe and to supply 47% of

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[3] World Nuclear News (2009), “Rokkasho reprocessing plant delayed again”. Dated 8 September, 2009, and available as http://www.world-nuclear-news.org/WR-Rokkasho_reprocessing_plant_delayed_again-0809094.html.

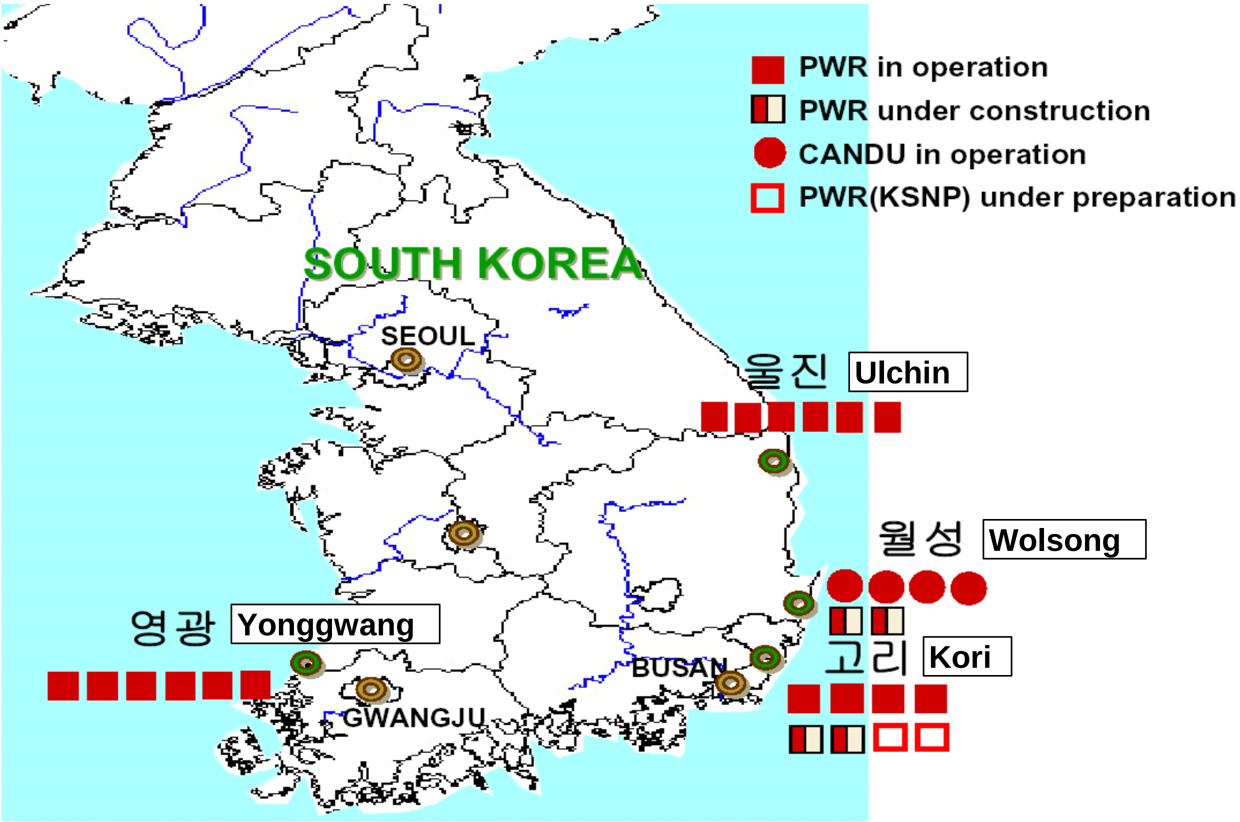
[4] The CANDU (CANada Deuterium Uranium) reactor is a type of pressurized heavy water reactor developed by Atomic Energy of Canada Limited (AECL). (http://en.wikipedia.org/wiki/CANDU).

total electricity generation as of 2015. Figure 2-2 shows the locations and current status of operation and construction of NPPs in ROK as of April 2009 (Kang, 2006; World Nuclear Association 2009).

Table 2-3: Current Status of Nuclear Power in the ROK, Existing and Planned Units

Site	Unit	Type	Capacity (MWe)	Operation
Kori	Kori-1	PWR	587	Apr. 1978
	Kori-2	PWR	650	Jul. 1983
	Kori-3	PWR	950	Sept. 1985
	Kori-4	PWR	950	Apr. 1986
	Sinkori-1	PWR	1000	Dec. 2010
	Sinkori-2	PWR	1000	Dec. 2011
	Sinkori-3	PWR	1350	Sept. 2013
	Sinkori-4	PWR	1350	Sept. 2014
	Sinkori-5	PWR	1350	Dec. 2018
	Sinkori-6	PWR	1350	Dec. 2019
Yonggwang	Yonggwang-1	PWR	950	Aug. 1986
	Yonggwang-2	PWR	950	Jun. 1987
	Yonggwang-3	PWR	1000	Mar. 1995
	Yonggwang-4	PWR	1000	Jan. 1996
	Yonggwang-5	PWR	1000	Apr. 2002
	Yonggwang-6	PWR	1000	Oct. 2002
Ulchin	Ulchin-1	PWR	950	Sept. 1988
	Ulchin-2	PWR	950	Sept. 1989
	Ulchin-3	PWR	1000	Aug. 1998
	Ulchin-4	PWR	1000	Dec. 1999
	Ulchin-5	PWR	1000	Jul. 2004
	Ulchin-6	PWR	1000	Jun. 2005
	Sinulchin-1	PWR	1400	Dec. 2015
	Sinulchin-2	PWR	1400	Dec. 2016
Wolsong	Wolsong-1	CANDU	679	Apr. 1983
	Wolsong-2	CANDU	700	Jul. 1997
	Wolsong-3	CANDU	700	Jul. 1998
	Wolsong-4	CANDU	700	Oct. 1999
Wolsong	Sinwolsong-1	PWR	1000	Oct. 2011
	Sinwolsong-2	PWR	1000	Oct. 2012

Figure 2-2: Current Status of Operation and Construction of NPPs in the ROK (from Kang, 2006)



2.3.3. *Nuclear Fuel Cycle Activities in the ROK—Enrichment and Fuel Fabrication*

The ROK mines no domestic uranium, though uranium deposits have been identified in the Daejon and adjoining Gumsan regions[5]. ROK companies and agencies are, however, active investors in uranium mining ventures abroad. The ROK has in the past contracted with US and European firms for enrichment, and in 2007 signed a ten-year agreement with the French firm Areva NC to provide enrichment services for its nuclear fuel needs (World Nuclear Association, 2009). The ROK has fuel fabrication capacity of 550 t/yr for LWR fuel and 700 t/yr for CANDU (Canadian Deuterium reactor) fuel, and is beginning a joint venture with a US firm to manufacture control elements for its newer reactors.

2.3.4. *Nuclear Fuel Cycle Activities in the ROK—Spent Fuel Management*

The ROK's policy on reprocessing of spent nuclear fuel has been a topic of discussion and debate amongst ROK government entities in recent years. To date, the ROK has not—with the exception of very small-scale test in 1982 (Kang et al, 2005)—sought to develop or build reprocessing technology—but some agencies involved in nuclear spent fuel management in the

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[5] World Nuclear Association (2010), "Nuclear power in South Korea", dated 18 March 2010, and available as http://www.world-nuclear.org/info/inf81.html.

ROK have shown an interest in doing so, spurred in part by the start of operations at the Rokkasho reprocessing facility in Japan, and by the "Global Nuclear Energy Partnership" (GNEP) concept led by the United States during the George W. Bush administration (Kang, 2006). The National Energy Committee, chaired by the ROK president and established in November 2006, is in charge of developing and examining plans for the spent fuel management, but a number of other agencies are involved in different aspects of nuclear energy and nuclear fuel cycle operation, management, and research and development (see Table 2-4, after Kang, 2006).

Table 2-4: ROK Authorities Responsible for Nuclear Spent Fuel-related Activities

Authority	Functions
National Energy Committee (NEC)	Decision-making authority in national energy and spent fuel management under the ROK President
Ministry of Commerce, Industry and Energy (MOCIE)	Supports NEC and controls KHNP
Korea Hydro and Nuclear Power (KHNP)	Responsible for storage of spent fuel
Atomic Energy Commission (AEC)	Decision-making authority in nuclear energy research and development under the ROK Prime Minister
Ministry of Science and Technology (MOST)	Supports AEC and controls KAERI
Korea Atomic Energy Research Institute (KAERI)	Nuclear research and development, including R&D on "advanced" nuclear fuel cycles

Park et al describe the ROK's attempts to site Low and Intermediate-level Waste (LILW) and pool-type away-from-reactor interim spent-fuel storage facilities[6]. Attempts in the 1980s and 1990s were unsuccessful due to national and local political opposition. In 2005, the ROK government obtained approval for siting a LILW (but not spent fuel) facility in Gyeongju, and construction on that two-square-kilometer facility began in 2007. Without additional options for storing spent fuel, the ROK will run out of at-reactor storage within the next decade. According to Ko and Kwan, if the ROK follows the capacity expansion plan laid out in the recent National Energy Basic Plan, it will need 10 to 22 interim waste facilities each the size of Gyeongju, which will be "almost impossible to site"[7].

The terms of the ROK's nuclear cooperation agreement with the United States, which is due to expire in 2014, commits the ROK to the use of an open fuel cycle, without reprocessing. ROK diplomatic efforts are underway to try and remove this constraint when the agreement is

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[6] Park S.-W., M. A. Pomper, and L. Scheinman (2010), "The Domestic and International Politics of Spent Nuclear Fuel in South Korea: Are We Approaching Meltdown?". Korea Economic Institute Academic Paper Series, March 2010, Volume 5, Number 3. Available as http://www.keia.org/Publications/AcademicPaperSeries/2010/APS-ParkPomperScheinman.pdf.

[7] W. I. Ko and E.-H. Kwon (2009), "Implications of the new National Energy Basic Plan for nuclear waste management in Korea", Energy Policy, Volume 37, Issue 9, September 2009, Pages 3484-3488. Available at doi:10.1016/j.enpol.2009.05.068. These authors offer sodium fast reactor-based recycling of nuclear fuel as a solution to the ROK's waste management dilemma.

renewed so as to allow pyroprocessing (a form of reprocessing in which plutonium and uranium remain mixed together after separation from the other components of spent fuel).

2.4. Nuclear Power and Nuclear Fuel Cycle Activities in the Democratic People's Republic of Korea (DPRK)

2.4.1. Introduction

The DPRK's nuclear activities are a major source of political tension in Northeast Asia. Its energy needs have been the stated underpinning of its drive to acquire both "home grown" (based on designs from other nations) and imported nuclear electricity generation capacity, but its reprocessing of spent fuel from its small gas-cooled, natural uranium-fueled reactor to produce plutonium for nuclear weapons has occupied the attention of much of the international community for most of the last two decades.

2.4.2. History and Current Status

DPRK scientists and technician first received training in nuclear technologies from the Soviet Union, starting in the 1960s. The Soviet Union also provided the DPRK with a pool-type research reactor, the IRT-DPRK, which began operation in 1965, along with related equipment such as hot cells. The reactor is located at Yongbyon, and was initially rated at 2 MW thermal (and eventually 8 MWth)[8].

The DPRK began developing domestic nuclear capabilities in the 1980s, with a 25 MW thermal reactor at Yongbyon that started operating in about 1985. The gas-cooled (CO_2), graphite-moderated Yongbyon reactor design is based on the 1950s British Calder Hall design, and is fueled with natural uranium. This unit, now partially decommissioned[9], is sometimes referred to as rated at 5 MW of electric power, though it is unclear whether it ever actually produced electricity[10]. The DPRK asserted that it wished to have a civilian nuclear power program in order to diversify its energy sources (then, as now, the DPRK is dependent mainly on domestic anthracite coal), and developed this small reactor as a first step towards larger gas-cooled reactors that were under construction at Yongbyon (50 MWe) and Taechon (200 MWe) until construction of those units was suspended as a result of the negotiations that consulted with the signing of the 1994 Agreed Framework. The Agreed Framework included an agreement to provide the DPRK with two 1 GWe LWRs, construction of which started at Simpo in the late 1990s, but was suspended in 2003 following a year of disagreements between the Agreed Framework parties over a number of issues, including the DPRK's alleged program to acquire uranium enrichment technologies. Construction of the Simpo reactors has not restarted, and nuclear materials were never transferred to the Simpo site. The DPRK has also, at various times in the past (prior to the Agreed Framework), entered into discussions with Russian officials to obtain light water reactors, including at the Simpo site.

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[8] Dreicer, J.S. (2000), "How Much Plutonium Could Have Been Produced in the DPRK IRT Reactor?". Science & Global Security, Volume 8, number 3, pages 315-328. Available as http://www.princeton.edu/sgs/publications/sgs/pdf/8_3Dreicer.pdf.

[9] D. A. Pinkston and A. F. Diamond (2005), Special Report on the Shutdown of North Korea's 5MW(e) Nuclear Reactor. Dated April 28, 2005, and available as http://cns.miis.edu/stories/pdfs/050428.pdf.

[10] The Yongbyon reactor did, however, produce heat for facilities at the site, and for other buildings in the surrounding area.

2.4.3. Nuclear Fuel Cycle Activities in the DPRK—Fuel Fabrication and Enrichment Research

The DPRK has uranium resources, uranium mines, and has, or at least had, facilities to prepare non-enriched fuel and fuel assemblies for its now partially-decommissioned (as of 2009) approximately 25 MW thermal (~5 MWe equivalent) gas cooled "Magnox"-type[11] reactor at Yongbyon. The DPRK is alleged to have begun a program to acquire uranium enrichment technologies, including attempts to buy materials for centrifuges used in enrichment, but it is as yet unclear how much progress it has been made on acquiring enrichment capabilities. A description of what is known about the DPRK's uranium reserves and mining history follows (from von Hippel and Hayes, 2007).

Figures on the DPRK's reserves of uranium are difficult to obtain, and their accuracy is unknown. It has been reported that uranium has been mined to supply the DPRK's domestic nuclear industry from mines located in various areas around the country, including Pyongsan, Pakchon, Hongnam, Jusong, Ungki, Sunchon 2, Hamheung, Hekumkang, and Najin[12]. Another source refers to a uranium mine near Hungnam (probably the same as "Hongnam"), where the Japanese built a cyclotron in 1943-44[13]. Two sources suggest that the DPRK's uranium deposits "are estimated at 26 million tons"[14]. One of the sources describes these deposits as "high grade ore", so it seems virtually certain that the references are to tonnes of ore, not tonnes of uranium metal (or uranium oxides). Another source states:

> "It has been estimated that, at its peak in the early 1990s, North Korea was able to produce about 300 tonnes of yellow cake [U_3O_8] annually, equal to approximately 30,000 tonnes of uranium ore."[15]

Other analysts of the subject have reported estimates of 3 and 4 million tonnes of "reasonably assured resources", based on older OECD and ROK estimates, respectively. Still another source cites a figure of 4.5 million tonnes of uranium ore, and quote "Russian scientists who have visited North Korea" as saying that the DPRK's "mining and milling capabilities produce 2000 tons of natural uranium, per year"[16].

The DPRK is reported to have exported significant amounts of uranium ore over the years, starting in (at least) the 1947-1950 period, with the export of "over 9,000 tons of uranium [presumably ore] and an unknown amount of monazite to the USSR", and continuing with a reported "$6 billion worth of uranium ore" to the USSR in 1985, "1,500 tons of monazite[17]

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[11] Absoluteastronomy.com, "Yongbyon Nuclear Scientific Research Center". Available as http://www.absoluteastronomy.com/topics/Yongbyon_Nuclear_Scientific_Research_Center. Magnox reactors are graphite-moderated, and use carbon dioxide gas as a coolant.

[12] Document in the authors files, referencing a number of Korean and international literature sources [ELE-96]

[13] Federation of American Scientists, "Hungnam N39°49 E127°37' Hungnam Chemical Engineering College Hungnam Fertilizer Complex", available as http://www.fas.org/nuke/guide/dprk/facility/hungnam.htm.

[14] Larry A. Niksch, United States Congressional Research Service (CRS), CRS Issue Brief for Congress: North Korea's Nuclear Weapons Program, updated January 17, 2006. The same figure is also quoted in Yo-Taik Song, "IN OUR TIMES SERIES, PART 6, The North Korean Nuclear Program: Technical and Policy Issues", available as http://www.phy.duke.edu/~myhan/ot6-song.html.

[15] North Korea's Nuclear Weapons Programme, by the International Institute for Strategic Studies, 2006, available as http://www.iiss.org/publications/strategic-dossiers/north-korean-dossier/north-koreas-weapons-programmes-a-net-asses/north-koreas-nuclear-weapons-programme.

[16] "North Korean Hullabaloo", by Paul Vos Benkowski, 6 - Nukewatch Pathfinder, Winter, 2006-2007, page 6.

[17] Monazite is a name for a group of rare earth phosphate minerals, the most common form of which (Monazite-(Ce)) contains Cerium, Lanthanum, Thorium, Neodymium, and Yttrium. Monazite is radioactive, and it seems likely to have been exported in

annually" in the 1990s to "China, Japan, Spain, and Hong Kong"[18]. More recently, an advertisement by the DPRK's International Chemical Joint Venture Corporation was published in an English-language DPRK trade journal in 2001 and 2002 advertised ammonium diuranate (ADU), a processed form of yellowcake, for sale on the international market[19]. A report in late 2006 that the DPRK and Russia had been negotiating, apparently since 2002, a deal that would give Russia "exclusive rights" to the DPRK's uranium deposits "in exchange for Moscow's support at six-party talks aimed at denuclearizing Pyongyang", suggested that Russia would enrich DPRK uranium for re-export to Vietnam and China as nuclear fuel. The report was dismissed as "rumors" by Russian authorities[20]. Exports from the DPRK to China of 90.54 tonnes of "Uranium, Thorium Ore and Concentrate" were listed in China Customs statistics for the year 2004. The listed value for these shipments, about $22,000 USD, suggests that the exports were of ore, not refined metal. Uranium exports from the DPRK to China are not listed for other years between 1995 and 2005[21].

2.4.4. Nuclear Fuel Cycle Activities in the DPRK—Spent Fuel Management

The DPRK has a facility at Yongbyon for the reprocessing of spent fuel from its gas-cooled reactor. Fuel from the Yongbyon reactor has been reprocessed to provide plutonium for the DPRK's nuclear weapons program. The DPRK is thought to have a considerable amount of liquid high-level waste, perhaps 500,000-750,000 liters, derived from its nuclear weapons program (Whang, 2007). The amount of HLW of the DPRK was estimated based on an assumption of 2-3 campaigns (that is, before 1994, in 2003, and in 2005) of reprocessing of spent fuels discharged from the 5 MWe graphite-moderated gas-cooled reactor at Yongbyon. It is unclear what the DPRK's plans are for disposing of this waste, or of its additional spent fuel (some of which were to have been transported out of the country under now-suspended agreements reached during the Six-Party Talks on the DPRK's nuclear weapons program).

2.5. Nuclear Power and Nuclear Fuel Cycle Activities in China

2.5.1. Introduction

China has been a nuclear weapons state since the 1960s, but did not develop a nuclear power program until the 1990s. At present, however, China is adding nuclear capacity much

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this instance primarily as a source of Thorium, though that is just the authors' conjecture. A description of Monazite can be found at Amethyst Galleries "THE MINERAL MONAZITE", http://www.galleries.com/minerals/phosphat/monazite/monazite.htm.

[18] "North Korea Profile, Nuclear Exports", prepared for the Nuclear Threat Initiative by the by the Center for Nonproliferation Studies at the Monterey Institute of International Studies, 2003, available as http://www.nti.org/e_research/profiles/NK/Nuclear/47_1273.html.

[19] Foreign Trade of the DPRK, 1 Jul 2001, and1 Oct 2002.

[20] NUKEWARS, "Moscow Dismisses Rumors On Uranium Deal With Pyongyang" by Staff Writers Moscow (AFP—Agence France-Presse), Dec 04, 2006; and "NKorea, Russia in secret deal over nuclear talks: report", Tokyo (AFP) Dec 03, 2006. Available as http://www.spacewar.com/reports/Moscow_Dismisses_Rumors_On_Uranium_Deal_With_Pyongyang_999.html.

[21] China Customs statistics as compiled by N. Aden for N. Aden, North Korean Trade with China as Reported in Chinese Customs Statistics: Recent Energy Trends and Implications, as prepared for the DPRK Energy Experts Working Group Meeting, June 26th and 27th, 2006, Palo Alto, CA, USA). Dr. Aden's paper is available as http://www.nautilus.org/fora/security/0679Aden.pdf.

faster than any other nation, with eleven reactors in service, 12 under construction, and construction on an additional dozen units due to start this year (World Nuclear Association, 2009). China has uranium enrichment capability, some uranium resources, and is developing a centralized spent fuel storage facility. A pilot scale facility to reprocess spent fuel to separate out plutonium and uranium has been constructed, and was due to go on line in 2008.

2.5.2. History and Current Status

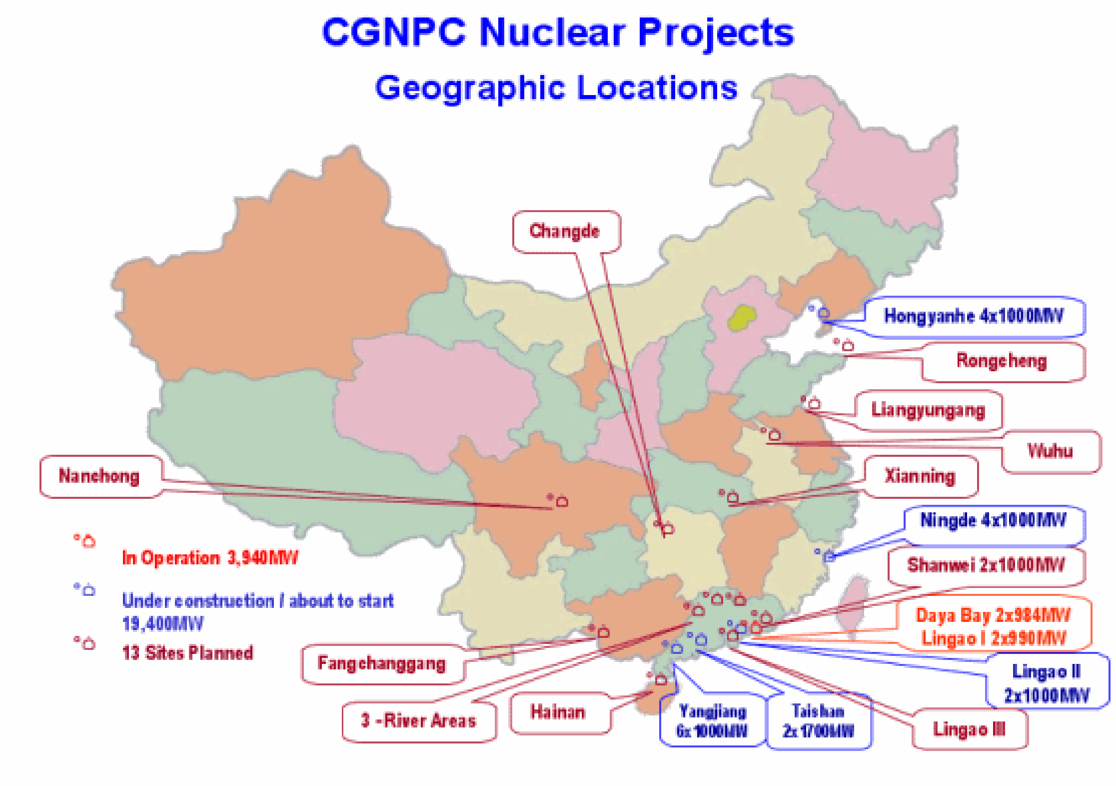
A research program in toward nuclear power development in China started in 1970, with the first commercial reactors going into operation in 1994 based on imported technologies. As of 2009, a total of 11 NPPs, including 9 PWRs and 2 pressurized heavy water reactors (PHWR), with a total net electric power capacity of 8.6 GWe have been developed in China. Nuclear power supplied 1.9% of total electricity generation (63 GWh) in China (including Hong Kong) in 2007, actually a slightly lower fraction than in 2003. Table 2-5 shows the current status and near-term nuclear power supply plan in China (Kang, 2006 and World Nuclear Association 2009). As of 2008, China had announced plans to increase its nuclear capacity to about 60 GWe by 2020, and 160 GWe by 2030. Locations and current status of operation and construction of NPPs in China as of the early 2009 are given in Figure 2-3 (from World Nuclear Association, 2009).

Table 2-5: Status of Existing Units and Near-term Nuclear Power Supply Plans in China as of Early 2009

Site	Unit	Type	Capacity (MWe)	Operation
Daya Bay	Daya Bay-1	PWR	944	1994
	Daya Bay-2	PWR	944	1994
Qinshan	Qinshan-1	PWR	279	Apr. 1994
	Qinshan-2	PWR	610	2002
	Qinshan-3	PWR	610	2004
	Qinshan-4	PHWR	665	2002
	Qinshan-5	PHWR	665	2003
	Qinshan-6	PWR	650	Under constr.
	Qinshan-7	PWR	650	Under constr.
Lingao	Lingao-1	PWR	935	2002
	Lingao-2	PWR	935	2003
Lingao Phase 2	Lingao-3	PWR	1080	Under constr.
	Lingao-4	PWR	1080	Under constr.
Tianwan	Tianwan-1	VVER	1000	2007
	Tianwan-2	VVER	1000	2007
Haiyang	Haiyang-1	PWR	1100	Planned
	Haiyang -2	PWR	1100	Planned
Hongyanhe 1	Hongyanhe-1	PWR	1080	Under constr.
	Hongyanhe-2	PWR	1080	Under constr.
	Hongyanhe-3	PWR	1080	Under constr.
	Hongyanhe-4	PWR	1080	Under constr.
Taishan	Taishan-1	PWR	1700	Planned
	Taishan-2	PWR	1700	Planned
Sanmen	Sanmen-1	PWR	1100	Under constr.
	Sanmen-2	PWR	1100	Planned

Ningde Phase 1	Ningde-1 Ningde-2	PWR PWR	1080 1080	Under constr. Under constr.
Ningde Phase 2	Ningde-3 Ningde-4	PWR PWR	1080 1080	Planned Planned
Fangchengang	Fangchengang-1 Fangchengang-2	PWR PWR	1080 1080	Planned Planned
Shidaowan		HTGR	200	Planned
Fuqing	Fuqing-1 Fuqing-2	PWR PWR	1080 1080	Under constr. Under constr.
Haiyang	Haiyang-1 Haiyang-2 Haiyang-3 Haiyang-4	PWR PWR PWR PWR	1100 1100 1100 1100	Planned Planned Planned Planned
Tianwan Phase 2	Tianwan-3 Tianwan-4	PWR PWR	1060 1060	Planned Planned
Changjiang	Changjiang-1 Changjiang-2	PWR PWR	650 650	Planned Planned
Dafan Phase 1, Xianning	Danfan-1 Danfan-2	PWR PWR	1080 1080	Planned Planned
Hongshiding 1 (Rushan)	Hongshiding-1 Hongshiding-2	PWR PWR	1080 1080	Planned Planned
Fangjiashan (Qinshan phase 5)	Fangjiashan-1 Fangjiashan-2	PWR PWR	1080 1080	Under constr. Planned
Xiaomoshan Phase 1	Xiaomoshan-1 Xiaomoshan-2	PWR PWR	1100 1100	Planned Planned
Pengze Phase 1	Pengze-1 Pengze-2	PWR PWR	1100 1100	Planned Planned
Wuhu	Wuhu-1 Wuhu-2	PWR PWR	1080 1080	Planned Planned
Yangjiang	Yangjiang-1 Yangjiang-2 Yangjiang-3 Yangjiang-4 Yangjiang-5 Yangjiang-6	PWR PWR PWR PWR ? ?	1080 1080 1080 1080 1000 1000	Under constr. Planned Planned Planned. being proposed being proposed

Figure 2-3: Current Status of Operation and Construction of NPPs in China



2.5.3. *Nuclear Fuel Cycle Activities in China—Fuel Fabrication and Enrichment*

China has uranium resources and produces about half of the uranium needed for its current reactor fleet, and is developing additional mines, but its resources are considered low-grade by international standards. China imports uranium from Russia, Kazakstan, Namibia, and Australia, and is actively pursuing joint ventures to provide it with access to resources in those countries and other nations.

China has two plants, with a total capacity of 2000 tU/yr, for the conversion of uranium oxide and metal to uranium hexafluoride. China has several older enrichment plants based on gaseous diffusion technology. These have been or are being shut down. Newer enrichment facilities have been developed using largely Russian centrifuge technology, and total about 1.5 million SWU per year. Additional enriched uranium is imported for the Daya Bay plant from Urenco in Europe. The contract supplies 30 percent of the uranium needs for that plant.

China has several fuel fabrication plants, and a goal to be self-sufficient in fuel fabrication, though it is importing the first two fuel assemblies and fabricated fuel rods for 17 reloads for the Taishan plant from France (World Nuclear Association, 2009).

2.5.4. Nuclear Fuel Cycle Activities in China—Spent Fuel Management

China declared its intention to pursue a closed fuel cycle, based on Purex technology, in 1987. All Chinese spent fuel is currently stored at its nuclear power plants. A civil reprocessing pilot plant with a capacity of 50 tHM/year was opened at Lanzhou in 2006, and plans are in place to expand its capacity to 100 tHM/year in 2008. A large commercial reprocessing plant is planned to be in operation in 2020. Selection for a repository site for HLW is planned by 2020, and actual disposal at the site seems to be planned to take place starting in 2050. There are six candidate locations for a repository. A centralized wet storage facility with a capacity of 550 tHM is under construction in the Lanzhou nuclear fuel complex, and could be doubled in capacity (UIC, 2007).

China may adopt pyroprocessing technology in the long-term, based on its expressed interest in participating in all dimensions of the US-proposed GNEP (Global Nuclear Energy Partnership) as of December 2006 (Weitz, 2007).

2.6. Nuclear Power and Nuclear Fuel Cycle Activities in the Russian Federation (RF) and the Russian Far East

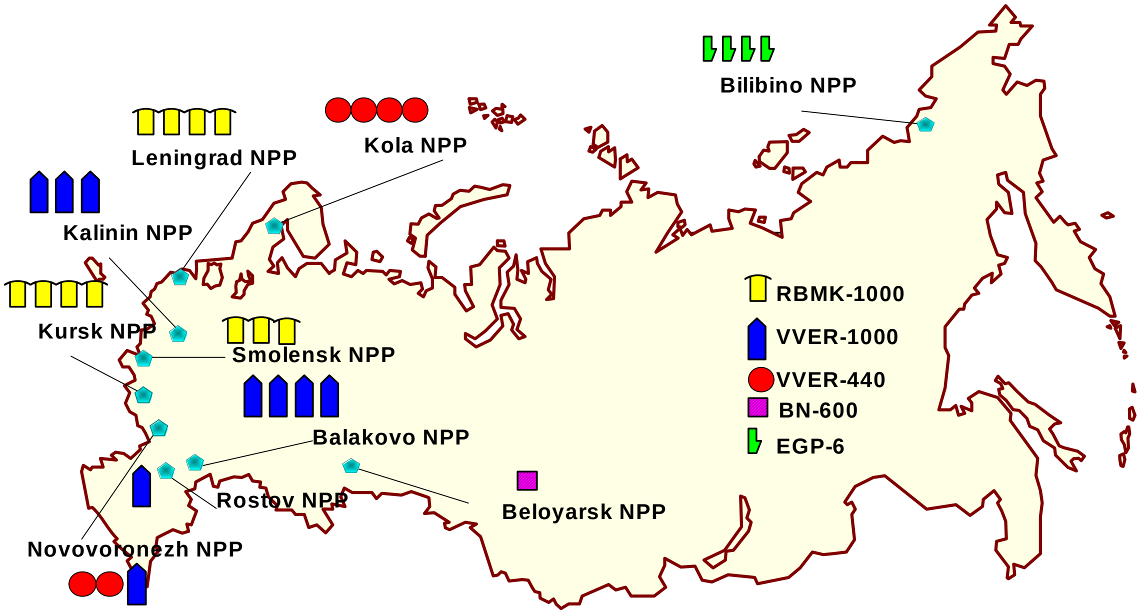
2.6.1. Introduction

Though the Russian Federation as a whole has an extensive nuclear power program, is a nuclear weapons state, has uranium resources, and operates both enrichment and reprocessing facilities, the Russian Far East (RFE) region has only one very small (48 MWe) operating power reactor. Development of commercial reactors on the 1 GWe scale has been under discussion in the RFE for many years, in part to serve local electricity users, but also for power exports to the ROK and China, but construction of new plants has not yet taken place.

2.6.2. History and Current Status

Russia’s first commercial nuclear reactors began operation in the early 1970s. Of its current fleet of 31 reactor units at 10 sites (with a net generation capacity of 21,743 MWe), only the Bilibino plant, with four small units of 11-12 MWe each, is located in the Russian Far East, in the far north of the region on the Arctic Sea (see Figure 2-4). Many of Russia’s existing reactors will reach the end of their original operational lifetimes in the next decade, and as a result, Russian nuclear authorities, including Rosatom, are considering and pursuing life extension and uprating for Russia’s existing plants. The small nuclear units at Bilibino will reach the end of their nominal 30-year operating lifetime within the next few years, but have received a 5-year operating license extension, and are due to be replaced during 2015-2020.

Figure 2-4: Nuclear Power Plants in Russia as of 2006 (10 plants, 31 units, with a gross generation capacity of 23242 MWe; from Dmitriev, 2006)



In addition to lifetime extension of existing units, Rosatom plans to complete the 9 GWe of capacity currently under construction, and to add additional capacity such that 23 percent of total electricity supplies can come from nuclear power as of 2020. The World Nuclear Association (2009) lists 44 nuclear units with a gross generation capacity of about 41 gross GWe as being under construction or proposed for operation by 2020, though 7 of these units totaling gross 8.4 GWe are listed as “deferred”.

Though a number of proposals, including proposals for power exports, have included large nuclear power plants in the Russian Far East, current plans seem to focus on only the addition of some small floating reactors (tens or hundreds of megawatts) in the near- to medium-term.

Russia has an experimental fast breeder reactor, the BN-600 at Beloyarsk, which is due to be replaced with a new BN-800 unit. Developing a fast breeder reactor fuel cycle in 2030 and beyond is a goal of the Russian nuclear program, with a proposed reactor fleet of 55 GWe light water reactors and 15 GWe of fast breeder reactors by 2040 (Dmitriev, 2006).

2.6.3. Nuclear Fuel Cycle Activities in the RF—Fuel Fabrication and Enrichment

The Russian Federation has significant uranium resources, totaling an estimated 10 percent of world resources, and a history of uranium mining and exports, though current uranium output is less than expected domestic requirements. Russia also has a long history of fuel fabrication and enrichment activities, with 18,700 tonnes/yr of uranium conversion capacity at its main plant in Angarsk, and 24 million SWU/yr of enrichment capacity at four plants located near the Urals and in Siberia. Some of this capacity serves nuclear programs in other countries, and some is devoted to enrichment of spent reactor fuel.

2.6.4. Nuclear Fuel Cycle Activities in the RF and RFE—Spent Fuel Management

Russia has spent fuel and radioactive waste storage facilities in several locations, with additional capacity under development. Some storage facilities accept spent fuel from Russian-built reactors in other nations, as well as domestic spent fuel. A 2003 proposal suggested Krasnokamensk in the RFE Chita region as the site for a major spent fuel repository, but as yet no long-term spent fuel facility exists in Russia.

Spent fuel reprocessing in Russia began as part of the military nuclear program. Currently, a 400 tHM/yr plant reprocesses fuel from smaller (VVER-440) nuclear units in Russia and other countries, fuel from naval and icebreaker reactors, and from the BN-600 breeder reactor. An additional reprocessing facility was under construction, but was canceled and due to be dismantled, though this decision seems to be currently under review.

2.7. Nuclear Power and Nuclear Fuel Cycle Activities in Australia

2.7.1. Introduction

Australia has some small reactors used for testing and education, but no commercial-scale reactor program. Development of nuclear power in Australia has been discussed a number of times in recent decades, but is not favored by the current government. Australia is, however, a major producer and exporter of uranium.

2.7.2. History and Current Status

Australia is involved in the nuclear cycle through nuclear research. The country has had a small research reactor (HIFAR) operating at Lucas Heights, in the southern suburbs of Sydney, since 1958. Amongst other things, this reactor has been used to produce radioactive isotopes for use in nuclear medicine (ANSTO, 2008). In January 2007 HIFAR was shutdown (although decommissioning will continue for up to ten years) (ANSTO, 2008b), to make way for the more sophisticated Open Pool Australian Light water reactor (OPAL), which, after a lengthy licensing process, went critical at Lucas Heights on 12 August 2006 (ANSTO, 2008a).

In the 1970s Australia had a long and deeply divisive debate over whether it should mine and export uranium. The outcome was a policy of limited export (from no more than three mines) and no further extensions of the nuclear fuel cycle in Australia beyond a few small test, educational, and medical physics reactors. Over subsequent decades there have been recurrent efforts by the nuclear industry to develop further stages of the nuclear fuel-cycle. Although these have occasionally gained some traction, deeply embedded opposition to this within the Australian community has consistently resulted in these proposals failing to reach fruition. At the time of this writing nuclear power reactors were prohibited by both current State and Commonwealth policy. (Falk et al, 2006).

Over 2006-7, climate change provided a new foundation for the nuclear industry, and its supporters, to once more argue for extensions of the nuclear fuel cycle in Australia, including extensions to uranium enrichment, high-level waste storage, and the introduction of nuclear reactors. In 2006, the conservative Federal Government responded to this advocacy by initiating a national debate over these proposals in the context of the challenges from climate change.

In June 2006, the then Prime Minister, John Howard, appointed a taskforce to review the case for and against expanding nuclear fuel-cycle activities in the country, galvanizing widespread debate in the media on nuclear issues. The taskforce, in its report released in December 2006, argued that in the context of climate change and increasing energy demand, it "sees nuclear power as a practical option for part of Australia's electricity production" (Commonwealth of Australia, 2006). One scenario it considered was the building of 25 nuclear reactors, each 1 GW in capacity, to produce a third of the country's electricity by 2050. However it also noted that "the earliest that nuclear electricity could be delivered to the grid would be 10 years, with 15 years more probable" (Commonwealth of Australia, 2006).

While the Australian public was somewhat open to the idea of nuclear power in the context of climate change, debate quickly turned to where nuclear reactors could be built, opening a political mine field. This theme was taken up by the Australian Labor Party (ALP), then in opposition. Despite the then Prime Minister's reassurances that he "wouldn't have any objection, none whatsoever" if a reactor were to be constructed next to his house (Allan, 2006), 66% of those surveyed in an opinion poll responded that they would in fact object to a reactor in their local area (Newspoll and The Australian, 2007).

By the time of the run-up to the November national election, nuclear power had emerged as so politically unpopular that the government was not referring to it, and the opposition ALP was using it, together with the need to act on climate change, as an effective weapon against re-election of the government. The election saw John Howard and his Liberal Party lose power, after eleven years in government, to the ALP. Led by Kevin Rudd, who became the new prime minister, the ALP assumed office with a clear election policy of opposition to the development of nuclear power in Australia (Evans, 2007).

2.7.3. Nuclear Fuel Cycle Activities in Australia: Fuel Fabrication and Enrichment Research

As of 2008, Australia had 714 kt (thousand tonnes) of uranium that was "reasonably assured [and] recoverable at costs of less than US$80/kg U". These reserves would last 72 years at 2006 rates of production (ABARE, 2008). Despite current sentiments against nuclear power and other fuel cycle activities, Australia remains a major uranium exporter. Its involvement in uranium extraction stretches back a century (Falk et al, 2006) and in 2007 the ALP (then in opposition) had, in its efforts to show itself to be financially conservative and commercially pragmatic, overturned its 25-year policy against new mines. Kevin Rudd had invoked other countries' energy security as a moral justification, telling the party's national conference, "Other countries are not as rich in energy options as we are" (Rudd, 2007). Since the ALP gained control of the government, plans have proceeded to add a fourth uranium mine to the three already in operation (ABARE, 2008b).

According to the Uranium Mining, Processing and Nuclear Energy Review Taskforce report, Australia held 38% of the world's low-cost uranium (less than US$40/kg) in 2005 (Commonwealth of Australia, 2006). The report also considered that besides the large amount of already discovered uranium, "there is significant potential" for the discovery of more deposits in

Australia (Commonwealth of Australia, 2006, p.24). With no current or planned commercial scale reactors, Australia lacks fuel fabrication and uranium enrichment capacity.

In April 2006, Australia signed two agreements with China for the sale of Australian uranium, although it did so in the face of some domestic controversy over whether the uranium could be used for weapons, or could free up Chinese uranium for use in weapons.

2.7.4. Nuclear Fuel Cycle Activities in Australia—Spent Fuel Management

Australia currently produces less than 50 cubic metres of low and intermediate level radioactive waste per year (Commonwealth of Australia, 2006). Much of this is stored at the Lucas Heights reactor, while intermediate level waste is sent overseas for reprocessing, and awaits return to Australia (Commonwealth of Australia, 2006). The Australian Government aims to establish a more permanent solution, in the form of a national nuclear waste repository. Three potential sites, on government land in the Northern Territory, have been identified. However attempts at establishing such a facility have met ongoing resistance since the mid-1980s from the community and state and territory governments, and implementation of the plan is still not assured.

Despite having no policy or facility to store high-level nuclear waste, Australia signed onto the Global Nuclear Energy Partnership (GNEP) in September 2007. GNEP was then an agreement between the US, China, Japan, France and Russia and a group of mostly Eastern European nations (Dept of Energy, 2007). Since its inception, the partnership has expanded to include Canada, the Republic of Korea, Italy, Senegal and the United Kingdom (Dept of Energy, 2008c). The partnership “seeks to develop worldwide consensus on enabling expanded use of economical, carbon-free nuclear energy” (Dept of Energy, 2008a) through a “closed fuel cycle” where supplier countries provide “fresh fuel and recovery of used fuel” to and from user countries. Australia currently has nowhere to put this used fuel, but has continued to participate in GNEP under the ALP government, and attended the organization’s second steering committee meeting in May 2008 (Dept of Energy, 2008b).

Besides GNEP, the Australian Government has been cooperating with other countries through the Forum for Nuclear Cooperation in Asia (FNCA). The forum exists to share information and views on nuclear issues in the Asian region, and Australia has been involved since its first meeting in 2000 (FNCA, 2000). One FNCA meeting has occurred since the ALP won power in 2007, and interestingly, an Australian representative attended (FNCA, 2007b), but did not sign the joint communiqué, which committed the forum to promoting the “utilization of civilian nuclear power as a clean energy source” (FNCA, 2007a).

2.8. Nuclear Power and Nuclear Fuel Cycle Activities in Taiwan (Chinese Taipei)

2.8.1. Introduction

As an island nation that, like Japan and the ROK, substantially lacks fossil fuel resources, Taiwan has turned to nuclear power to diversify its energy system. Taiwan has six operating commercial nuclear reactors, the first of which went into service in 1978. About 20 percent of Taiwan’s electricity is generated by these nuclear units. An additional two reactor units are nominally under construction, but construction has been stalled for some time by political and other considerations.

2.8.2. History and Current Status

Like ROK and Japan, Taiwan has few fossil or hydroelectric energy resources and has to import more than 90% of its energy supplies. Currently, there are three nuclear power plants (NPP) operating in Taiwan, each with two generating units per site. As of early 2009, 6 NPP units, including 4 BWRs and 2 PWRs, had a total capacity 5.142 million kW (GWe). These NPPs are scheduled to be retired in 2018, 2021 and 2024 respectively. Nuclear Power Plant No. 4 (Lungmen), with a total capacity of 2.7 GWe, located in the northeastern coast near Taipei, is reported to be in its final stages of construction, but completion of the unit, once scheduled for 2010, has been delayed by debates over the future role of nuclear energy in Taiwan. Table 2-6 shows the current status and near-term deployment of NPPs in Taiwan (from Kang, 2006). The locations of NPPs in Taiwan as of the end of 2005 are shown in Figure 2-5 (Kang, 2006).

Table 2-6: Status and Near-term Nuclear Power Supply Plan in Taiwan

Site	Unit	Type	Capacity (MWe)	Operation
Chinshan	Chinshan-1 Chinshan-2	BWR BWR	604 604	1978 1979
Kuosheng	Kuosheng-1 Kuosheng-2	BWR BWR	948 948	1981 1983
Maanshan	Maanshan-1 Maanshan-2	PWR PWR	890 890	1984 1985
Lungmen (near Taipei)	Lungmen-1 Lungmen-2	ABWR ABWR	1350 1350	Under const. Under const.

Figure 2-5: Location of Nuclear Power Plants in Taiwan

2.8.3. Nuclear Fuel Cycle Activities in Chinese Taipei—Fuel Fabrication and Enrichment

Taiwan lacks uranium resources, and depends on international sources for enrichment services.

2.8.4. Nuclear Fuel Cycle Activities in Chinese Taipei —Spent Fuel Management

The spent fuel management policy of Taiwan is to use direct disposal. Taiwan has, however, apparently considered reprocessing in the past. Taiwan conducted plutonium-separation experiments until the mid-1980s, according to the IAEA (Kerr, 2005).

For spent fuel management, Taiwan considers on-site dry storage as a favorable option before implementing final disposal. Commissioning of interim storage facilities were, as of 2007, anticipated at a Chinshan site in 2008, and at a Kuosheng site in 2009. While a long-term investigation plan is being undertaken by Taiwan Power Company (TPC) to select a suitable longer-term repository for spent fuel, regional or international cooperation is also being pursued by Taiwan as an alternative path to disposal (WNT, 2007).

2.9. Nuclear Power and Nuclear Fuel Cycle Activities in Indonesia

2.9.1. Introduction

Though it has no commercial nuclear industry at present, development of nuclear power has been and is being discussed in Indonesia, and a first reactor is nominally planned for operation in about 2020.

2.9.2. History and Current Status

For more than three decades, successive Indonesian governments have announced an intention to build one or more nuclear power stations. Indonesia has had a nuclear research program, under the National Atomic Energy Agency, since the 1960s. While other locations have been discussed (Hibbs, 2008), most proposals have indicated sites on the island of Java, with the preferred site for many years being on the Muria peninsula on the north coast of Java. The peninsula, which juts out into the Java Sea in a line north of Jogjakarta, is dominated by the multiple peaks of the 1602 metre-high volcano, Gunung Muria, 25 kilometers from the planned site. Government interest in construction of nuclear power plants in Indonesia has waxed and waned over the years, as political and economic crises have had their effect. Seismic issues are a concern at the Muria site, and recent local political and social opposition (including opposition from local Islamic groups) has emerged. Though a regulatory body for Indonesia’s nuclear industry has been set up, its authority has been undermined by charges of corruption. While the sum total of these concerns leaves the prospects for nuclear power in Indonesia uncertain, two nuclear units remain in the governments plans for the decade starting in 2020.

2.9.3. Nuclear Fuel Cycle Activities in Indonesia—Fuel Fabrication and Enrichment

Indonesia has some domestic uranium resources, but thus far, no commercial uranium production.

2.9.4. Nuclear Fuel Cycle Activities in Indonesia —Spent Fuel Management

Consideration of spent fuel management is in its early stages in Indonesia.

2.10. Nuclear Power and Nuclear Fuel Cycle Activities in Vietnam

2.10.1. Introduction

Like Indonesia, Vietnam has been discussing the possibility of developing a nuclear power program for a number of years, and plans to operate its first reactor starting in about 2020.

2.10.2. History and Current Status

Interest in nuclear energy in Vietnam dates back more than three decades. The Vietnam Atomic Energy Commission was established in 1976, and operates research facilities and programs covering a number of topic areas (see www.vaec.gov.vn).

Electric power demand in Vietnam is forecast to increase many-fold in the next two decades. Ensuring an adequate power supply for the economy is one of the big challenges for sustainable development of the country. Though Vietnam can and will develop additional power plants using coal, oil, gas, hydropower, and renewable energy, nuclear energy is also an option for the country (Pham, 2009; this article is the source for some of the text below).

Preparation for development of nuclear power in Vietnam has been carried since the 1990s, but only, thus far, at the level of general overview research. From 2002-on, more intensive investigations began when the Prime Minister directed the preparation of a pre-feasibility study report on the use of nuclear power. The pre-feasibility report on construction of the first nuclear power plant in Vietnam was prepared by Institute of Energy (Electricity of Vietnam Group) in coordination with other organizations. This report was completed and submitted to the Prime Minister in August 2005. At the end of April 2008, the Institute of Energy was entrusted by the Ministry of Industry and Trade and Electricity of Vietnam Group to preparing an Investment Report on construction of nuclear power plants at sites in Phuoc Dinh and Vinh Hai, Ninh Thuan provinces. At each site, development of two nuclear units with capacities of 1000 MW each are to be investigated with anticipated operations anticipated to begin in 2020. In Vietnam's current power plan, a total of four 1000 MW nuclear units are assumed to be operational in Vietnam by 2025. The planning of potential sites is being studied by Institute of Energy, and implementation plans for specific sites will be prepared soon.

Construction and putting into operation of nuclear power plants, as well as the development of a nuclear power industry in Vietnam, depends on many factors, some of the most important of which include arranging for radioactive waste management, keeping production costs low and stable, and achieving political and social consensus on the desirability and safety of nuclear power. The current sentiment in Vietnam is optimistic toward the future of this new industry. Starting the industry right will be very important for success, as it makes the nation more confident about its energy perspectives, but a failure in proper planning or an incident of some sort associated with a nuclear facility will make it more difficult to develop a Vietnamese nuclear power industry in the future.

Recent new articles have reported that Vietnam's National Assembly have approved the construction of two nuclear power plants (each with a capacity of 2000 MW each, so likely composed of two units each), at a projected cost of over $11 billion, and that Electricity of Vietnam has signed a deal with Russian firms to purchase Russian-supplied nuclear reactors[22].

2.10.3. Nuclear Fuel Cycle Activities in Vietnam —Fuel Fabrication and Enrichment

Vietnam has some uranium resources, but no active mining program to date.

2.10.4. Nuclear Fuel Cycle Activities in Vietnam—Spent Fuel Management

Consideration of spent fuel management is in its early stages in Vietnam.

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[22] See, for example, Vu Trong Khanh and Patrick Barta (2009), "Vietnam Assembly Approves Nuclear Plants", Wall Street Journal dated November 26, 2009, and available as http://online.wsj.com/article/SB125913876138763683.html; and Nuclear Power Daily(2008), "Vietnam, Russia sign deals on defence, nuclear energy", dated December 15, 2009, and available as http://www.nuclearpowerdaily.com/reports/Vietnam_Russia_sign_deals_on_defence_nuclear_energy_999.html.

3. Nuclear Energy Paths by Country

3.1. Introduction

Nuclear power is only one of a number of different power generation choices that can be made by a country. Power generation choices in general are made by a combination, varying by country, of commercial actors (for example, privately- and publicly-owned utilities) and public decisionmakers. More than most other sources of power, however, the choice of nuclear power depends on public policy—for financial assistance with the considerable up-front costs of nuclear technologies, for support for fuel cycle infrastructure such as spent fuel management facilities, for support for training of scientists and technicians, and for regulatory oversight of domestic nuclear industries, for example. As such, a number of different nuclear paths—the number and timing (and sometimes, types) of nuclear generating unit additions or replacements in future years—are generally plausible for each country, depending on how public policy evolves. The choice of a nuclear path, however, can have a significant influence on patterns of financial investment, transmission and distribution system deployment, security arrangements, and, of course the magnitude of the inputs to and outputs from the nuclear fuel cycle.

In the remainder of this paragraph we outline possible nuclear power capacity expansion (and, in some cases, contraction) paths for each of the nine countries covered in this report.

3.2. Background and Methods

3.2.1. Nuclear Energy Paths to 2030

Plans for nuclear generation capacity development are made in the context of developing overall plans for meeting national demand for energy services—specifically, energy services provided by electricity. To make sure that nuclear energy paths occur in context, we base our nuclear capacity paths on models of energy system development through 2030 in each of the nine countries. With the exception of the DPRK—for which energy paths are based on work by Nautilus—we based the nuclear paths described below on electricity forecasts and related electricity sector development paths included in LEAP (Long-range Energy Alternatives Planning) models prepared by collaborating groups in each country. To facilitate the work of the collaborating groups, they were each asked to develop a “Business as Usual” (BAU) nuclear path, based on recent trends and/or government plans for the nuclear power sector, “Maximum Nuclear” (MAX), in which they were asked to estimate the most nuclear capacity that could reasonably be developed in the country through 2030, and “Minimum Nuclear” (MIN), in which country teams were asked to identify the minimum capacity that seemed plausible to be developed through 2030. In those counties that currently lack nuclear power, the MIN path was often, by default, no added capacity.

It should be noted that though the nuclear paths to 2030 are generally based on the work of country teams, the ongoing nature of the LEAP modeling efforts in each country mean that there are typically some differences between the paths modeled here and the very latest paths being modeled by collaborating country teams. In addition, in some cases country teams have taken a somewhat different approach to specifying nuclear scenarios, whereas we have tried to adopt approaches to estimating capacity additions by path that are largely consistent across countries.

The three nuclear energy paths per country serve as the basis for estimating the nuclear fuel cycle parameters—from requirements for uranium ore through requirements for spent fuel management, as well as inputs, outputs, and costs of fuel cycle activities—that are described in in Chapter 5. The three paths drive a range of possible results for consideration as policymakers choose directions for nuclear energy policy.

3.2.2. Nuclear Energy Paths to 2050

All paths prepared by EASS country teams include projections through 2030. For the purposes of evaluating regional nuclear cooperation scenarios, all of which involve the commitment to organizations and infrastructure that would persist well beyond 2030, nuclear capacity and output data for each country were roughly extrapolated to 2050. Extrapolations were performed using existing projections for nuclear capacity expansion by site where available, as well as by continuing trends of expansions through 2030.

3.3. Summary of Regional Nuclear Energy Paths

Tables 3-1 and 3-2, and Figures 3-1 through 3-3, summarize historical trends and future projections for nuclear electricity generation capacity (GWe) and energy production (TWhe) under three different sets of nuclear energy paths in each country: BAU, Maximum Nuclear (MAX), and Minimum Nuclear (MIN). These tables and graphs do not differentiate between the types of reactors used, but the overwhelming bulk (much greater than 90 percent) of capacity is and will be of the light water reactor (pressurized water reactor and boiling water reactor) type, with almost all of the rest being CANDU reactors. The BAU, MAX, and MIN paths represent very different nuclear futures, especially for China and the countries now considering nuclear power (Indonesia, Vietnam, Australia, and, though in a slightly different category, the DPRK), but the MIN case, especially, also represents a marked departure from the past for major nuclear energy users Japan and the ROK, which essentially are in the process of phasing out nuclear power in the MIN case, while increasing their dependence on nuclear energy in the MAX case. As of February 1, 2010, the World Nuclear Association listed a total of 372.7 GWe of "operable" nuclear reactors worldwide[23]. Nuclear generation capacity in the nine countries considered here would total nearly 85 percent of total current world nuclear capacity by 2050, and the growth in capacity alone in the region in the MAX path would be nearly the same as current world capacity. The MAX path implies an average annual growth in regional nuclear capacity of 4.5 percent annually from 2010 through 2050, the BAU path implies 3.5 percent annual growth, and the MIN case implies average growth of less than half a percent annually, with higher growth early in the period nearly balanced by capacity declines after about 2030.

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[23] World Nuclear Association (2010), "World Nuclear Power Reactors & Uranium Requirements", available as http://www.world-nuclear.org/info/reactors.html.

Table 3-1: Regional Nuclear Generation Capacity, Summary of BAU, MAX, and MIN Paths

	Total Nuclear Capacity Net of Decommissioned Units (GWe)								
	RAU (Reference) Case			Maximum Nuclear Case			Minimum Nuclear Case		
Nation	2010	2030	2050	2010	2030	2050	2010	2030	2050
Japan	47	62	64	47	68	69	47	20	2
ROK	19	33	35	19	42	47	19	18	9
China	10	120	170	10	161	257	10	93	84
RFE	0	3	6	0	6	11	0	1	1
Taiwan	5	7	7	5	9	11	5	3	3
DPRK	-	2	2	-	6	6	-	-	-
Indonesia	-	2	6	-	4	13	-	-	-
Vietnam	-	10	20	-	15	30	-	-	-
Australia	-	2	6	-	7	20	-	-	-
TOTAL	81	241	316	81	318	464	81	134	97

Table 3-2: Regional Nuclear Electricity Output, Summary of BAU, MAX, and MIN Paths

	Total Nuclear Electricity Output (TWhe)								
	RAU (Reference) Case			Maximum Nuclear Case			Minimum Nuclear Case		
Nation	2010	2030	2050	2010	2030	2050	2010	2030	2050
Japan	331	437	448	331	475	487	331	139	12
ROK	148	260	278	148	332	372	148	139	68
China	68	930	1,327	68	1,265	2,026	68	736	660
RFE	0	23	41	0	41	77	0	6	6
Taiwan	38	50	50	38	64	80	38	21	21
DPRK	-	17	17	-	50	50	-	-	-
Indonesia	-	16	47	-	31	94	-	-	-
Vietnam	-	74	149	-	112	223	-	-	-
Australia	-	16	47	-	55	158	-	-	-
TOTAL	586	1,823	2,404	586	2,426	3,567	586	1,041	767

Figure 3-1: Trends in Regional Nuclear Generation Capacity, BAU Path

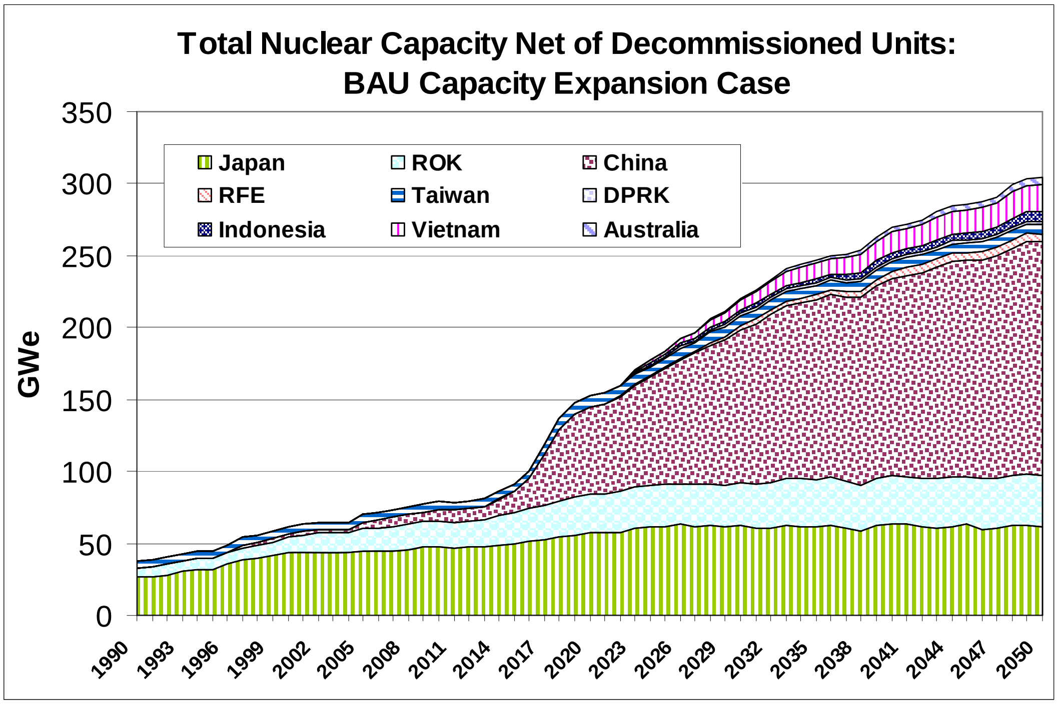


Figure 3-2: Trends in Regional Nuclear Generation Capacity, MAX Path

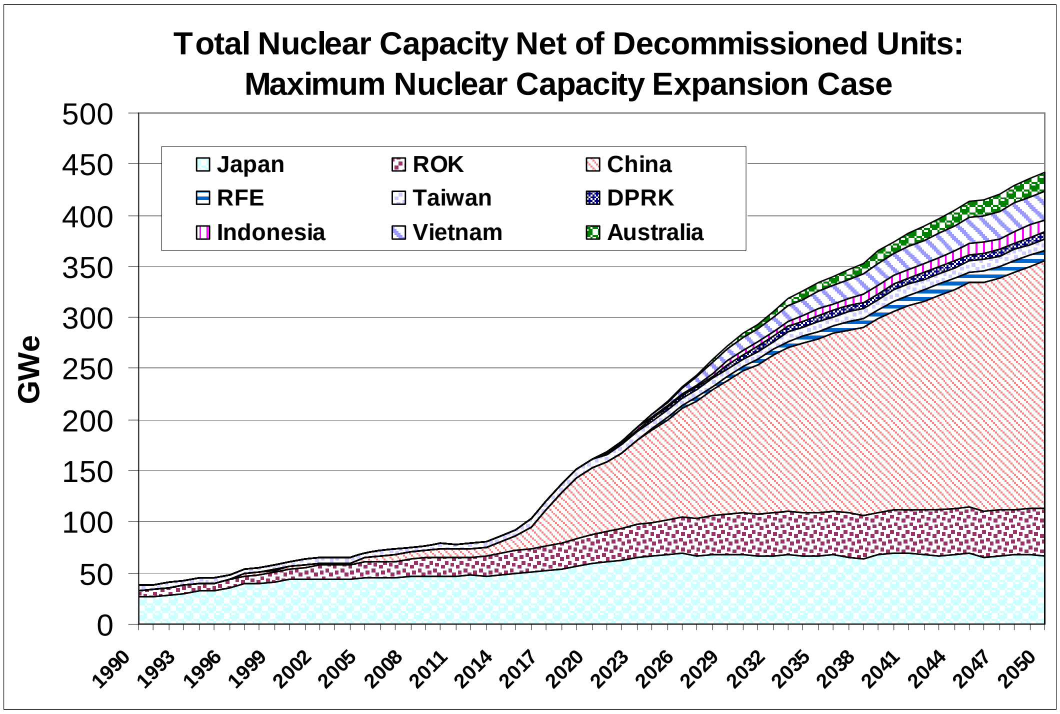
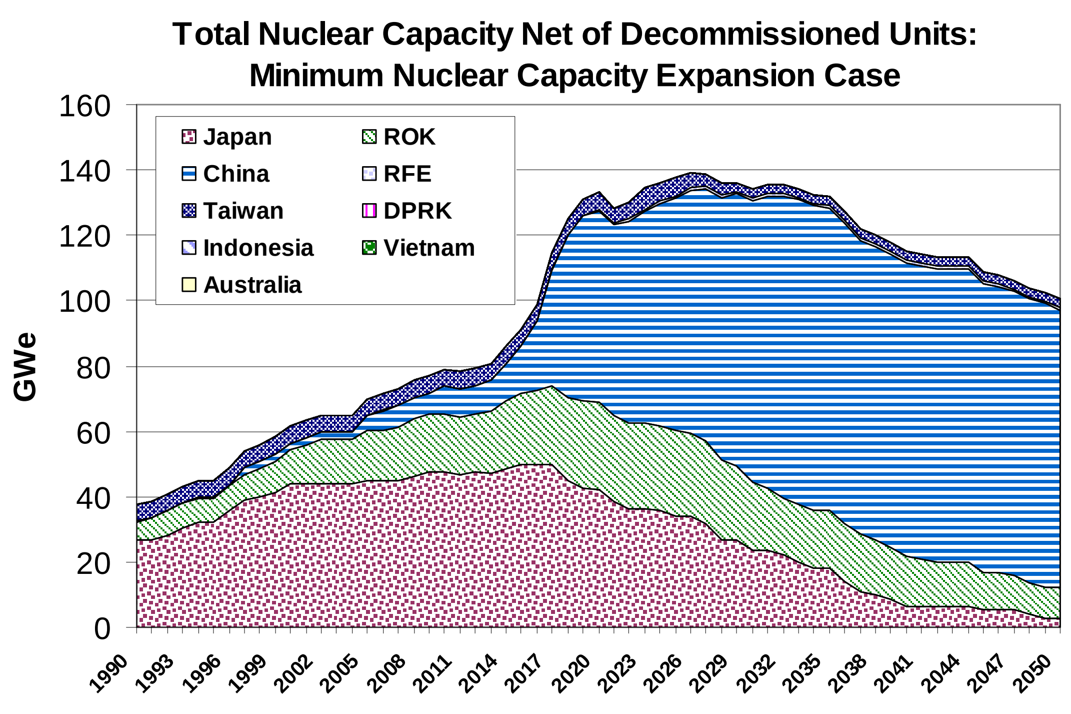


Figure 3-3: Trends in Regional Nuclear Generation Capacity, MIN Path



The subsections of this chapter that follow provide brief summaries of the different nuclear energy paths as prepared for each country

3.4. Nuclear Energy Paths for Japan

To date, four different future energy paths for Japan have been developed, though evaluation of some of the paths is still ongoing. The paths developed include the Business-as-Usual (BAU) path, assuming generally that existing policies continue. Two variants that assume BAU demand but model different trends for nuclear power generation capacity (the “Minimum Nuclear” and “Maximum Nuclear” paths), and a “National Alternative” path that emphasizes aggressive application of energy efficiency and renewable energy measures.

3.4.1. Business as Usual Path for Japan

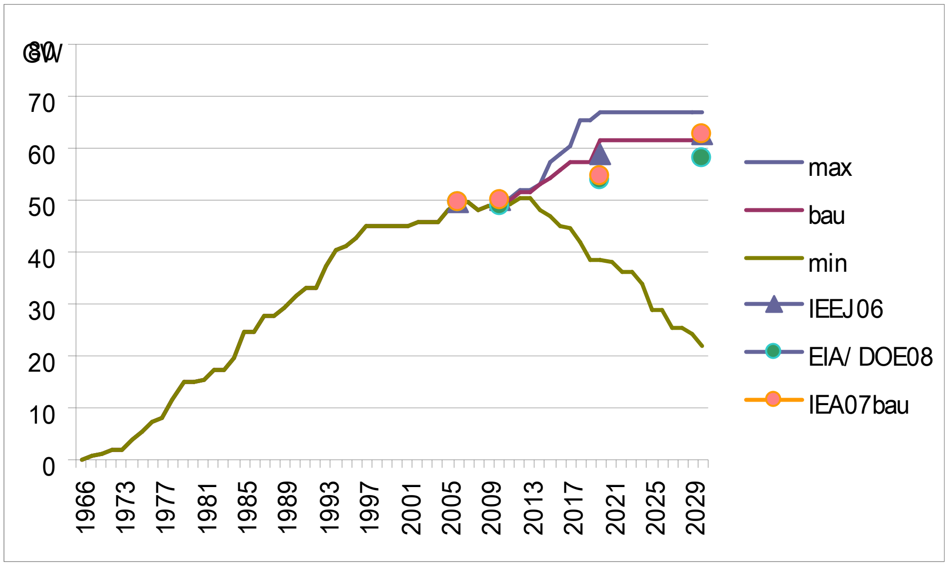
The **BAU path** was developed to match as closely as possible the “reference” or “BAU” cases outlined by Advisory Committee on Energy and Natural Resources under Ministry of Economy, Trade and Industry (ACENR/METI 2008) and the Institute of Energy Economics, Japan (IEEJ 2006). Energy demand in the BAU path generally follows the IEEJ Long-term Outlook (IEEJ 2006), which provides more detailed end-use breakdowns than the outlook by ACENR/METI, but the ACENR/METI outlook was used as a guide for trends in electricity generation capacity, which is not included in the IEEJ figures. ACENR/METI’s projections for nuclear capacity are slightly lower than those of IEEJ (61.50 GW versus 62.86 GW by 2030). The BAU case as modeled generally assumes that operating lifetimes for nuclear plants existing as of 2006 are 50 years. For the BAU path, we assumed an average capacity factor of 80 percent for 2008 through 2050. This is somewhat lower than industry estimates, but consistent with the history of nuclear power in Japan. Capacity factors for the nuclear reactor fleet in Japan have only exceeded 80 percent on average in four years since 1984, and average capacity factors in recent years have been considerably less, for a host of reasons.

For the **BAU case**, we assume that a total of 10 additional units will be completed by 2020, yielding a total capacity of about 61 GW by then, with no new additions to 2030, but with most (10 of 12 from 2020 through 2030) existing units reaching the end of an assumed 50-year lifespan--which itself assumes life extension from their nominal 40-year life) replaced in the year after decommissioning with new 1380 MWe units, resulting in a slight net increase in capacity between 2020 and 2030.

3.4.2. Minimum and Maximum Nuclear Paths for Japan

The **Minimum Nuclear** and **Maximum Nuclear** paths were developed based on a review of projections of nuclear capacity by several groups in Japan and elsewhere (IEEJ 2006, EIA/DOE 2008, IEA 2007). At present 53 nuclear units with total capacity of 48.09 GW are operating in Japan as of January, 2009. Starting in March, 2007, the capacity of the Hamaoka-5 unit has been reduced from 1.38 to1.267 GW due to an accident involving a low pressure turbine blade, and as of January 2009, Chubu Electric has decided to close the Hamaoka-1 and Hamaoka-2 units; plans were recently announced for the Hamaoka-6 unit, with capacity of 1.38 GW, to be built and start operation by 2018-2023. As another point of reference for scenarios of future nuclear capacity, the Japanese government announced the “Japan’s Nuclear Energy National Plan” in August, 2006 (METI 2006). The Plan is designed to maintain nuclear electricity generation at 30 to 40 percent of electricity requirements for 80 years into the future, by extending the operating life of existing reactors from 40 years to 60 years, replacing existing LWRs with new LWRs, and transitioning to the use of Fast Breeder Reactors (FBRs) from about the year 2050. Figure 3-4 compares various outlooks for nuclear generation capacity in Japan, as published by a range of Japanese and international groups with earlier versions of the BAU and Minimum Nuclear and Maximum Nuclear paths prepared by the Japan EASS team (but modified slightly as described below).

Figure 3-4: Paths for Nuclear Generation Capacity in Japan through 2030 with Projections by other Groups (GW)



Note: Data shown for "IEA07 bau" in Figure 3-1 are estimated from nuclear energy output data reported by the IEA (IEA, 2007) using a linear trend in capacity factors starting at 85% in 2015 and reaching 90% by 2030.

We have assumed for the **Minimum Nuclear** path that only three reactors now under construction—the Tomari-3, Shimane-3, and Ohma plants, will be completed, and that no other reactors will be built before 2030. We further assume, for the Minimum Nuclear path, that starting in 2015, existing nuclear units are decommissioned promptly when they reach their 40-year operating lifetime, and are **not** replaced. The net result of these assumptions is a year-2030 capacity of about 20 GW—much lower than any of the projections in Figure 3-1 by that year. The Minimum Nuclear path therefore reflects a situation where the Japanese public and policy establishment turns firmly against nuclear power within the coming decade.

For the **Maximum Nuclear case**, four units, with a total capacity of about 5 GW, are added beyond the BAU case by 2020, yielding a capacity scenario similar to the plans submitted to METI by electric utilities (METI 2008). The Maximum Nuclear case also assumes that an average life extension to 50 years is implemented, and that existing reactor units are replaced with new units in the year after they reach that lifetime limit.

3.4.3. Alternative Path for Japan

The **National Alternative** path—which is still being updated—includes a combination of demand-side energy efficiency and renewable energy measures, aggressively applied, and targeted at reducing electricity generation requirements. Most of the measure implementation assumptions used in the National Alternative path are likely to be as described in Nakata et al (2003a and 2003b). Energy efficiency assumptions for this path are based on the outlook published by the Institute of Energy Economics, Japan (IEEJ, 2006), and renewable energy assumptions are based on estimates from the Ministry of Environment (MOE, 2008).

3.4.4. Extension of Paths Results to 2050

To extend the above paths for Japan to 2050, we have made the simple assumptions on decommissioning and replacement of existing units at the end of their assumed operating lifetimes, as described above, but have not phased in additional new reactors (reactors on new sites) in the 2030 to 2050 timeframe. Figure 3-5 shows the nuclear capacity assumptions through 2050 for each of the three nuclear paths for Japan, and Figure 3-6 describes nuclear generation (terawatt-hours) by path through 2050. Due to lack of new sites for reactors, and a likely stagnation in the amount of electricity required in Japan (a product of many factors, including declining population, continued economic shifts away from heavy industries, and increasing energy efficiency, for example), capacity in the MAX case is not very different from that in the BAU case, while the MIN case reflects, essentially, as decision by Japan to move away from nuclear power.

Figure 3-5: Nuclear Capacity Paths for Japan through 2050 (GWe)

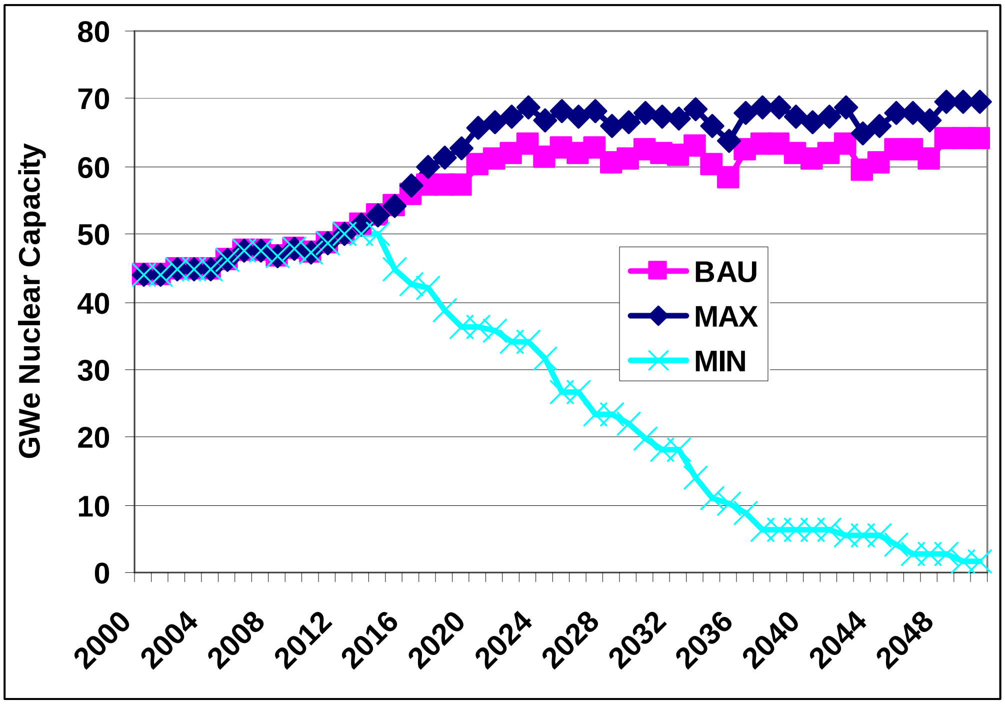
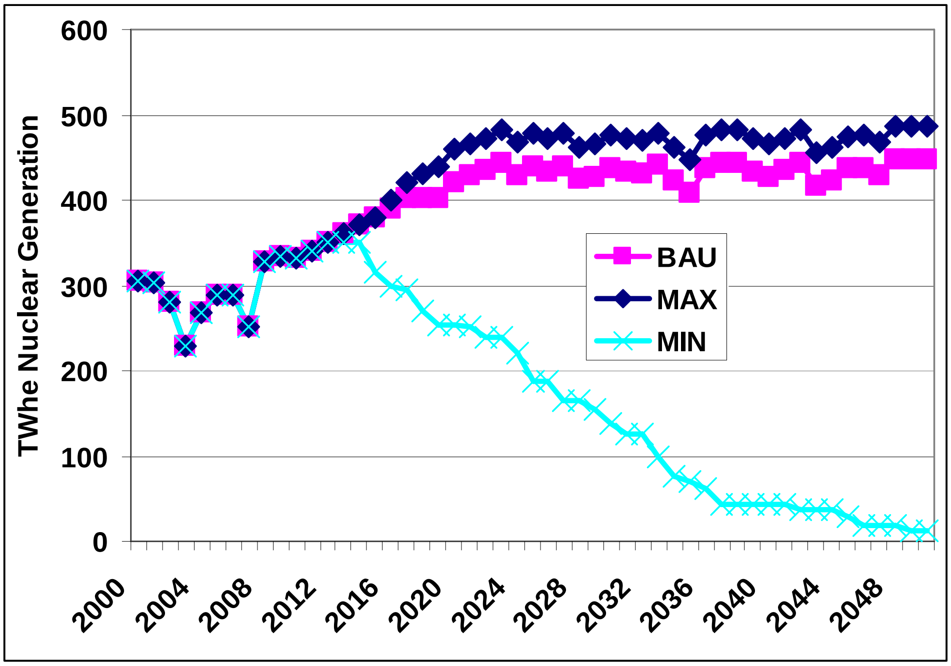


Figure 3-6: Nuclear Generation by Path for Japan through 2050 (TWhe)



3.5. Nuclear Energy Paths for the ROK

No new (undeveloped) sites for nuclear reactors are thought to be practical in the ROK, though sites for deployment of additional reactors in a unified Korea (or under a scenario where the DPRK and ROK cooperate closely) north of the demilitarized zone have been considered, including the site of the now suspended light water reactor project that was coordinated by the Korean Peninsula Energy Development Organization (KEDO) as a part of the 1994 Agreed Framework between the United States and the DPRK (KEDO, 1994). Absent the availability of sites in the DPRK, the ultimate capacity of nuclear power for the ROK over time will therefore depend on decisions as to when (and if) new reactors will be built on these remaining sites, when existing reactors will be decommissioned (that is, whether life extension for existing reactors will be employed), and whether those older reactors that are decommissioned will be replaced by new units.

3.5.1. Business as Usual Path for the ROK

The **Business as Usual path** for the ROK includes the addition of 9 new reactor units—the Sinkori, Sinulchin, and Sinwolsong units listed in Chapter 2—between 2010 and 2019. Thereafter, new 1400 MWe PWR units are added one year after existing units (PWR or CANDU) are decommissioned. Existing PWR units are assumed to be decommissioned after 40 years, and CANDU units after 30 years. In order to determine the rate of fuel burn-up, we assume a 90 percent capacity factor from 2008-on. This is slightly higher than the average capacity factor experienced from 2000 through 2007.

3.5.2. Maximum Nuclear Path for the ROK

The **Maximum Nuclear path** follows the BAU path through 2019, with one additional 1400 MWe reactor added in 2017. Thereafter, the Maximum Nuclear path continues to add reactors until, by 2026, all 36 possible placements for individual reactor units on the existing reactor sites in the ROK are occupied. After 2026, new 1400 MWe units are added one year after existing reactors are decommissioned, and existing reactors from 2020 on are decommissioned following an extended average lifetime 50 years for PWRs, and the standard lifetime of 30 years for CANDU units.

3.5.3. Minimum Nuclear Path for the ROK

The **Minimum Nuclear path** follows the BAU path through 2016, but assumes that no additional reactors are built after that time, and that existing reactors are decommissioned immediately following the end of their rated lifetimes (40 years for PWRs, 30 years for CANDU units). As is the case in Japan, this path reflects a situation in which the public and policymakers have lost confidence in nuclear power (and/or a new, much more attractive, power generation technology has emerged).

3.5.4. Extension of Paths Results to 2050

To extend the above paths for the ROK to 2050, we have made the simple assumptions on decommissioning and replacement of existing units at the end of their assumed operating lifetimes, as described above, but have not phased in additional new reactors (reactors on new sites) in the 2030 to 2050 timeframe. Figure 3-7 shows the nuclear capacity assumptions through 2050 for each of the three nuclear paths for the ROK, and Figure 3-8 describes nuclear generation (terawatt-hours) by path through 2050.

Figure 3-7: Nuclear Capacity Paths for the Republic of Korea through 2050 (GWe)

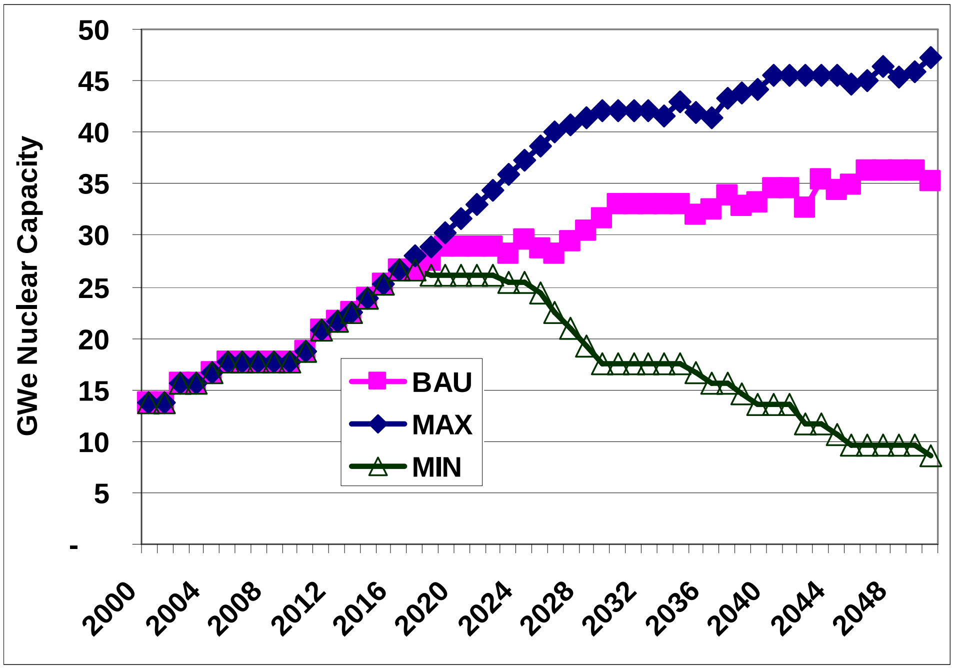
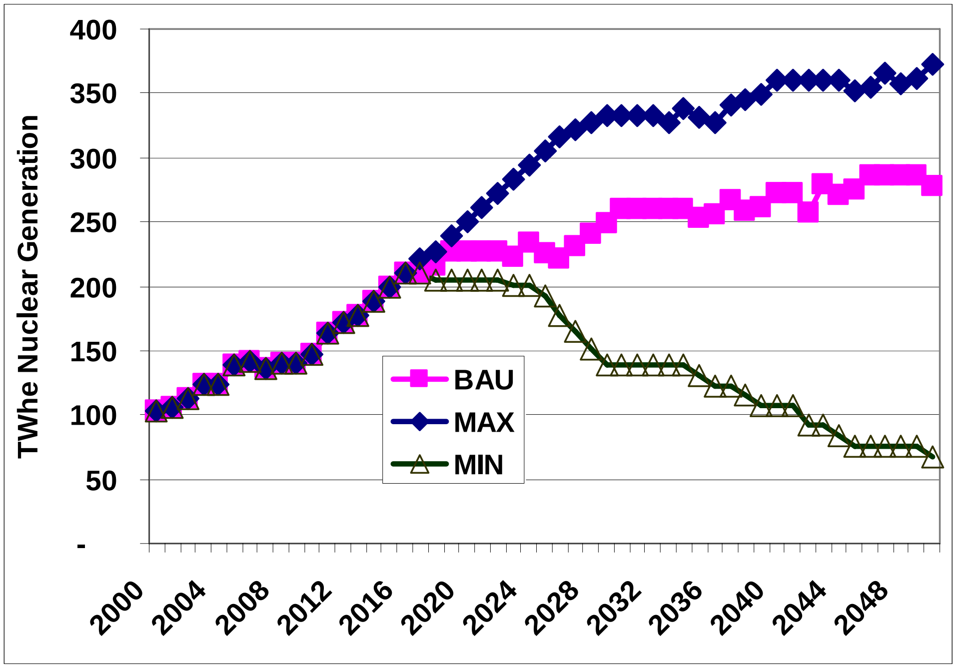


Figure 3-8: Nuclear Generation by Path for the Republic of Korea through 2050 (TWhe)



3.6. Nuclear Energy Paths for the DPRK

Developing nuclear energy paths for North Korea is a different sort of exercise than developing nuclear paths for other nations. For a start, little is known about the North Koreans' own plans for their future energy sector, although their aspirations for nuclear power in general have been made quite clear. In addition, the DPRK's nuclear energy future arguably depends much more upon reaching agreements with other nations—most notably the ROK and the US—on its nuclear energy programs, than upon its own policies and plans, which cannot really be brought to fruition without the consent and support of the international community. As a result, the BAU, Maximum Nuclear, and Minimum Nuclear paths outlined below are even more speculative in nature than those for other AES nations.

3.6.1. Business as Usual Path for the DPRK

Our "Business as Usual" energy path for the DPRK does not really, in fact, reflect recent trends in the North Korean energy economy. Rather, it is what we have called, in previous publications (for example, von Hippel and Hayes, 2007 and von Hippel and Hayes, 2008a), as the "Redevelopment path". Below we describe, in a very qualitative way, what a medium-term "Redevelopment" path might look like for the DPRK economy and, by extension, for the DPRK energy sector. This qualitative sketch is a first step to the estimation of the quantitative attributes of such a path—what the path might mean in terms of future terajoules, tonnes of coal, and megawatts—and, by extension, what it might mean for a DPRK nuclear sector.

First and foremost, the "Redevelopment" pathway implicitly assumes a major breakthrough in relations with the ROK (and probably the United States as well), resulting in some investment in the industrial and energy infrastructure in the DPRK from outside the country, and much increased foreign development aid. The "Redevelopment" path also assumes, however, that the DPRK government essentially maintains its integrity. If the current DPRK government loses power, rapid reunification of North and South Korea may result, which probably means very large, very fast changes for the DPRK energy sector, providing that the unified Korea can obtain internal and external financing for infrastructure reconstruction in the North.

A “**Redevelopment**” pathway for the DPRK would likely be built upon the following assumptions:

- With some political and economic opening, coupled with increased foreign aid, the DPRK economy starts to revive in earnest, for example, in 2011—but note that the structure of the economy may well evolve along quite different patterns than those prevailing in 1990. We would acknowledge that as of this writing (mid 2009), such an opening seems far from certain, but if there has been any constant in the DPRK’s relations with its neighbors and the international community, it has been that no trend, even negative trends, seem to persist for long.
- Industrial production increases, particularly in the lighter industries; and there is increased demand for transport.
- There is an increase in household energy use, with trends toward using more electricity, LPG, and kerosene in homes.
- There is a considerable increase in commercial sector activity, and a relatively small increase in military sector energy use[24].
- Refurbishment of electric transmission and distribution infrastructure takes place, coupled with refurbishment of existing hydro plants, building of new hydro capacity, the re-starting and expansion of the DPRK's east coast refinery, and partial retirement of coal-fired electricity generating capacity.
- Modest improvements in energy efficiency take place.

This pathway, or one very much like it, may in fact be one of the only ways that DPRK infrastructure can be sufficiently rehabilitated to use within the DPRK even some of the power from nuclear reactors such as those that were being built by KEDO until 2002. There is at present no way to use 1000 MW-class reactors within the existing DPRK grid[25], so to use such a reactor interties to other countries must be constructed, and preferably, from a political and practical perspective, the DPRK grid would need to be totally rebuilt as well. Had the

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[24] Depending on the nature of the diplomatic breakthrough, the degree to which it is embraced by the DPRK leadership, and the economic opportunities it offers to North Korean citizens, it is entirely possible that the DPRK armed forces may be partially demobilized, resulting in lower military energy use. Partial mobilization seemed to be under discussion in the DPRK as of about 2002, just before the start of another period of chilling in the DPRK’s relations with the international community.

[25] Nuclear safety concerns (including back-up power for coolant pumps and controls) and the attributes of a large-capacity nuclear unit operating in a small power grid—the DPRK grid is far below the minimum size to support 1 GW reactors) are key reasons why these reactors cannot operate under current conditions. See D. Von Hippel et al (2001), "Modernizing the US-DPRK Agreed Framework: The Energy Imperative", Nautilus Institute Report, available as http://www.nautilus.org/archives/papers/energy/ModernizingAF.PDF.

construction of the KEDO reactors at Sinpo continued, interconnection issues could have been both a huge problem that could have led to poor relations between the DPRK and the outside for years to come, or, if handled correctly, could have constituted a huge opportunity for building of economic links (and better relations) between the countries of the region. If construction of the LWRs at Sinpo is taken up again in the future, this technical consideration, and its various solutions and non-solutions, will remain.

Given the above considerations, we assume, for the BAU (alias Redevelopment) case, that construction resumes on the LWRs previously started by KEDO (the Korean Peninsula Energy Development Organization) at the Kumho site in the DPRK reactors in approximately the middle of the next decade (say, 2014 or 2015), and construction on the first of the two reactor units is completed by 2020 (1050 MWe). It is further assumed that the DPRK and the ROK are by that time on the road to economic, if not political, integration (if not unification), and the reactor(s) at Kumho are connected to one or two—if no transmission link to the Russian Far East or China is developed—large transmission lines to the ROK. Effectively, the Kumho reactor, at least for the first few years of operation, would be part of the ROK, not DPRK grid, though some power from the ROK grid would likely be provided back to areas of the DPRK. Our assumption is that the second nuclear unit on the Kumho site would not be completed immediately after the first, but that the DPRK and the international community would take some time to make sure that, for example, economic arrangements regarding the first reactor are handled smoothly, IAEA nuclear materials and safety protocols are followed appropriately by the reactor operators (probably a mix of ROK and DPRK workers), and that sufficient training is provided to DPRK officials and workers so that they can appropriately host the facility. We therefore assume that the second reactor on the Kumho site is commissioned in 2026. No other nuclear capacity in the DPRK is assumed to be added through 2050 in this path. We have assumed that nuclear capacity in the DPRK in both the BAU and Maximum Nuclear paths operates at an average capacity factor of 80 percent—below that in the ROK, but perhaps more consistent with a situation where operation of commercial reactors is a new experience.

3.6.2. Maximum Nuclear Path for the DPRK

Our "Maximum Nuclear" capacity expansion path for the DPRK is an accelerated, extended version of the BAU/Redevelopment path described above. Here, a political breakthrough occurs such that economic opening and political reconciliation between the DPRK and other key parties (mainly the US and ROK, but possibly Japan as well) occurs rather rapidly in the next few years, an agreement is reached promptly on the terms and conditions for the completion and operation of the reactors at Kumho, and all of the parties to the agreement adhere to its provisions. Given these admittedly optimistic conditions, we assume that the first of the two LWR units could be completed by 2018, with the second on line in 2020. Further, consistent with greenhouse reduction emissions reduction goals on the Korean peninsula as a whole (and with the Maximum Nuclear path in the ROK), we assume that a second site can be found in the DPRK—probably on the Southwest coast so that the plants can serve both Pyongyang and Seoul--that is suitable for 3 reactor units, each of 1400 MWe (consistent with newer ROK units), which are assumed to go on line in 2026, 2028, and 2030.

3.6.3. Minimum Nuclear Path for the DPRK

There are (at least) two distinct possible "Minimum Nuclear" paths for the DPRK, both of which have the same effective outcome—no new development of nuclear power in the DPRK, including no completion of the Kumho plants, or at least not as nuclear units. A first Minimum Nuclear path might be similar to the "Recent Trends" path we have described in previous publications, in which an international political solution to the DPRK nuclear weapons issue is not forthcoming within the next decade, and as a result the DPRK economy and energy sector continues with only minimal aid and assistance from outside, thus nuclear power—at least on the commercial LWR scale—is not developed. A second type of Minimum Nuclear path could provide the same economic services as in the Redevelopment path, but, perhaps in coordination with a similar policy in the ROK towards a "nuclear free Korean peninsula", would do so using exclusively fossil and renewable fuels.

3.6.4. Extension of Paths Results to 2050

It is assumed that in the BAU/Redevelopment and Maximum Nuclear paths, sites for new reactors are likely to be sufficiently rare/difficult to develop in the DPRK that, coupled with the limited capability of the DPRK (or joint DPRK/ROK) grid to absorb additional nuclear capacity, no additions of capacity take place by 2050 beyond those described above, and none of the plants developed under the BAU or Maximum Nuclear paths will need to be decommissioned before 2050. Figure 3-9 shows the nuclear capacity assumptions through 2050 for each of the three nuclear paths for the DPRK, and Figure 3-10 describes nuclear generation (terawatt-hours) by path through 2050.

Figure 3-9: Nuclear Capacity Paths for the DPRK through 2050 (GWe)

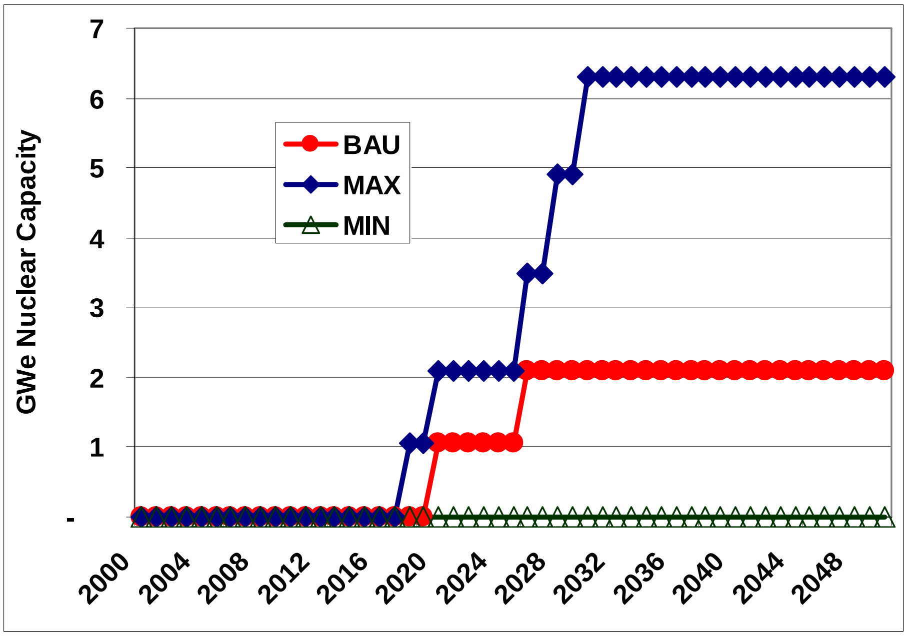
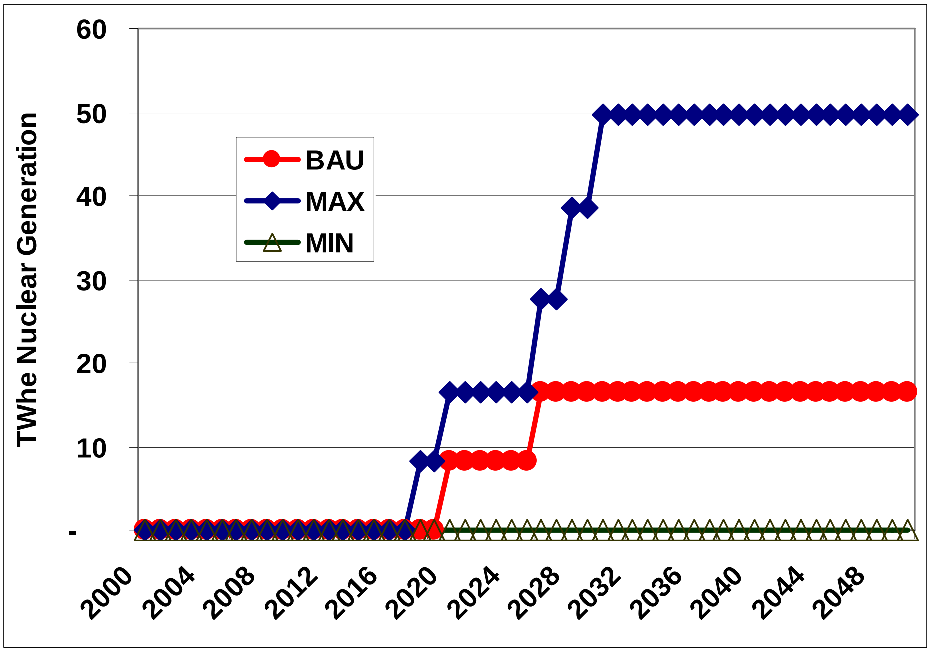


Figure 3-10: Nuclear Generation by Path for the DPRK through 2050 (TWhe)



3.7. Nuclear Energy Paths for China

3.7.1. Business as Usual Path for China

China's nuclear power program, as noted above, started only in the early 1990s, but is set to accelerate rapidly in the coming decade and beyond. For the BAU case, we assume that all of the plants listed in Table 2-4 will be complete and on-line by about 2017, with a further group of plants as named in "Nuclear Power in China" Briefing Paper #68, February 2008[26] assumed to come on line between 2018 and 2030 at an average rate of about 4500 MWe per year. These additions yield a total nuclear generation capacity by 2030 of about 120 GWe, with just under 70 GWe built by 2020. The 2030 BAU capacity is below the 160 GWe target reportedly (World Nuclear Association, 2009) announced in May 2007 by the National Development and Reform Commission. After 2030, we assume that nuclear capacity additions slow somewhat as the overall Chinese economy matures (and population begins to decline); 3000 MWe are assumed to be added annually from 2031 through 2050. Existing nuclear power plants are assumed to be decommissioned after 40 years (LWRs) and 30 years (heavy water reactors), yielding a net nuclear capacity in 2050 of about 170 GWe. We assume that the average capacity factor of Chinese nuclear plants from 2008 onward is 90 percent, which is roughly consistent with experience in the Chinese nuclear industry over the last few years.

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[26] This reference was formerly available at www.uic.com.au/nip68.htm, but is no longer on that site. The (apparently) updated version of this reference, "Nuclear Power in China", a World Nuclear Association Information Paper (dated 5/18/09), available as http://www.world-nuclear.org/info/inf63.html, names many of the same plants in a table labeled "Further nuclear power units proposed", but does not provide estimates of on-line dates.

3.7.2. Maximum Nuclear Path for China

The "Maximum Nuclear" path for China adds nuclear capacity at an even more aggressive rate than the BAU path. We assume that capacity additions will be the same as in the BAU path through 2015, but will add an average of 2000 MWe of nuclear capacity per year beyond what is included in the BAU path from 2015 through 2019, and 3000 MWe per year additional from 2020 through 2030. This pace of additions meets the 160 GWe-by-2030 target of the National Development and Reform Commission (see above). After 2030, we assume that climate change policy and other considerations cause capacity additions to continue at a relatively high rate; 5000 MWe are assumed to be added annually from 2031 through 2050. Existing nuclear power plants are assumed to be decommissioned after 50 years (LWRs) and 30 years (heavy water reactors), yielding a net nuclear capacity in 2050 of about 257 GWe.

3.7.3. Minimum Nuclear Path for China

The "Minimum Nuclear" path for China assumes that, due to a combination of factors that could include the high capital costs of nuclear plants, public concerns about the safety of nuclear power and nuclear spent-fuel disposal, or technological breakthroughs that dramatically reduce the costs of other power sources, nuclear power development in China slows significantly in the coming decades from its recent early pace. Like the Maximum Nuclear path, the Minimum Nuclear path is assumed to add capacity at the same rate as the BAU path through 2015 (that is, completing the reactors now under construction), but will begin to slow after that, with one fewer reactor unit (1000 MWe) added annually from 2016 through 2019, and 2000 MWe per year less capacity additions than in the BAU case from 2020 through 2030. After 2030, we assume that capacity additions cease, but that existing reactors are decommissioned when they reach the end of 40-year operating lifetimes (LWRs) or 30-year lifetimes (heavy water reactors). The combination of these assumptions means that in the Minimum Nuclear path, China's nuclear reactor fleet reaches just under 65 GWe in 2020, peaks at a bit over 93 GWe in 2030, and declines, with decommissioning of early units, to just under 84 GWe by 2050.

3.7.4. Extension of Paths Results to 2050

The extension of the BAU, Maximum Nuclear, and Minimum Nuclear path capacity assumptions to 2050 has been carried out as described above. Naturally, a number of uncertainties affect the accuracy of these assumptions. Uncertainties include the extent to which new reactor types are developed and deployed after 2030, including both new proliferation-resistant and "fail safe" reactor types and, for example, fast breeder reactors designed to extend uranium supplies. Other uncertainties include, as noted in connection with the Minimum Nuclear path, considerations of cost relative to other generation alternatives, and social/political/environmental considerations in China, possibly including local political and other considerations related to power plant siting. Figure 3-11 shows the nuclear capacity assumptions through 2050 for each of the three nuclear paths for China, and Figure 3-12 describes nuclear generation (terawatt-hours) by path through 2050.

Figure 3-11: Nuclear Capacity Paths for China through 2050 (GWe)

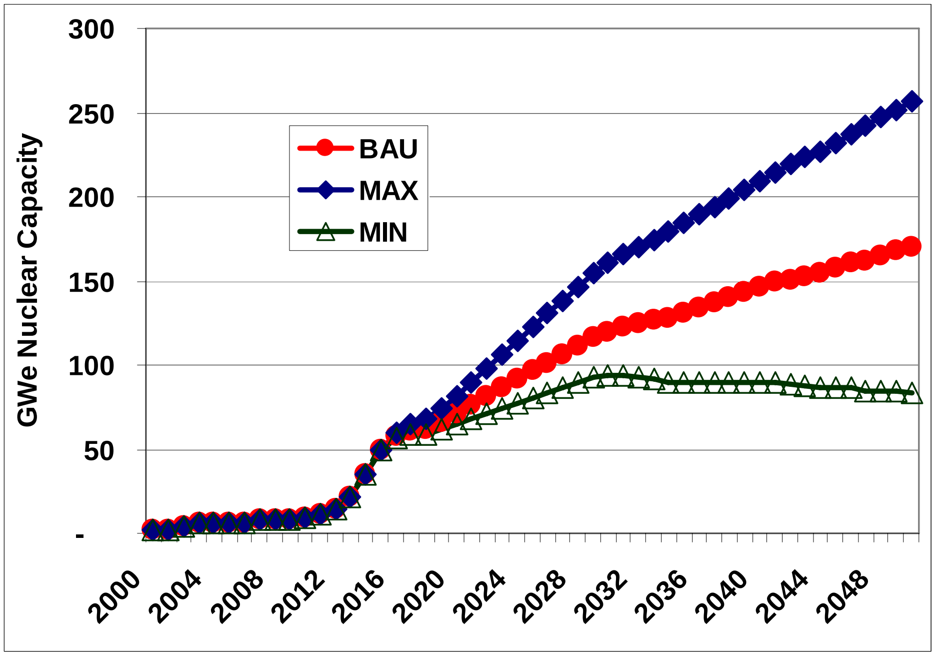
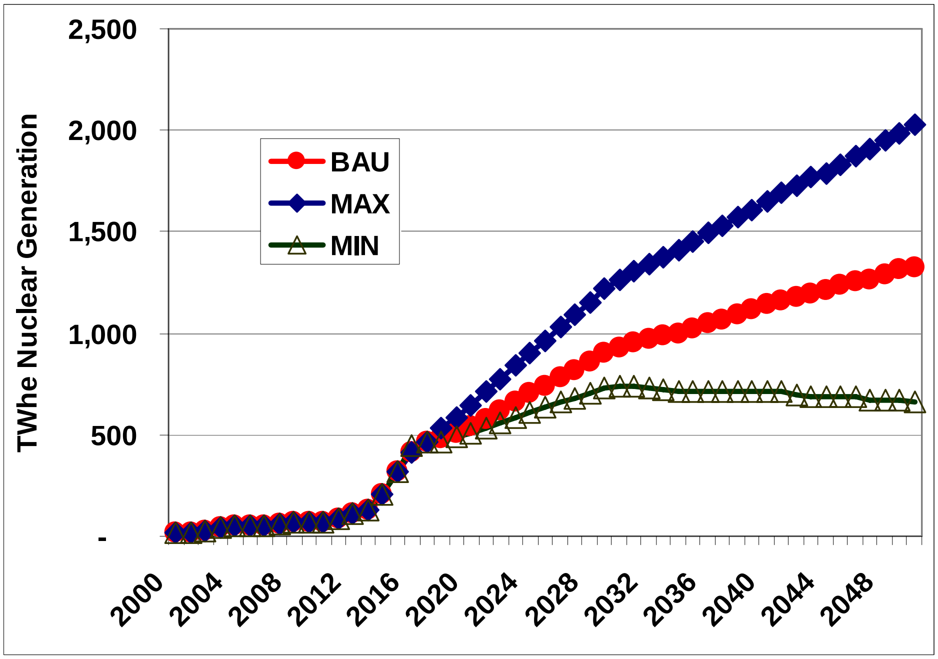


Figure 3-12: Nuclear Generation by Path for China through 2050 (TWhe)



3.8. Nuclear Energy Paths for Russia/Russian Far East

3.8.1. Introduction

As noted in Section 2.6, though Russia as a whole has an extensive nuclear power program, and plans to update and expand its fleet of reactors, the Russian Far East is at present home to only one small nuclear plant that provides electricity and district heat in the far north of the region (the Chukotka area).

In the discussions of BAU, Maximum Nuclear, and Minimum Nuclear paths for the Russian Far East (RFE) presented below, inputs and results are shown only for the RFE, but overall Russian Federation results are provided in summary as well, based on literature sources since nuclear spent fuel generation and enrichment are, and are likely in the future to continue to be, national activities, not confined to the RFE.

3.8.2. Business as Usual Path for Russia and the RFE

Changes in nuclear generation capacity in the RFE through 2030 are based on data provided in Gulidov and Ognev (2007). We assume that a 70 MWe floating nuclear power plant will be brought on line in an as-yet unspecified location in the northern part of the RFE, and a second such unit will be brought on line in 2018 to replace the Bilibinskaya combined heat and power reactors (4 12 MWe units) as they reach the end of their operating lives. The Primorskaya NPP with 600 MWe of capacity (2 x VVER-300 units) is assumed to be implemented in 2017 and 2019 to help meet the increase in domestic power and electricity demand in the RFE. We further assume that a four-unit nuclear plant that has been studied in the past, the “Far Eastern NPP”, located in Khabarovskiy Krai, with 2.56 GW in four VVER-640 units, will be built over the period 2025 through 2028, though this plant is not a firm part of existing plans. It is likely that the output of the Far Eastern NPP would be devoted to electricity exports, and/or to providing electricity for export-oriented industries (such as Aluminum production). We assume that the relatively low historical capacity factor (about 32-34%) of the small nuclear units now in use in the RFE will increase to 70 percent once larger units are constructed late in this decade, and to 80 percent after 2030 once the larger Far Eastern NPP is built.

For Russia as a whole, Gulidov and Ognev (2007), citing the document “General Plan for Electric Power Industry up to 2020”, show “base case” nuclear capacity rising from 23.3 GWe in 2006 to 26.7 GWe in 2010, 37.9 GWe in 2015, and 53.1 GWe in 2020. In a “Max Case”, capacity rises to 58.8 GWe in 2020. An earlier presentation by Dmitriev (2006) shows overall nuclear capacity (“Desirable and expected composition and structure of reactor park of Russia”) rising to 45 GWe in 2020, 55 GWe in 2030 (of which 5 GWe would be fast breeder reactors), and 70 GWe in 2040 (of which 15 GWe would be FBRs).

3.8.3. Maximum Nuclear Path for Russia and the RFE

The Maximum Nuclear path for the RFE follows the BAU path through 2020, but assumes that the development of the Far Eastern NPP is moved forward in time, for completion between 2021 and 2024, and that another reactor complex similar to the Far Eastern NPP are completed in the RFE by 2029, yielding a total nuclear capacity of 5.2 GWe in that year. This path reflects an assumption that exports of power and/or energy-intensive materials to China, Korea, and perhaps Japan will become a focus of activities in the RFE, and that nuclear power will be chosen, perhaps with an eye toward climate change impacts, as one of the key means of producing electricity for export.

3.8.4. Minimum Nuclear Path for Russia and the RFE

The Minimum Nuclear path for the RFE also follows the BAU path through 2020, but thereafter assumes that no further development of nuclear capacity in the RFE takes place, leaving RFE total nuclear capacity at 740 MWe from 2020 through 2050. This path assumes either that markets and infrastructure for export of electricity and/or energy-intensive from the RFE remain substantially undeveloped, or that policies for power sector expansion focus on generation by other means.

3.8.5. Extension of Paths Results to 2050

For the BAU path, we assume that a plant roughly equivalent in capacity to the "Far Eastern NPP" built in 2025-2028 is built in 2035-2038, again designed for export of either power or goods from industries (such as metals or fertilizer) that use considerable electricity. In the Maximum Nuclear path, we assume that two more similar complexes are built in the decade starting 2030, resulting in total RFE nuclear generation capacity of just under 11 GWe by 2039. No changes in capacity in any path are included after 2040, and, as noted above, no changes in RFE nuclear capacity in the Minimum Nuclear path are included after 2020. Figure 3-13 shows the nuclear capacity assumptions through 2050 for each of the three nuclear paths for the RFE, and Figure 3-14 describes nuclear generation (terawatt-hours) by path through 2050.

Figure 3-13: Nuclear Capacity Paths for the RFE through 2050 (GWe)

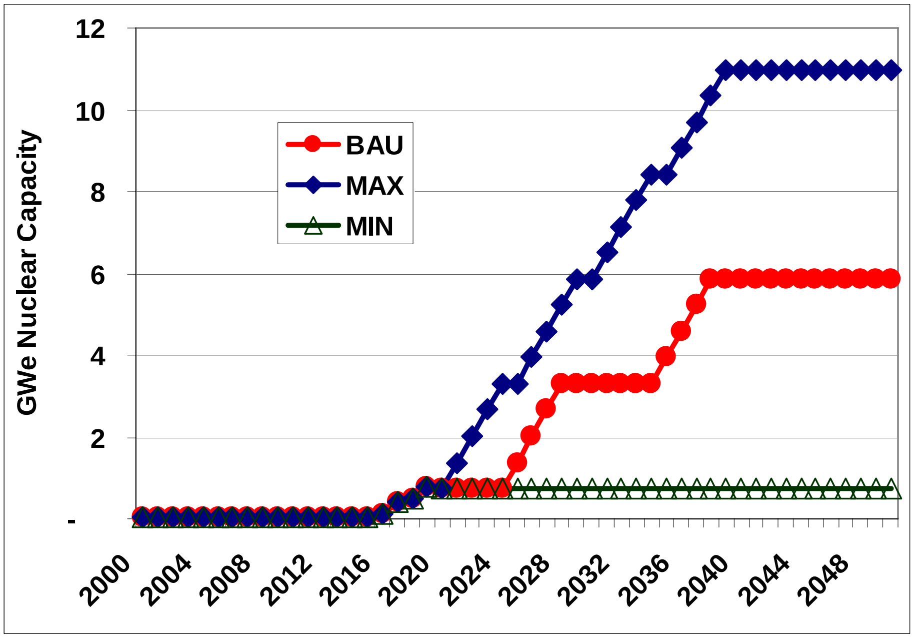
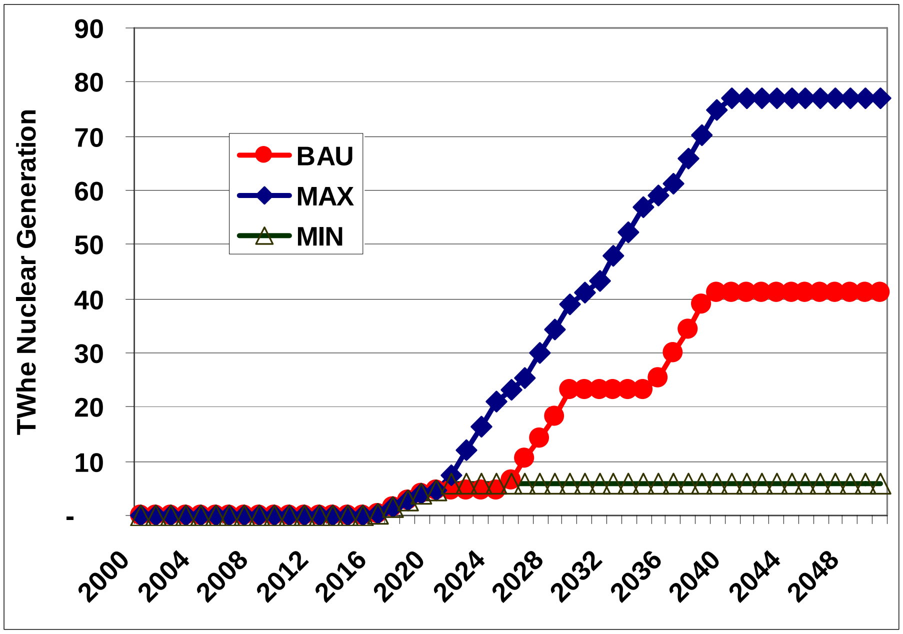


Figure 3-14: Nuclear Generation by Path for the RFE through 2050 (TWhe)



3.9. Nuclear Energy Paths for Australia

As noted in section 2.7, above, Australia currently, although it is a major exporter of uranium, lacks commercial nuclear power reactors, and the social and political prospects for acceptance of nuclear power are at present rather bleak. As a result, the nuclear paths below are of an arguably even more speculative nature than paths for most other countries included in the EASS project.

3.9.1. Business as Usual Path for Australia

Given a current government and a populace that is not, in present, in favor of developing nuclear power on a commercial scale, commissioning of nuclear power reactors in Australia would appear to be relatively far in the future, if they occur at all. For the BAU path, we assume that by late in the decade of 2010, public opinion, perhaps influenced by global climate change concerns, begins to shift, and nuclear power is again considered an option for Australia, but one embraced with caution and as one element of many in addressing climate change. This is, of course, highly speculative. For the BAU path, we assume that a first LWR of about 1 GWe goes on line in Australia in 2025, with additional reactors of similar size commissioned, on average, every five years. By 2050, the total capacity would thus be 6 GWe, about a quarter of the amount included in a higher scenario for nuclear capacity by a Australian taskforce on nuclear power convened in 2006 (Commonwealth of Australia, 2006).

3.9.2. Maximum Nuclear Path for Australia

A Maximum Nuclear path for Australia would require a significant change in public and political attitudes toward nuclear power. Such a change could be the result, as suggested in the context of the BAU path, of global climate change concerns, or of new international agreements for the handling of nuclear spent fuel that the public finds agreeable. We assume, for the Maximum Nuclear path, that the first commercial nuclear reactor in Australia comes on line in 2022 (requiring a change in policy within the next 5 years or so), and new reactors are added every year or two such that total nuclear capacity by 2050 is 20 GW.

3.9.3. Minimum Nuclear Path for Australia

The Minimum Nuclear Path for Australia, in keeping with recent policy trends, includes no commercial nuclear generation capacity through 2050, and no expansion of uranium production capacity beyond the recently added fourth uranium mine.

3.9.4. Extension of Paths Results to 2050

Nuclear power paths for Australia were developed through 2050 as indicated above. Figure 3-15 shows the nuclear capacity assumptions through 2050 for each of the three nuclear paths for Australia, and Figure 3-16 describes nuclear generation (terawatt-hours) by path through 2050.

Figure 3-15: Nuclear Capacity Paths for Australia through 2050 (GWe)

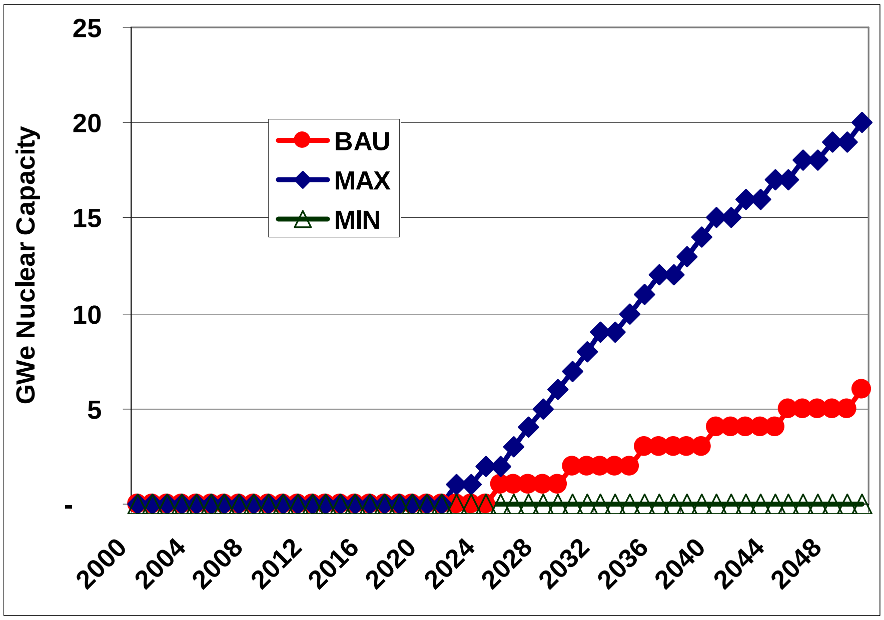
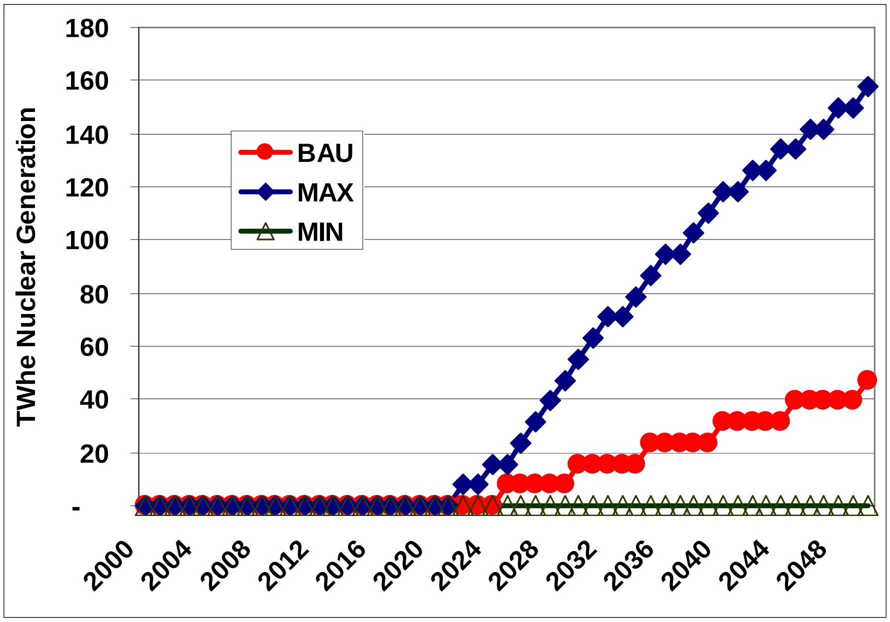


Figure 3-16: Nuclear Generation by Path for Australia through 2050 (TWhe)



3.10. Nuclear Energy Paths for Taiwan

As of 2009, the future of nuclear energy in Taiwan appears to hinge primarily on whether the reactors under construction at the fourth (Lungmen) nuclear power site in Taiwan are ultimately completed, whether the older reactors at other sites are replaced, and what operating lifetime is assumed for the older reactors. These and other factors are addressed in the different nuclear paths described below.

3.10.1. Business as Usual Path for Taiwan

In the BAU path for Taiwan, we assume that political hurdles to completion of the Lungmen reactors are ultimately overcome, resulting in the units being completed and placed on line in 2014 and 2015. Thereafter, we assume that the attitude toward nuclear power in Taiwan remains ambivalent at best, such that all existing plants are retired following completion of their nominal 40-year lifetimes, but only one of the 3 retired pairs of reactors is assumed to be replaced. The Kuosheng reactors are assumed to be retired on schedule, and replaced 2 years later by new 1350 MWe units. The net result of the BAU additions and retirements is that Taiwan's nuclear capacity is 6.75 GWe in 2026 (up from 5.14 GWe in 2009), remaining at that level through 2050. For the BAU and other paths, capacity factors for nuclear plants are assumed to average 85 percent, slightly higher than the average performance of the country's nuclear fleet from 2000 through 2007.

3.10.2. Maximum Nuclear Path for Taiwan

The Maximum Nuclear path for Taiwan parallels the BAU path through 2011. In 2012, we assume that the urgency of providing new power supplies and responding to climate change emission reduction challenges paves the way for the Lungmen reactors to be completed rapidly, with the units going on line in 2012 and 2013. Thereafter, we assume that the operating life of the existing six reactor units is extended to 50 years, and that when that lifetime is reached, units are replaced in the year after decommissioning with new 1350 MWe units. The result is that in the Maximum Nuclear case, Taiwan's nuclear generation capacity reaches 10.8 GWe by 2038 and remains at that level through 2050.

3.10.3. Minimum Nuclear Path for Taiwan

The Minimum Nuclear path for Taiwan assumes that social and political forces combine to cause nuclear power to be phased out over time, presumably as new, inexpensive, renewable sources of energy become available. In this path, the Lungmen reactors are still completed, to take advantage of the investment already made in their infrastructure, but not until 2019/2020. All other reactors are decommissioned promptly as their original 40-year lifetime elapses, and are not replaced. The result of this scenario is that by 2026, only the total 2.7 GWe of the Lungmen plant remains operating, and does so through 2050.

3.10.4. Extension of Paths Results to 2050

Nuclear capacity paths were extrapolated to 2050 as noted above. The central assumption in all three paths is that no new sites for nuclear reactors in Taiwan will to be developed, presumably due to a combination of technical and social/political considerations, and that existing sites cannot accommodate additional units. Figure 3-17 shows the nuclear capacity assumptions through 2050 for each of the three nuclear paths for Taiwan, and Figure 3-18 describes nuclear generation (terawatt-hours) by path through 2050.

Figure 3-17: Nuclear Capacity Paths for Taiwan through 2050 (GWe)

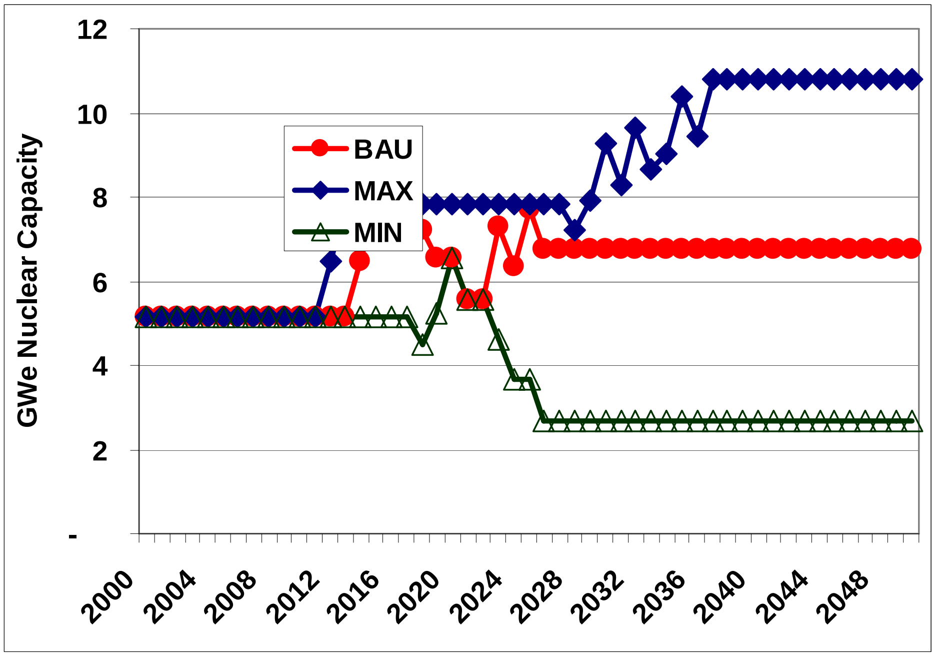
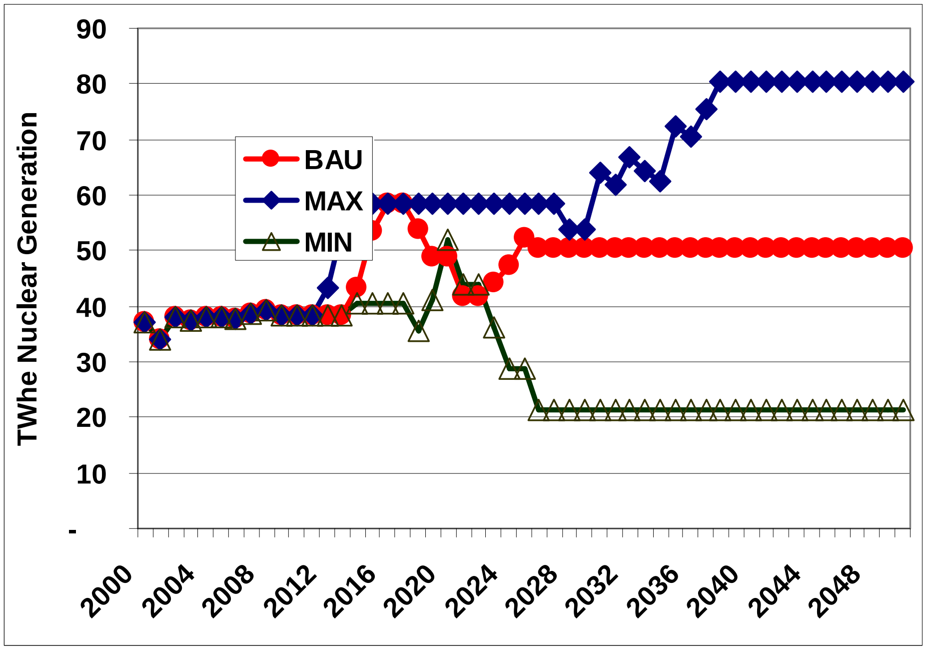


Figure 3-18: Nuclear Generation by Path for Taiwan through 2050 (TWhe)



3.11. Nuclear Energy Paths for Indonesia

Though Indonesia's only nuclear reactors are small research units at present, development of a commercial nuclear power sector in Indonesia has been under discussion for some years. A government plan published in approximately 2005 called for the first of four nuclear reactor units to be under construction in 2010, and operational by 2016[27]. The remaining three reactors included in the plan were to have gone on line in 2017, 2023, and 2024. Since the publication of that plan, social—including local opposition to reactors at the generally preferred site at Muria, on Java—political and other factors have delayed progress on commercial nuclear development. With support from some government and power sector officials, as well as from international reactor vendors, nuclear power remains, however, a part of plans for Indonesia's power sector, though the timing of reactor deployment is far from certain.

3.11.1. Business as Usual Path for Indonesia

For the BAU path, we assume that agreements can be reached regarding the siting of a pair of reactors at a site on Java within the next few years. These reactors, each with a capacity of 1.05 GWe, are assumed to come on line in 2020 and 2021. The BAU path includes no further reactor development before 2030, but does include additional reactors after 2030 (see below). For the BAU and Maximum nuclear cases, an average annual capacity factor of 85 percent is assumed in all years in which reactors operate, and new reactors are assumed to begin producing power for the grid at the beginning of the year in which they are nominally completed.

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[27] See Indriyanto A.R.S., B. T. Wattimena, and F. V. C. Mulia (2007), "Indonesia Energy Overview". Prepared for Prepared for the "Asian Energy Security Project Meeting", Beijing, PRC, October 31-November 2, 2007, and available as http://www.nautilus.org/energy/2007/beijingworkshop/papers/IndonesianEnergy.ppt.

3.11.2. Maximum Nuclear Path for Indonesia

In a Maximum Nuclear path, we assume that the combination of a desire on the part of government to demonstrate progress toward climate change mitigation goals, the desire to reserve domestic oil and gas for export, and other considerations yield a more streamlined development of the first two reactor units, resulting in on-line dates of 2018 and 2019. A second pair of reactors, also located on Java (as the only Indonesian grid large enough to accommodate the units by that time) are assumed to be brought only line in about 2025 and 2026, approximately the same "spacing" as the 2005 government plan described above. Further units are added after 2030 (see below).

3.11.3. Minimum Nuclear Path for Indonesia

We assume that in a Minimum Nuclear Path, commercial nuclear power would not be developed in Indonesia by 2030 (or 2050). Factors that might stymie the development of nuclear power, bringing about a path without nuclear development, include continued and/or expanded social and political opposition to nuclear energy development, concerns about seismic safety at potential nuclear sites in Indonesia, and/or development/deployment of alternative power sources with desirable economic, environmental, or other characteristics.

3.11.4. Extension of Paths Results to 2050

Extension of nuclear paths to 2050 is particularly speculative for application to a country where commercial energy development has not yet really begun. That said, for Indonesia, we assume that in the BAU path, a second pair of nuclear reactors goes on line in 2034 and 2035, most likely in Java, and a third pair of reactors begins operation about 10 years later. The third pair of reactors could be located on an island other than Java, if the grid on that island is by then large enough to support the reactor and/or if interconnections between Indonesian islands and/or with neighboring countries are sufficient to provide the needed grid support.

For the Maximum nuclear case, we assume that approximately twice as much nuclear capacity is developed after 2030 as in the BAU path, with four pair of reactors coming on line in 2031/2032, 2035/2036, 2041/2042, and 2045/2046, respectively.

Figure 3-19: Nuclear Capacity Paths for Indonesia through 2050 (GWe)

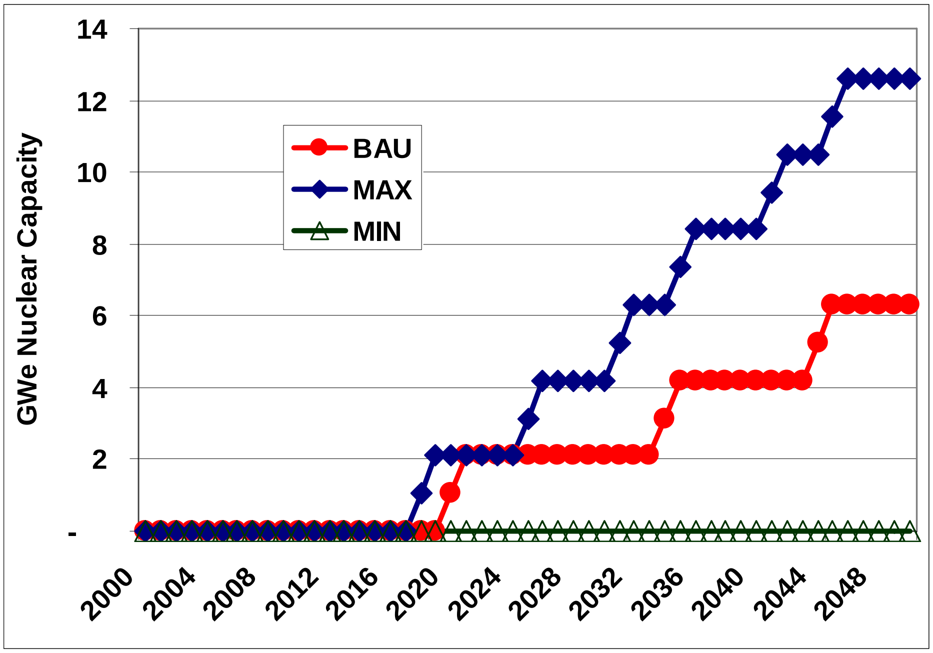
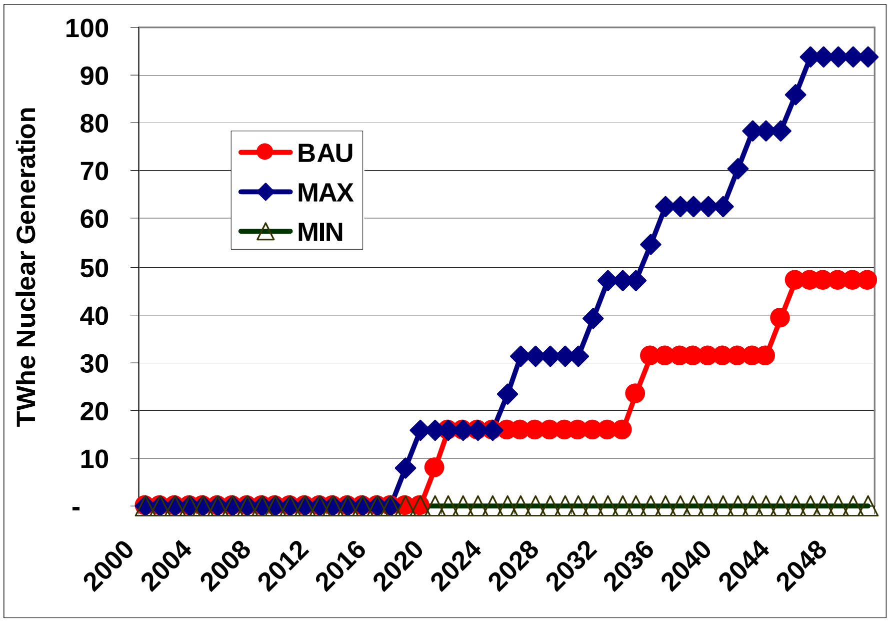


Figure 3-20: Nuclear Generation by Path for Indonesia through 2050 (TWhe)



3.12. Nuclear Energy Paths for Vietnam

Vietnam’s commercial nuclear industry, like Indonesia’s, is still very much in the development phase. Like Indonesia, Vietnam plans the implementation of several reactor units by 2025 (as noted in section 2.12, above). Unlike Indonesia, however, significant resistance to nuclear power in Vietnam has yet to emerge, and Vietnam's relatively limited oil and gas prospects have made nuclear power an attractive option.

3.12.1. Business as Usual Path for Vietnam

The Business As Usual path for Vietnam assumes that the first four reactor units—those included in the most recent existing utility capacity expansion plan—would be built between 2020 and 2024, and that a fifth unit would be added in 2025, and five more units by 2030 (for a total of 10 GWe of capacity), representing a firm commitment to the use of nuclear power as one of Vietnam's generation options. In the BAU path, as well as in the Maximum Nuclear path, an average annual capacity factor for nuclear generation of 85 percent is assumed all years in which reactors operate, and new reactors are assumed to begin producing power for the grid at the beginning of the year in which they are nominally completed.

3.12.2. Maximum Nuclear Path for Vietnam

The Maximum Nuclear Path for Vietnam assumes an even stronger commitment to nuclear power than the BAU path. Here the first nuclear unit also goes on line in 2020, but development of the sector is accelerated such that by 2025 there are 11 reactor units operating, with 15 units (totaling 15 GWe) by 2030.

3.12.3. Minimum Nuclear Path for Vietnam

As with Indonesia, we assume that in a Minimum Nuclear Path, commercial nuclear power would not be developed in Vietnam by 2030 (or 2050). Factors that might stymie the development of nuclear power, bringing about a path without nuclear development, include the development of social and political opposition to nuclear energy development, perhaps as a result of nuclear incidents at reactors in other countries, or unexpectedly high reactor costs. Development/deployment of alternative power sources, especially solar power, with desirable economic, environmental, or other characteristics for Vietnam relative to nuclear power might also be expected to reduce the drive to develop the nuclear sector.

3.12.4. Extension of Paths Results to 2050

In each of the BAU and Maximum Nuclear paths, we assume that the rate of nuclear power development slows somewhat as the Vietnamese economy matures (and the rate of growth of electricity requirements declines), such that in each path nuclear capacity doubles between 2030 and 2050.

Figure 3-21: Nuclear Capacity Paths for Vietnam through 2050 (GWe)

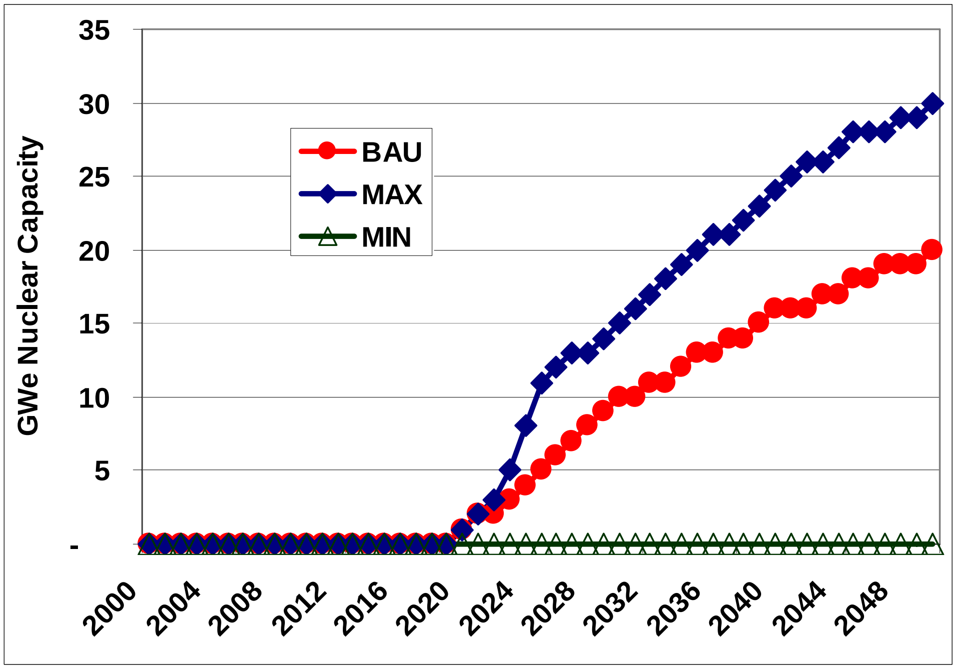
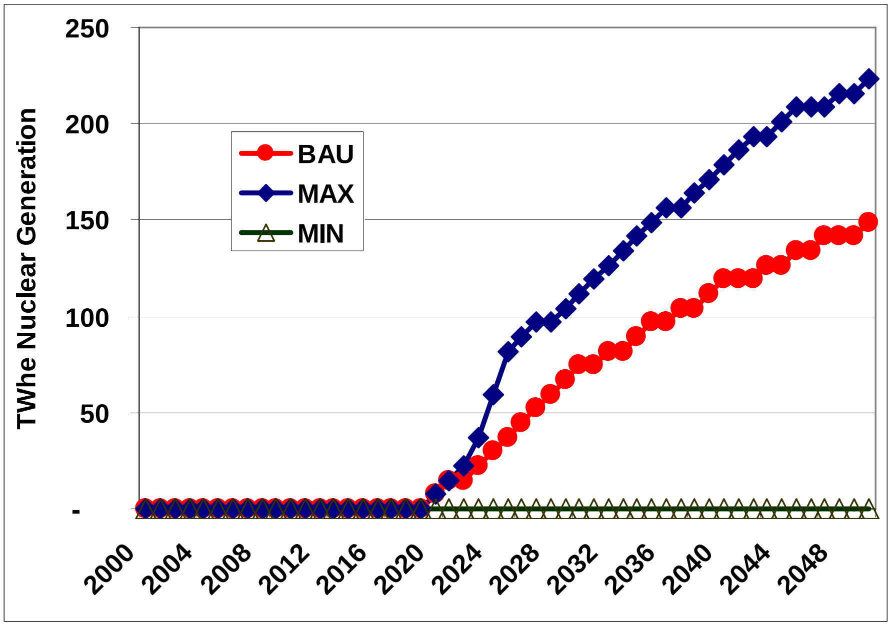


Figure 3-22: Nuclear Generation by Path for Vietnam through 2050 (TWhe)



4. Regional Nuclear Fuel Cycle Options

4.1. Introduction

Cooperation on nuclear fuel cycle activities could take place between all of the countries of East Asia and the Pacific whose nuclear energy activities and plans were described in Chapters 2 and 3, or a narrower group of several countries within the region, or a broader group of countries that could include nations outside the region. At their least demanding (in terms of costs and institutional arrangements between nations), cooperation options can involve relatively modest types of activities such as straightforward scientific, educational, and technical exchanges, to collaborations (for example, through the IAEA or other international agencies) on sharing of information on nuclear "best practices". More complex options include consortiums for purchasing of raw uranium or of enriched fuel. More complex still are arrangements to share enrichment and spent-fuel management facilities. An IAEA Expert Group in 2005 produced a generic review of multilateral approaches to the nuclear fuel cycle, and some of that group's observations and suggestions are reflected in the proposals by other groups summarized below, as well as in the regional cooperation scenarios elaborated and evaluated in this Report[28]. A few of the benefits—and challenges—of regional cooperation on nuclear fuel cycle issues are described below[29].

Potential Benefits of Cooperation

- Scientific, educational, and technical exchanges on nuclear fuel cycle issues help to assure that countries have a common understanding and knowledge base with regard to fuel cycle issues. Such exchanges help provide countries new to nuclear power with a good grounding in the issues, while assuring cooperating countries and the international community more broadly of the competence of nuclear scientists and technicians in new nuclear countries, and creating long-term connections between nuclear energy experts in different nations.
- Sharing nuclear facilities, whether then are enrichment, reprocessing, or spent-fuel facilities, provides viable alternative for countries that may, due to political, social, geological, or other concerns, have few positive prospects for domestic siting of such facilities.
- Achieving economies-of-scale for enrichment facilities, reprocessing centers, or geologic repositories might be another reason to undertake cooperation activities. A large-capacity repository could offer economic benefits for the host and participating countries, allowing partners to achieve substantial economies of scale by sharing fixed capital costs, operating costs, and financial liabilities. A regional/international storage facility (using, for example, dry-cask storage), unlike a repository, offers few economies of scale because the cost per kilogram for storing fuel from a single reactor is only modestly higher than the cost per kilogram for storing fuel from dozens of reactors[30].

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[28] IAEA (2005), Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report submitted to the Director General of the International Atomic Energy Agency. Document # INFCIRC/640, dated 22 February 2005, and available as http://www.iaea.org/Publications/Documents/Infcircs/2005/infcirc640.pdf.

[29] Some of the text in this section is adapted from Kang, J. (2007), Regional Spent Fuel Management in Northeast Asia: Status, Initiatives, and Issues. Prepared for the Nautilus Institute East Asia Science and Security Collaborative project.

[30] Bunn, M. and et al. (2001), Interim Storage of Spent Nuclear Fuel: A Safe, Flexible, and Cost-Effective Near-Term Approach to Spent Fuel Management. A Joint Report from the Harvard University Project on Managing the Atom and the University of Tokyo Project on Sociotechnics of Nuclear Energy. June 2001.

- Creating a new revenue source for a host country. The host country that accommodates a regional/international repository or other large fuel-cycle facility could receive significant income through payments by participating countries.

- Sharing nuclear facilities may help to assure that all countries maintain consistent practices and quality control standards in working with nuclear materials, as well as consistent levels of safeguards, monitoring, and verification in nuclear fuel cycle activities. As such, sharing facilities may help to build confidence between nations.

- Sharing of spent-fuel and reprocessing facilities can help to reduce proliferation risks by avoiding unnecessary accumulation of separated plutonium. Some countries want to develop reprocessing capacity largely because they lack the means to dispose of their spent fuel. A regional/international repository would offer an alternative place for spent fuel and thus avoid unnecessary reprocessing.

Potential Challenges Involved in Cooperation

Implementing regional or international facilities, including those for spent fuel/radioactive waste storage/disposal, will likely involve overcoming obstacles such as:.

- Ethical issues in the region. There is some public perception that countries that have the benefits of nuclear power generation should bear the burden of storing and disposing of their radioactive wastes. This argument raises ethical and fairness issues that would oppose the concept of a regional/international repository. To obtain public and political support, an arrangement for the regional/international repository should be based on a fair and equitable sharing of benefits between a repository host and other participating countries.

- Complicating national policies in the management of spent fuel/HLW. The regional/international repository could distract national spent fuel and radioactive waste management programs with hopes for an international facility. If such a facility is not forthcoming, or is delayed in implementation, national needs for spent fuel management could become critical without national solutions being in place.

- Increasing transportation requirements in the region. The regional/international repository will involve frequent transportation of spent fuel/radioactive waste from participating countries to a host country, and increasing concern over nuclear accidents during the transportation that may lead radioactive release to the environment. Proliferation risks due to diversion of materials during transport are also a concern.

In the remaining sections of this chapter, we summarize some of the many previous proposals for regional fuel cycle activities in East Asia (or potentially involving East Asia), then provide descriptions of the four nuclear fuel cycle cooperation “scenarios” (of which one is, essentially, lack of cooperation) that are analyzed in this Report.

4.2. Previous Proposals for Regional Fuel Cycle Activities in East Asia

Regional (East Asia), and indeed, global nuclear fuel cycle cooperation proposals have been offered by a number of groups and individuals over the past two decades and earlier. Below we provide brief descriptions of these prior proposals[31].

4.2.1. Proposals for Nuclear Sector Cooperation During the 1990s and Before

Interest in regional/international spent fuel/radioactive waste storage/disposal increased significantly in the 1970s and early 1980s. In 1977, the IAEA reported that regional fuel cycle centers were feasible and would offer considerable nonproliferation and economic advantages. In 1982, the IAEA concluded a project of the International Fuel Cycle Evaluation (INFCE) in which IAEA expert groups suggested an establishment of international plutonium storage and international spent fuel management (Bunn and et al., 2001).

In the mid-1990s, the concept of the International Monitored Retrievable Storage System (IMRSS) was proposed by Wolf Hafele. The IMRSS envisioned international sites where spent fuel, and possibly also excess separated plutonium, could be stored under monitoring for an extended period but could be retrieved at any time for peaceful use or disposal[32].

In the mid-1990s through the late 1990s, a number of proposals for nuclear power sector cooperation in the Asia-Pacific region, on topics ranging from safety to proliferation to waste management, were developed. Tatsujiro Suzuki summarized a comparison of various proposals for regional nuclear cooperation offered during the period, and concluded that there are potential areas of cooperation where common needs and interests exist. Table 4-1 (from Kang, 2007, after Suzuki, 1997, and Tanabe and Suzuki, 1998) provides a brief description of those proposals. At present, none of these proposals have been implemented to a significant degree.

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[31] Documents by other authors, including, for example, Y. Yudin (2009), Multilateralization of the Nuclear Fuel Cycle: Assessing the Existing Proposals, United Nations Institute for Disarmament Research, report # UNIDIR/2009/4, available as http://www.unidir.ch/pdf/ouvrages/pdf-1-978-92-9045-195-2-en.pdf, provide a more thorough review of the proposals described below and other proposals than can be offered in this Report.

[32] Hafele, W. (1996), "The Concept of an International Monitored Retrievable Storage System". In: Uranium Institute Symposium, London, UK, August 1996.

Table 4-1. Comparison of Various Late-1990s Proposals for Regional Nuclear Energy Cooperation in the Asia-Pacific Region[33]

	Area of Cooperation								
	Promotion of peaceful use of nuclear power					Prevention of nuclear proliferation			
	Safety	Public Relations	Industry Co-operation	Spent Fuel Mgt.	Waste Mgt.	Regional Safe-guards	Pu Mgt	Non-Prolif. Export Control	Nuclear Disarm.
A	x		x	x	X	X		X	
B	x	X	x	x	x	x		x	X
C	x	X	x	x	x			X	
D	x		X(enrich)	x	x	(x)			
E	x		X						
F				x	X(R&D)			(x)	
G	X			X				X	
H	X			X	X	X	X	X	X
I	X			X	X	(x)	(X)	X	
J	X			X	X	X	X	X	
K	X		X(R&D)	X	X		X	X	
L	X			X	X	X	X	X	
M	x								

<u>Notes for Table 4-1</u>: Large "X" means that a proposal puts emphasis on the topics noted in the column headings, while small "x" means that a proposal discusses the item but with relatively less importance.

Identification of Proposals described in Table 5

A: ASIATOM (H. Murata, 1997)

B: ASIATOM (K. Kaneko, 1996) – Treaty

Both proposals A and B address all aspects of nuclear energy cooperation, including non-proliferation aspects of regional cooperation. Murata's proposal specifically addresses "regional safeguards" systems, while Kaneko's proposal was detailed with the draft charter of the Aisatom scheme, which is quite comprehensive.

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[33] Notes to Table 4-1 are based on data in Suzuki, 1997 and Tanabe and Suzuki, 1998, and from private communication with Tatsujiro Suzuki, Dec. 5, 2007.

C: PACIFICATOM (T. Kano, 1995) – Open Frame

Although Kano's proposal also addresses a comprehensive scheme, it emphasizes cooperation on the civilian nuclear energy side, rather than on non-proliferation.

D: R. Imai, 1995

Imai's proposal put the emphasis on a “nuclear fuel cycle center” concept, especially for enrichment, but does also address waste management and possible reprocessing.

E: T. Sakairi, 1997 – Safety Centre

The “Asian Nuclear Safety Centre” proposal, offered by Sakairi, lists specific areas that are not effectively covered by existing organizations or international arrangements. Examples of potential areas of cooperation include emergency aid, evaluation visits, and transfer of specific equipment needed to improve safety. In order to achieve these objectives, Sakairi proposes that the basic characteristics of the Asiatom organization should be “hybrid,” i.e. a non-governmental organization with full governmental support.

F: A. Suzuki, 1996 – Project basis

A. Suzuki specifically proposed the establishment of “East Asian Collaboration for Intermediate Storage (EACIS)”, which was to be devoted only to spent fuel storage within a definite period of operation. By not deciding the eventual fate of stored spent fuel, which could either be reprocessed or directly disposed of, this proposal was intended to avoid conflicts over the ultimate disposition of the spent fuel among the interested nations. A. Suzuki (1996) also proposed the establishment of an “East Asian Collaboration for Underground Research (EACUR).” The EACUR facility was to be devoted not to the purpose of final disposal, rather to R&D on technologies needed for geological disposal of radioactive waste. Such collaborations do exist among researchers in the US and Western Europe, but not among researchers in Asian countries as of yet. This is another potential area that all nations in the region can find useful.

G: K. Uematsu, 1996

H: PACATOM (R. Manning, 1996)

I: W. Dircks, 1995

J: Regional Compact (J. Choi, 1996)

K: Y.M. Choi, 1996 (KAERI)

L: J. Carlson, 1996 (AUS)

All of the 6 proposals above (G, H, I, J, K and L) discuss specific aspects of regional safeguards or nuclear fuel cycle center concepts. Uematsu is more positive on reprocessing and recycling, while all of the other variants are not so positive on these topics and thus emphasize regional spent fuel management schemes to discourage reprocessing. While the EURATOM regional safeguards model was often cited as a model, all of the proposals emphasize the geopolitical difficulties among East Asian countries and the need for confidence building measures among them.

M: ANSCO, 1997 (KAIST)

The “Asia Nuclear Safety Consultation Organization (ANSCO)” proposed by the Korea Advanced Institute of Science and Technology (KAIST, 1997) also addresses the issue of nuclear safety in Asian region. This proposal is the only proposal that a governmental organization has offered concerning regional nuclear cooperation in the Asian region. The main purposes of ANSCO were described as promoting “discussion and consultation on nuclear safety related issues and implementation of cooperation programs”, and providing guarantees of “prompt and effective response and cooperation in nuclear emergency situations” in the area.

4.2.2. Proposals for Enrichment Cooperation

As with cooperation on management of nuclear spent fuels, proposals for cooperation on uranium enrichment, many involving East Asian and Pacific countries, have been offered for at least two decades. The following summarizes some of the proposals on international enrichment and/or LEU fuel supply cooperation that have come forth in the last 10 years or so[34].

- The **Global Nuclear Energy Partnership (GNEP)**, proposed by the United States during the George W. Bush administration (in 2006), had as its enrichment component a proposal to establish a group of enriched fuel supplier states, and a requirement that those states provide enriched fuel to non-supplier nations at a reasonable cost, while reducing the potential for proliferation of sensitive technologies, in part through cooperation with the IAEA on nuclear safeguards[35]. The GNEP “Statement of Principles” reads in part[36]:

  > “Establish international supply frameworks to enhance reliable, cost-effective fuel services and supplies to the world market, providing options for generating nuclear energy and fostering development while reducing the risk of nuclear proliferation by creating a viable alternative to acquisition of sensitive fuel cycle technologies.”

  A weakness of GNEP was that it encouraged countries that are currently not enrichment suppliers to quickly develop or acquire enrichment technologies, so as to be among the “haves” (as opposed to “have-nots” in GNEP. GNEP has received setbacks in recent years when the U.S. Congress cut funding to the program in 2008, and eliminated funding (except for a parallel but related “Advanced Fuel Cycle Initiative” that funds reprocessing research and development) for 2009[37].

- The **International Uranium Enrichment Center (IUEC) and LEU Nuclear Fuel Bank**, was proposed by Russia in 2006, and initiated by Russia shortly thereafter. The concept is

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[34] Several of these proposals are noted in T. Suzuki and T. Katsuta (2009), “A Proposal of Multilateral Nuclear Fuel Cycle Approach: “International Nuclear Fuel Management Arrangements (INFA)””, presentation prepared for A-MAD Project Mini Workshop on Policy Recommendations for Nuclear Disarmament and Non-proliferation, September, 2009, and available as http://a-mad.org/download/MNA_Suzuki_Katsuta_AMAD_090930.pdf

[35] GNEP and other enrichment cooperation proposals are discussed in L. Tomero (2008), “The future of GNEP: The international partners”, Bulletin of the Atomic Scientists web edition, dated 31 July 2008, available as http://www.thebulletin.org/web-edition/reports/the-future-of-gnep/the-future-of-gnep-the-international-partners.

[36] Global Nuclear Energy Partnership (GNEP, 2007), Global Nuclear Energy Partnership Statement of Principles, available as http://gneppartnership.org/docs/GNEP_SOP.pdf.

[37] World Nuclear Association (2009), “Global Nuclear Energy Partnership”, last updated November, 2009, and available as http://www.world-nuclear.org/info/inf117_gnep.html.

for Russia to host the IUEC at its existing Angarsk Electrolytic Chemical Combine[38]. Membership in the enrichment center, intended to be on an "equal and non-discriminatory basis", requires charter states to forego developing their own enrichment facilities, and be in compliance with their nonproliferation obligations (including membership in the Treaty on the Non-Proliferation of Nuclear Weapons). Russia's enrichment technology, under this arrangement, is not to be revealed to member states (that is, to remain a "black box" to users). In 2007, the proposal was augmented to include creation of a "Fuel Bank", also at Angarsk, of two 1000-MW reactor loads of low-enriched uranium so as to assure supply to member countries. This LEU fuel bank is to be controlled, and its operation safeguarded, by the IAEA, in part to assure participating nations that their fuel supply would not be vulnerable to political decisions by fuel suppliers. In November, 2009, the IAEA Board of Governors agreed to the creation of a Fuel Bank in Russia, and authorized the IAEA Director General to "to conclude and subsequently implement the Agreement with the Russian Federation to establish a reserve of LEU for supply to the IAEA for its Member States…"[39].

- In 2006, **NTI (the Nuclear Threat Initiative)** pledged $50 million toward an **International Fuel Bank** to be run by the IAEA. Since then, $100 million in matching contributions have been pledged by countries including the United States, Norway, the United Arab Emirates, Kuwait, and the European Union, reaching NTI's matching funds threshold by early 2009. Similar to the Russian proposal, but not affiliated with a specific enrichment center, the goal of the Fuel Bank concept by NTI "…is to help make fuel supplies from the international market more secure by offering customer states, that are in full compliance with their nonproliferation obligations, reliable access to a nuclear fuel reserve under impartial IAEA control should their supply arrangements be disrupted. In so doing, it is hoped that a state's sovereign choice to rely on this market will be made more secure.[40]" As of early 2010, the IAEA was planning to site the LEU repository at a remote site in Kazakhstan, at a metallurgical factory with existing storage infrastructure. The facility would store 60 tonnes of LEU reactor fuel, and "the [IAEA] would assume complete control of the Kazakh site as well as ownership of the nuclear material it would store.[41]" The NTI proposal has not yet been voted upon by the IAEA Board of Governors, but may be taken up at the Board's meeting in June, 2010[42].
- In April of 2007, **Germany** proposed to the IAEA the creation of **a multilateral enrichment facility**, established by a group of interested states, to be placed in a host states but on an "extraterritorial basis"[43]. Like the Russian proposal, and similar to the Fuel Bank NTI

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[38] A. Loukianova (2008), "The International Uranium Enrichment Center at Angarsk:A Step Towards Assured Fuel Supply?", NTI Issue Brief, updated November, 2008, available as http://www.nti.org/e_research/e3_93.html.

[39] IAEA (2009), Request by the Russian Federation regarding its Initiative to Establish a Reserve of Low Enriched Uranium (LEU) for the Supply of LEU to the IAEA for its Member States: Resolution adopted by the Board of Governors on 27 November 2009. Document GOV/2009/81, dated 27 November 2009, and available as http://www.iaea.org/Publications/Documents/Board/2009/gov2009-81.pdf.

[40] NTI (2009), NTI/IAEA Fuel Bank Hits $100 Million Milestone; Kuwaiti Contribution Fulfills Buffett Monetary Condition, NTI press release dated March 5, 2009, available as http://www.nti.org/c_press/release_Kuwait_Fuel_Bank_030509.pdf.

[41] NTI (2010), "IAEA to Pursue Nuclear Fuel Bank in Kazakhstan". Global Security Newswire, dated Jan. 11, 2010, available as http://gsn.nti.org/gsn/nw_20100111_3105.php.

[42] D. Horner (2010), "IAEA Board Approves Russian Fuel Bank Plan". Arms Control Today » January/February 2010, available as http://www.armscontrol.org/act/2010_01-02/FuelBank.

[43] T. Rauf and Z. Vovchok (2007), "Fuel for Thought". IAEA Bulletin 49-2, March 2008, pages 59-63, available as http://www.iaea.org/Publications/Magazines/Bulletin/Bull492/49204845963.pdf. This publication provides brief description of

proposal, the facility would help assure supplies of enriched fuels to nations that qualify based on adherence to their non-proliferation treaty commitments and related IAEA safeguards. The core elements of this proposal are 1) that the host country would "cede administration and sovereign rights" over an area to the IAEA; 2) that states or firms could form agreements with the IAEA to erect commercial enrichment plants, with arrangements such that no competitive advantage (relative to others in the enrichment market) would accrue to the firms in the IAEA-administered area; and 3) that the IAEA draw up a list of criteria that states would need to meet in order to receive shipments of enriched fuel from the facility[44]. This concept would not involve limits on the use of nuclear technology beyond those imposed by the Non-proliferation Treaty, and would not involve the transfer of enrichment technology to the IAEA. Also, the plant would be run as a commercial market enrichment service, and administered by the IAEA as, effectively, the "state body", but not subsidized or run in the commercial sense by the IAEA.

- The so-called **"Six-Country" Proposal of a Nuclear Fuel Assurance Backup System**, offered in 2006 by the enriched fuel supplier nations France, Germany, the Netherlands, Russia, the United Kingdom, and the United States, proposed that enrichment suppliers would substitute enrichment services for each other to cover supply disruptions for enriched fuel consumers that have "chosen to obtain suppliers on the international market and not to pursue sensitive fuel cycle activities". Further, the proposal would provide "physical or virtual" reserves of LEU fuel for use in the event that other fuel assurances fail[45].
- Also in 2006, **Japan** proposed an **IAEA Standby Arrangements System for the Assurance of Nuclear Fuel Supply**. This system would be managed by the IAEA and would offer information, provided voluntarily by nuclear fuel supplier countries, on the status of uranium ore, reserves, conversion, enrichment, and fuel fabrication in each country. The goal of this system is to help prevent disruption in international fuel supplies by acting as a kind of "early warning" system of impending supplier shortfalls for states purchasing fuel or fuel services. If a disruption in supply takes place, under this system, the IAEA acts as intermediary in helping a consumer country find a new supplier country[46].

4.2.3. Recent Proposals for Integrated Cooperation on Spent Fuel Management and Enrichment

In the 1990s, a commercial group called Pangea was looking for an international geologic repository for both spent fuel and radioactive wastes. Envisioning a facility for disposing of 75,000 MT heavy metal of spent fuel/HLW, Pangea initially selected Australia for its proposed

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12 multilateral fuel cycle proposals, most focusing on enrichment and LEU fuel banks, and including the proposal described above.

[44] IAEA (2007), Communication received from the Resident Representative of Germany to the IAEA with regard to the German proposal on the Multilateralization of the Nuclear Fuel Cycle. IAEA document # INFCIRC/704, dated 4 May 2007, and available as http://www.iaea.org/Publications/Documents/Infcircs/2007/infcirc704.pdf.

[45] United Nations Institute for Disarmament Research (2009), UNIDIR project "Multilateral Approaches to the Nuclear Fuel Cycle". Available as www.unidir.org/pdf/activites/pdf3-act396.pdf.

[46] Rauf and Vovchok (2007), as cited above, and Y. Yudin (2009), Multilateralization of the Nuclear Fuel Cycle: Assessing the Existing Proposals, United Nations Institute for Disarmament Research, report # UNIDIR/2009/4, available as http://www.unidir.ch/pdf/ouvrages/pdf-1-978-92-9045-195-2-en.pdf,

repository, but is seeking other sites around the world after confronting political opposition in Australia (Bunn and et al., 2001).

During the late 1990s to early 2000s, two proposals involving depository sites in Russia were presented. One is a concept of the Nonproliferation Trust (NPT) that called for establishing a dry cask storage facility in Russia that would accept 10,000 MT heavy metal of spent fuel from abroad, and would include eventual spent fuel disposal. The other is a concept offered by MINATOM[47], which suggested a plan for an international spent fuel service involving offering temporary storage with later return of the spent fuel, or reprocessing of spent fuel without return of plutonium or radioactive wastes for customer countries (Bunn and et al., 2001).

In 2003, Dr. Mohamed El Baradei suggested multinational approaches to the management and disposal of spent fuel and radioactive waste (El Baradei, 2003). In 2005, commissioned at Dr. M. El Baradei's suggestion in 2003, the IAEA published a report on Multilateral Approaches to the Nuclear Fuel Cycle in which the IAEA concluded that such approaches are needed and worth pursuing, on both security and economic grounds (IAEA, 2005).

In January 2006, Russian President Vladimir Putin announced a Global Nuclear Power Infrastructure (GNPI) initiative to provide the benefits of nuclear energy to all interested countries in strict compliance with nonproliferation requirements, through a network of international nuclear fuel cycle centers (INFCC). INFCC are conceived as being related to the provision of enrichment services and to spent fuel management issues through the provision of reprocessing and the disposal of residual waste within the framework of INFCC, under IAEA safeguards (Ruchkin and Loginov, 2006).

In February 2006, the U.S. George W. Bush administration proposed the Global Nuclear Energy Partnership (GNEP) in which the GNEP proposed fuel supply guarantees and take back arrangements. The goal of GNEP is to establish and sustain "cradle to grave" fuel services or leasing arrangements over time and at a scale commensurate with the anticipated expansion of nuclear energy by helping to solve the nuclear waste challenge[48].

In 2008, Tatsujiro Suzuki and Tadahiro Katsuta proposed the idea of an "International Nuclear Fuel Management Association (INFA)" as a multilateral nuclear fuel cycle approach (Suzuki and Katsuta, 2008). The central principles of the INFA are universality, meaning avoiding discrimination between nuclear "haves" and "have nots", transparency, meaning that the IAEA "Additional Protocol" or equivalent safeguards arrangements should be applied for all facilities, and demand should come first before supply, and economic viability, meaning that the activities of the Association should be consistent with global nuclear fuel market activities, and that the economic rationale of the Association should be clearly defined to support nuclear fuel cycle programs. Suzuki and Katsuta summarized the concepts of the INFA proposal as being:

1. A non-governmental approach is used to help induce private corporations to participate, with possible examples being the World Association of Nuclear Operators (WANO), and the World Institute for Nuclear Security (WINS). As such, consumers and suppliers would share in the management responsibility
2. Demand comes first before supply

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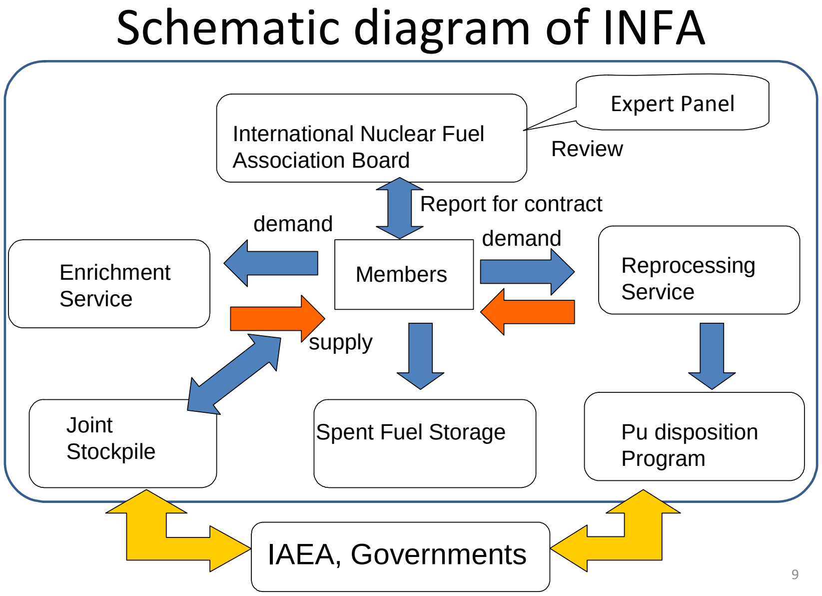
[47] Ministry for Atomic Energy of Russia

[48] US DOE, July 2007. GNEP Overview Fact Sheet.

3. Fuel assurance, in which suppliers get assured demand, and buyers get assured supply, with competitive prices and joint stockpile arrangements providing an emergency backup
4. Spent Fuel Management, in which on-site dry cask storage as the first priority, and nuclear fuel suppliers will have a backup "emergency spent fuel storage capacity" if no capacity (site) is found.
5. A plutonium disposition program in which “Excess plutonium" specified by the owners will be disposed by a private consortium (with government funding assistance).

Figure 4-1 shows a diagram of the INFA concept (from Suzuki and Katsuta, 2008).

Figure 4-1:



4.2.4. Conclusion: Previous Proposals as a Source of Ideas for East Asia Regional Cooperation

Table 4-2, below (from Braun, 2006[49]), provides a comparison and summary of several of the proposals for enrichment and integrated fuel cycle cooperation described above. These and the many other proposals for cooperation on elements of the nuclear fuel cycle, and in some cases for the fuel cycle as a whole, provide a rich source of ideas for design of a regional nuclear fuel cycle cooperation approaches in East Asia. We have drawn, implicitly or explicitly, on some of these designs in the nuclear fuel cycle “scenarios” evaluated for this project, but much

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[49] C. Braun (2006), “Technical Review of Fuel Assurance Proposals”. Presentation at the IAEA Special Event on: “New Framework for the Utilization of Nuclear Energy in the 21st Century: Assurance of Supply and Nonproliferation”, Vienna, Austria, September 20, 2006. Available as www.pub.iaea.org/mtcd/meetings/PDFplus/2006/cn147-braun.pdf.

further work, including more detailed “mining” of previous proposals, will be required to elaborate East Asian nuclear fuel cycle cooperation opportunities that prove attractive.

Table 4-2: Summary of Selected Cooperation Proposals

	Multilateral Approaches INFCIRC/640[50]	**Russian Nuclear Centers**	**U.S. GNEP Initiative**	**WNA Proposal**[51]	**Six Countries Proposal**
Problem to be Solved	Replacing National Facilities with Regional Fuel Center Facilities	Giving Up Sensitive National Fuel Cycle Facilities	Giving Up Sensitive National Fuel Cycle Facilities	Disrupted Enrichment, Reprocessing Contracts	Disrupted Enrichment Contracts
What is Assured	Spent Fuel Storage, Front End Supply	Front End Supply, possibly Back End Services	Front End Supply, Ultimately Spent Fuel Take-Back	Enrichment Services, Access to Reprocessing	Enrichment Services (Reprocessing)
Assurance Mechanism	Multilateral Nuclear Fuel Cycle Centers	Russian Enrichment Facilities	U.S. Provided Diluted HEU – Fuel Bank	Collective Suppliers Guarantee, IAEA Stockpile	Backup Commercial Contracts
Eligibility	Regional States Agreeing to Participate in Regional Center	NWS-Designated - IAEA Approved	NWS-Designated - IAEA Approved	IAEA Approved Meeting All NPT Obligations	IAEA Approved Meeting All NPT, Obligations
Practical Aspects	Defining Functional Role, Facilities to be Used	Solution to Iran Problem as Model for Center Implementation	Depends on Future Administration, Tie-in with Tech. Programs	Implementing Suppliers Collective Guarantee, IAEA Stockpile	Back-up of Last Resort, Switch Commercial Contracts to Other Willing Enrichers
Role of IAEA	Fostering Regional Fuel Cycle Center Agreements, Safeguards	Management, Approvals, Safeguards	Approvals, Safeguards	Approve Triggering of Collective Suppliers Guarantee, Manage Backup Stockpile	Approve Transfer of Commercial Contracts to Other Enrichers
Role of Industry	Managing, Operating Centers	Performing Fuel Services at Designated Center	Perform Fuel Services per USG Instructions	Perform Enrichment, Reprocessing Contracts	Perform Enrichment Contracts

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[50] IAEA (2005), Multilateral Approaches to the Nuclear Fuel Cycle: Expert Group Report submitted to the Director General of the International Atomic Energy Agency. Report # INFCIRC/640, dated 22 February 2005, and available as www.iaea.org/Publications/Documents/Infcircs/2005/infcirc640.pdf.

[51] World Nuclear Association (2006), Ensuring Security of Supply in the International Nuclear Fuel Cycle. WNA Report, dated 12 May, 2006, available as www.world-nuclear.org/reference/pdf/security.pdf.

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4.3. Nuclear Fuel Cycle Scenarios Adopted for this Study

For the EASS project, the project team has developed four nuclear fuel cycle scenarios, each with components related to the “front end” (fuel provision/enrichment) and “back end” spent-fuel management/reprocessing) of the cycle. Many of the components used in these scenarios have commonalities with or draw from the regional and international proposals reviewed briefly in the previous section of this Chapter. Though some of these scenarios call for regional facilities, the proposals are generic in terms of where—both in terms of nations and in terms of particular sites—shared facilities would be located. Particular sites and nations are not identified because there are a large number of different possible configurations of sites, too many to consider meaningfully here, including, in some cases, either having a single centralized set of facilities or multiple distributed facilities. Further, it is not our purpose, in this Chapter of this Report, to look at the particular countries or sites as hosts, rather to explore the general energy security costs and benefits of different physical and institutional nuclear fuel cycle options. Clearly there are current legal and/or political constraints—local, national, and sometimes international—to almost any regional nuclear initiative (and many national ones), but given the timelines and energy/environmental imperatives involved, it is conceivable that some of the constraints could eventually be relaxed or worked around in the future. Some of the constraints faced for likely host countries are discussed in Chapter 5 in the contexts of their own nuclear programs.

To place the nuclear fuel cycle scenarios we have developed in the context of regional energy futures, we are using the three sets of energy paths developed by our collaborating country teams to set the parameters for the cooperation scenarios in terms, for example, of enrichment quantities required, nuclear materials transport implied, and nuclear spent fuel/wastes to be managed, stored, and disposed of. These three sets of energy paths—as described in Chapter 3 of this report—include, in each country, a “Business as Usual” Case in which current policy trends persist, a “Maximum Nuclear” case in which each country adopts nuclear power at a rate that our collaborating teams consider to be the maximum feasible, and a “Minimum Nuclear” case where events and popular opinion conspire to force policymakers to restrain (or halt) the growth of nuclear generation capacity. Using these three cases, we assess the relative costs and benefits of the four cooperation scenarios under a range of different nuclear capacity/energy production “conditions” to see which scenarios are more attractive at what levels of nuclear power adoption—taking into account parameters like existing reprocessing and spent fuel management capacities in the region, as well as issues such as management of nuclear fuel cycles for potential new members of the nuclear energy “club” in the region (Vietnam, Indonesia, North Korea, and—less likely—Australia). For each path and each cooperation scenario, we track key physical parameters such as the amounts of uranium fuel (in tonnes of ore and metal) and enrichment capacity needed (in SWU) and quantities of spent fuel to be managed (in tHM) through each step in the transport and transformation of nuclear materials. We also estimate the economic costs of each Scenario under each nuclear capacity path, and review the energy security (broadly defined) costs and benefits of each scenario relative to each other. The results of these analyses are presented in Chapter 5 of this report. Documentation of our assumptions, sources, and analysis are presented in Chapter 5 and in Annexes to this Report in order make them accessible for review by others so as to inform policy dialog on the nuclear issue.

4.3.1. Summary of Scenarios

Under the direction of nuclear energy/nuclear proliferation expert Professor Tatsujiro Suzuki of Japan, the EASS project team has developed four cooperation "scenarios", and has worked to identify how the key energy security costs and benefits of those scenarios--both quantifiable and non-quantifiable—compare from one scenario to the other. The scenarios, and some (but hardly all) of the key policy issues they suggest, are as follows:

1. "**National Enrichment, National Reprocessing**": In this scenario the major current nuclear energy users in East Asia (Japan, China, and the ROK), and perhaps others as well, each pursue their own enrichment and reprocessing programs. This is likely to be the highest cost of the scenarios, would raise significant proliferation concerns (not the least of which would be the DPRK's reaction to ROK enrichment and reprocessing), and would create growing stockpiles of plutonium in several nations (in addition to the large stockpile Japan already holds). Disposal of high-level nuclear wastes from reprocessing would be up to each individual country, with attendant political and social issues in each nation. Security would be up to the individual country, and as a result, transparency in the actions of each country is not a given.
2. "**Regional Center(s)**": This scenario features the use of one or more regional centers for enrichment and reprocessing/waste management, drawn upon and shared by all of the nuclear energy users of the region. We will likely avoid identifying a particular country host for the facilities, but China and Russia are obvious candidates. Here economies of scale will likely reduce costs relative to having each country effectively "go it alone" as in case 1, but possible policy issues include managing a multilateral facility on the sovereign soil of a country in a notoriously fractious region, maintaining control of likely huge, over time, stocks and flows of enriched uranium, separated plutonium and/or mixed-oxide fuel, securing transport of nuclear materials between countries and the facilities, and the potential "downside" for participating non-host nations, from an energy diversity point of view, of funneling all nuclear activities through a particular country.
3. "**Fuel Stockpile/Market Reprocessing**": Here, the countries of the region purchase natural and enriched uranium internationally, but cooperate to create a fuel stockpile that the nations of the region can draw upon under specified market conditions. Reprocessing services are purchased from international sources, such as France's AREVA or from Russia, while some spent fuel continues to be stored in nations where nuclear generation is used. This option is likely less expensive than either scenarios 1 or 2, but raises or leaves unaddressed issues such as national spent fuel/waste management policies, dependence on far-away sources for fuels and services (and related transportation issues), and ownership and handling of plutonium stockpiles built up in other countries.
4. "**Market Enrichment/Dry Cask Storage**": In this, likely the cheapest of the four scenarios for participants, countries in the region (with the possible exception of China) would continue to purchase enrichment services from international suppliers such as URENCO in Europe, the USEC in North America, and Russia. All spent fuel, after cooling in ponds at reactor sites, would be put into dry cask storage either at reactor sites or at intermediate storage facilities. Possible questions raised by this approach include: To what degree will countries be tolerant to exposure to international market forces? Will international enrichment capacity suffice for all nuclear energy development cases? Is on-site waste

storage possible in all countries (politically/socially)? Is it more secure to have plutonium and uranium stay mixed in (relatively) small quantities of spent fuel in many different locations? How can the required security over many waste storage locations be assured over centuries and millennia?

Close variants of these scenarios were used as the basis for analysis by Tadahiro Katsuta, a member of the EASS project team, in his September, 2009 work "Nuclear Fuel Cycle in East Asia", in which he describes scenarios for cooperation, and analyzes spent fuel requirements and costs for fuel-cycle management in four countries (Japan, China, the ROK, and Taiwan) through 2030[52].

4.3.2. "National Enrichment, National Reprocessing"

The **"National Enrichment, National Reprocessing"** scenario assumes that the three major East Asian nuclear power users—Japan, the Republic of Korea, and China—each pursue independent programs of "front-end" and "back-end" nuclear fuel cycle development. Under this scenario, each of these three countries would expand (Japan, China) or develop (ROK) uranium enrichment and fuel fabrication facilities sufficient to fully meet its needs for reactor fuel by the year 2025 (Japan and China) and 2030 (ROK). In the National Enrichment, National Reprocessing scenario, it is assumed that Taiwan does not pursue enrichment activities, and that the DPRK, Indonesia and Vietnam (and Australia, if it pursues nuclear power) likewise do not develop enrichment facilities, at least within the 2010 to 2050 time frame, although some preliminary steps toward enrichment may take place in some of these countries. Nuclear reactors in the RFE will use fuel enriched in Russia. With regard to spent fuel management, the National Enrichment, National Reprocessing scenario assumes that Japan will continue to develop and use reprocessing capacity sufficient to handle 80 percent of its annual spent fuel output by 2030. By the same year, with China will have developed reprocessing capacity sufficient to handle 50 percent of its spent fuel output, and the ROK will be reprocessing 60 percent of its spent fuel. Reprocessing will start in both the ROK and China by 2025. It is assumed that the remaining spent fuel in each of the three countries will be held in interim dry-cask-type storage, while longer-term storage arrangements are developed. The DPRK, Taiwan, Indonesia, Vietnam, and Australia do not, under this scenario, develop commercial-scale reprocessing, though some of these countries (most likely, Vietnam) might well, in the type of climate of minimal regional cooperation characterized by this scenario, experiment with reprocessing before 2050. The National Enrichment, National Reprocessing case assumes that an average of 25 percent of spent fuel from RFE reactors would be reprocessed, likely in Siberia, with the remainder kept in interim storage at or near reactor sites in the RFE. Spent fuel in nations not pursuing reprocessing before 2050 is assumed to be placed in interim dry-cask-type storage when sufficiently cooled in at-reactor spent fuel pools.

Under the National Enrichment, National Reprocessing Case scenario, the approach to each of the elements of the fuel cycle, by country, is assumed to be as follows:

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[52] T. Katsuta (2009), "Nuclear Fuel Cycle in East Asia", A Proposal on Nuclear Disarmament and Non-Proliferation Policy from Japan, dated September 2009, and available as http://a-mad.org/download/CGP_AMAD_EAv1.pdf.

Uranium Mining and Milling

In the Reference scenario, it is assumed that China continues its development of domestic uranium mines and mills sufficient to continue to supply half of its uranium needs through 2050. Japan and the ROK are assumed to continue to import all of their uranium needs; the same applies to Taiwan. Australia, as a major uranium exporter, is assumed in those cases where it pursues nuclear power to supply its own uranium. Indonesia and Vietnam, both of which have uranium resources but at present no significant production, are assumed to start supplying uranium for domestic use in 2025, with mining and milling capacity growing to provide half of their domestic uranium needs by 2030, and continuing at that level through 2050. The DPRK is likewise assumed to provide the equivalent of half of its domestic uranium needs by 2030, with mining (at the level required) starting in 2020, though actual fuel fabrication for DPRK reactors may take place elsewhere (see below). uranium for reactors operating in the RFE will be sourced from Russia, though not necessarily from the RFE itself.

Uranium Transport

Processed uranium (probably largely as U_3O_8 "yellowcake") transport in the National Enrichment, National Reprocessing scenario takes place within countries for all uranium produced indigenously (as noted above), and otherwise travels largely by sea from producer countries (mainly Australia and Canada, but also, especially in the case of China, from other nations including Namibia and Kazakhstan, where joint ventures with Chinese firms are underway. Where uranium is imported from major producer countries, it is typically transported by sea. Sometimes transport of refined but unenriched uranium takes place in dedicated ships, but more often, it seems that it is transported in standard ocean freighters. For transport by freighter, yellowcake is packed in metal drums placed in standard shipping containers[53]. As such, we have assumed that the cost of yellowcake transport is similar to the cost of shipping other goods in container vessels.

Uranium Conversion and Enrichment

As noted in the introduction to this National Enrichment, National Reprocessing Case, the enrichment situation in the countries of Asia and the Pacific is assumed to be as follows:

- Japan continues to develop facilities such that it enriches all of its own nuclear fuel by 2025. Japan's domestic enrichment is assumed to ramp up from a total average used enrichment capacity of 300,000 kg SWU per year in 2010[54] to enrichment of all needed domestic fuel by 2025.
- China likewise continues to develop facilities such that it enriches all of its own nuclear fuel by 2025, rising from a level of about 1.5 million kg SWU/yr in 2009 and about 3 million kg SWU in 2015 (World Nuclear Association, 2009[55]).

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[53] See, for example, World Nuclear Association (2010), "Transport of Radioactive Materials", available as http://www.world-nuclear.org/info/inf20.html, last updated January, 2010.

[54] Current enrichment capacity is listed in http://www.world-nuclear.org/info/inf79.html ("Nuclear Power in Japan", World Nuclear Association, January, 2010) as "seven cascades each of 150,000 SWU/yr, though only two are operating. Its eventual capacity is planned to be 1.5 million SWU/yr. It has been testing a lead cascade of its new Shingata design, and expects to re-equip the plant with this, starting in April 2010, and with the new equipment to come on line in September 2011".

[55] The World Nuclear Association (2009), in "Uranium Enrichment", available as http://www.world-nuclear.org/info/inf28.html, suggest that China's enrichment capacity planned for 2015 will be about 3.3 million kg SWU/yr, which we round down to production of 3 million SWU/yr.

- The ROK develops facilities such that it enriches all of its own nuclear fuel by 2030, with enrichment assumed to start in 2015. The ROK's enrichment facilities are also assumed, under this scenario, to produce nuclear fuel for any reactors located in the DPRK.
- Taiwan continues to use purchase enrichment services from countries outside the region, meaning the United States and the EU.
- Vietnam and Indonesia likewise purchase enrichment services from outside the region, probably from the US and EU, but possibly from Russia or China.
- Australia, in the cases where nuclear power is developed, obtains its enrichment from the United States or EU.

Based on these assumptions, the amount of uranium enrichment capacity required in Japan, China, and the ROK, and the incremental capacity required in Russia to cover use of enriched uranium in RFE reactors, is presented in Table 4-3 for each of the three sets of national nuclear paths. We assume that those countries that enrich uranium also provide their own conversion of uranium oxide to uranium hexafluoride gas (UF_6) for use in centrifuge enrichment plants, as well as conversion of enriched UF_6 back to uranium oxide for preparation of nuclear fuel pellets. Note that this table has **not** been corrected for the impacts of reprocessing on enriched fuel requirement, and thus represents approximate requirements for enrichment as if MOx fuel were not used. Please seem Chapter 5 for results by that have been corrected for MOx fuel use.

Table 4-3: Estimated Required Enrichment Capacity by Country, National Enrichment, National Reprocessing Scenario

Units: metric tons enriched fuel as U		**Annual Total Enriched Fuel Requirements for Uranium Enriched In-country for Domestic Use**					**Annual Total Enrichment Out-of Country**	**Total Regional Enrichment Requirements**
	Year	China	Japan	ROK	RFE	TOTAL	TOTAL	TOTAL
BAU Nuclear Expansion Path	2010	228	56	-	0.4	285	1,354	1,639
	2030	2,689	1,276	838.5	63.0	4,867	547	5,414
	2050	3,798	1,221	801.4	111.9	5,932	921	6,853
MAX Nuclear Expansion Path	2010	228	56	-	0.4	285	1,354	1,639
	2030	3,782	1,382	1,125.3	111.9	6,401	701	7,102
	2050	5,823	1,326	1,233.8	209.7	8,593	1,500	10,092
MIN Nuclear Expansion Path	2010	228	56	-	0.4	285	1,354	1,639
	2030	2,039	378	378.1	15.9	2,811	58	2,869
	2050	1,799	33	184.8	15.9	2,033	58	2,091

Units: million kg SWU		**Annual Total Enrichment Services Requirements for Uranium Enriched In-country for Domestic Use**					**Annual Total Enrichment Out-of Country**	**Total Regional Enrichment Requirements**
	Year	China	Japan	ROK	RFE	TOTAL	TOTAL	TOTAL
BAU Nuclear Expansion Path	2010	1.6	0.4	-	0.0	2.0	9.5	11.6
	2030	19.0	9.0	5.9	0.4	34.3	3.9	38.2
	2050	26.8	8.6	5.6	0.8	41.8	6.5	48.3
MAX Nuclear Expansion Path	2010	1.6	0.4	-	0.0	2.0	9.5	11.6
	2030	26.7	9.7	7.9	0.8	45.1	4.9	50.1
	2050	41.0	9.3	8.7	1.5	60.6	10.6	71.1
MIN Nuclear Expansion Path	2010	1.6	0.4	-	0.0	2.0	9.5	11.6
	2030	14.4	2.7	2.7	0.1	19.8	0.4	20.2
	2050	12.7	0.2	1.3	0.1	14.3	0.4	14.7

Fuel Fabrication

In, we assume that those countries that enrich their own uranium under the National Enrichment, National Reprocessing Case also fabricate their own reactor fuel, and those countries that do not, import prepared fuel rods and assemblies from abroad. Imports of fabricated fuel will likely, in most cases, be from the US and/or the EU, with exception of the RFE (from elsewhere in Russia) and the possible exception of the DPRK (from the ROK, or the US via the ROK). To the extent that mixed-oxide (MOx) fuels are used by those countries that also reprocess uranium, it is assumed that the countries that use MOx fuels also prepare MOx fuel pellets, fuel rods, and fuel assemblies, though this has not historically always been the case (see reference below to a recent shipment to Japan of MOx fuel elements prepared in France).

Transportation of Fresh Reactor Fuel

For those countries with domestic enrichment plants, reactor fuel is assumed to be transported in-country to nuclear power facilities much as it is today, largely by road and rail. For those countries importing some or all of their reactor fuel, fresh fuel assemblies are assumed to travel mostly by ship, with journeys completed by road and/or rail for those plants located inland or away from harbors.

Those countries that enrich nuclear fuels will also need to transport depleted uranium, either as UF_6 or in the form of uranium metal or oxide[56], to locations where it will be stored and ultimately disposed of or (less frequently, based on current practice) used for other purposes.

Electricity Generation

Electricity generation using nuclear fuels—meaning evolution of nuclear capacity and electricity production by nuclear power plants—follows the Business as Usual, Maximum Nuclear, and Minimum Nuclear paths for each country as described in Chapter 3 of this report.

We assume that the use of MOx fuels by the countries of the region starts in Japan, where MOx use is well-established by 2017. Based on recent reports, MOx recycling started in late 2009 at one unit of the Genkai plant in Kyushu[57], and will start in 2012 for the Shioku, Chubu and Chugoku plants. We assume this phase-in for this scenario. By 2017, in Japan, we assume that 25 percent of the reactor fleet uses 20 percent MOx fuels in their reactor cores, ramping up to 50 percent of the fleet using 20 percent MOx by 2030 and remaining at that level through 2050. This schedule for MOx fuel introduction is slightly less ambitious than the recently announced goals of the Federation of Electric Companies of Japan[58], but takes into account a pattern of recent delays in MOx fuel use in Japan relative to previous goals[59]. We further

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[56] Most depleted uranium (95 percent in the US, for example) is stored as UF_6 (Wikipedia, http://en.wikipedia.org/wiki/Depleted_uranium, and Argonne National Laboratory, http://web.ead.anl.gov/uranium/faq/storage/faq16.cfm and http://web.ead.anl.gov/uranium/faq/storage/faq23.cfm)

[57] C. Tordesillas, "MOX fuel provides electricity for nuclear plant", Asian Power, published 14 December, 2009, available as http://www.asian-power.com/news/1820.

[58] Reuters (2009), "Japan delays MOX nuclear fuel goal by 5 years". Reuters.com, posted June 12, 2009. Available as http://www.reuters.com/article/rbssIndustryMaterialsUtilitiesNews/idUST34756220090612.

[59] Current plans in Japan reportedly call for the use of MOx fuel in "16 to 18 reactors" by March, 2016. Previous plans called for this level of implementation of MOx fuel use by fiscal year 2010 (Federation of Electric Companies of Japan (2008), "Japan's MOx Program", dated March, 2008, and available as http://www.japannuclear.com/nuclearpower/moxprogram. Despite this announced delay, a load of MOx fuel reprocessed and fabricated into fuel elements in France has recently been shipped to Japan (see, for example, Nuclear Power Industry News (2009), "AREVA MOX Nuclear Fuel Shipment To Arrive In Japan As Early As Today", dated May 18 2009, and available as http://nuclearstreet.com/blogs/nuclear_power_news/archive/2009/05/18/areva-mox-nuclear-fuel-shipment-to-arrive-in-japan-as-early-as-today.aspx).

assume that China and the ROK also use MOx fuels in their reactors, but starting later—in 2025, in 10 percent of the reactor fleet, ramping up to 50 percent of the fleet by 2050. As in Japan, we assume that MOx fuel use is limited to 20 percent of the fuel elements in any reactor core. As DPRK reactors are assumed to be effectively operated by the DPRK, MOx use assumptions applying to the ROK are assumed to also apply to the DPRK. We assume that MOx fuel is not used in any of the other countries covered by this Report through 2050.

Spent Fuel Management, Including Reprocessing

We assume that in all countries, spent reactor fuel, including spent MOx fuel, will be stored in spent fuel pools at reactor sites for at least six years before being moved to other storage or reprocessing. In the countries that are assumed to reprocess spent fuel under this National Enrichment, National Reprocessing Scenario (Japan, the ROK, and China), as noted in the summary description of the National Enrichment, National Reprocessing Scenario, 80 percent, 60 percent, and 50 percent, respectively of cooled spent fuel (assumed roughly equivalent to the spent fuel produced six years previously, though in practice older spent fuel could be reprocessed first) is ultimately reprocessed, with domestic reprocessing reaching this level in Japan by 2020, and in the other two countries by 2030. Reprocessing will start on a commercial scale in both the ROK and China by 2025, and therefore ramp up rather quickly to the target levels above. In Japan, although test runs of spent fuel have been sent through the Rokkasho reprocessing plant for many years, we assume that full scale operation of the plant begins to ramp up in 2013. Recent reports indicate that the commercial start-up of the facility has been delayed multiple times, the most recent to at least late 2010[60], thus our assumption of a 2013 start-up is an educated guess. Although as of the time of this writing we were unable to find annual estimates of Japan's historical and current shipments of spent fuel to Europe for reprocessing, we assume for the purpose of this analysis that about 50 percent of cooled Japanese spent fuel was reprocessed in Europe as of 2000, declining to zero by 2012 ahead of the opening of Rokkasho in 2013[61]. As the ROK is assumed to be doing most or all of the handling of both fresh and spent fuels from DPRK reactors, approximately 60 percent of cooled DPRK reactor fuel is also assumed to be reprocessed, but in the ROK. It is assumed that the remaining spent fuel in each of these four countries and in the RFE will be held in interim dry-cask-type storage facilities in-country, but not at reactor sites, pending the development of domestic permanent storage (see below). In the DPRK (with the exception of fuel reprocessed in the ROK), Taiwan, Indonesia, Vietnam, and Australia, it is assumed that commercial-scale reprocessing is not developed, spent fuel accumulates in spent fuel pools until the pools are nearly (90%) full, and then is transferred to interim dry-cask storage, likely at reactor sites, but possibly at one or more

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[60] See, for example, Citizens' Nuclear Information Center (2009), "Rokkasho Reprocessing Plant: 14 Month Delay", reporting on an announcement by Japan Nuclear Fuel Ltd., of an extension of "the estimated date of completion of construction and testing of its Rokkasho Reprocessing Plant by fourteen months to October 2010". Article available as http://cnic.jp/english/newsletter/nit132/nit132articles/rokkasho.html.

[61] The World Nuclear Association (2010), in "Japanese Waste and MOX Shipments From Europe", (available as http://www.world-nuclear.org/info/inf39.html, updated January, 2010), notes that "From 1969-1990, some 2940 tonnes of used fuel in total was shipped (in over 160 shipments) by these utilities to France for reprocessing. Shipments of about 4100 tonnes were to the UK, and by mid 2007 more than 2600 tonnes of oxide fuel had been reprocessed there, plus a small amount of Japanese Magnox used fuel." This suggests that at least 7000 tonnes of spent fuel had been sent to Europe for reprocessing by 2007, and possibly more. This quantity represents about 67% of the cooled spent fuel available by 2007, or possibly slightly less, since the World Nuclear Association figures seem to be in terms of uranium oxides, as opposed to tonnes of heavy metal. Since Japanese shipments to reprocessing centers in Europe were winding down in the 2000s (shipments to France apparently ended in 2005), we use 50 percent reprocessing as a starting value for approximately 2000, pending receipt of better data, and an end date for European reprocessing of Japanese spent fuel of 2012.

centralized locations. An average of 25 percent of spent fuel from RFE reactors is assumed to be reprocessed, likely in Siberia at Zheleznogorsk, if the "RT-2" plant planned there is finished[62], with the remainder kept in interim storage at or near reactor sites in the RFE. Reprocessing of RFE spent fuel is assumed to start in 2021, approximately when the first spent fuel from the first large RFE reactor would have cooled sufficiently to reprocess, and be ramped up to 25 percent of total cooled fuel by 2022, given that the reprocessing is taking place at existing facilities in Russia that are not solely dedicated to the RFE.

It should be noted that spent MOx fuel does have significantly different radiological properties relative to spent LEU fuel (fresh fuel that contains only low-enriched uranium). For example, after initial cooling, spent MOx fuel produces significantly more heat for a significantly longer time than spent LEU fuel[63]. We have assumed that the use of MOx in limited quantities (on the order of 20 percent of fuel in a reactor core), and in carefully chosen positions in the fuel arrays and cores of standard LWRs, could be cooled for the same length of time as standard LEU spent fuel in standard at-reactor spent-fuel pools. Careful operation of the spent fuel pools, however—so as to keep spent MOx fuel with LEU fuel that has already cooled for a number of years, for example—will likely be necessary[64] [65]. We also assume that mixtures of spent MOx and spent standard LEU fuel can be stored in dry casks in more or less the same way as spent LEU fuel, though it is possible, depending on the mixture used, that casks with MOx fuel in them may require more shielding and/or may need to operated with fewer elements per cask, due to the different decay products and greater heat from MOx fuel. For the purposes of this study, we assume treatment of the two spent fuel types is generally the same and costs the same, though in practice back-end treatment of MOx fuel is more complex and possibly somewhat more expensive. We do assume, however, that spent MOx fuel is NOT reprocessed for further use in LWRs before 2050, due to its very different properties relative to spent LEU fuel.

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[62] World Nuclear Association (2009), "Nuclear Power in Russia". Dated 8/12/2009 and available as http://www.world-http://www.world-nuclear.org/info/inf45.html?ekmensel=c580fa7b_702_738_366_7. If the reprocessing plant at Zheleznogorsk is not completed, spent fuel from RFE reactors to be reprocessed would presumably be sent to the "RT-1" plant at the Mayak Chemical Combine, at Ozersk, near Kyshtym 70 km northwest of Chelyabinsk in the Urals, for which an expansion of capacity was approved in 2008.

[63] Kang, J., F. N. von Hippel, A. MacFarlane, and R. Nelson (2002), "Storage MOX: A Third Way for Plutonium Disposal?". Science and Global Security, volume 10, pages 85–101, 2002.

[64] F.N. von Hippel and K. Janberg, personal communications, 2009. The key point here is that the characteristics of MOx fuel, both in terms of its fission properties during operation in an LWR, and in terms of its radiological properties when removed from the reactor core as spent fuel, are significantly different from standard (not reprocessed) LEU fuel. As a result, the use of MOx fuel with LEU fuel in standard LWRs requires careful planning and management, with fuel rods/pins containing MOx fuel positioned carefully within fuel assemblies and within the reactor core in order to maintain fuel temperatures in a safe range and allow safe control of the reactor. If handled appropriately, and "diluted" in assemblies and cores with enough standard LEU fuel pins, MOx fuel can be handled as a spent fuel more or less the same as LEU spent fuel.

[65] The information from these experts is contradicted somewhat by a passage in the "MIT Report" (*The Future of Nuclear Power, An Interdisciplinary MIT Study*, 2003, page 121), which reads (in part), "In practice, current reactors employing UOX and MOX are fueled with a 2:1 ratio of UOX to MOX fuel". Other references suggest that France is currently using approximately 30% MOx in some of its reactors, that the US DOE calls for reactors using 40% MOx cores, and that future reactors capable of using 50% (Europe) and 100% (Japan) MOx cores are under design. See, for example, A. Sowder (2009), "Readiness of Current and New U.S. Reactors for MOX Fuel", presentation at North Carolina and Virginia Health Physics Societies Joint 2009 Spring Meeting, New Bern, North Carolina, 13 March 2009, available as http://hpschapters.org/northcarolina/spring2009/FAM.4.pdf. Sowder and other authors do, however, acknowledge some of the technical difficulties associated with the use of MOx fuels in LWRs designed primarily for UOx fuels, so pending the receipt of solid information to the contrary, we continue to use 20% as an average MOx fraction for light-water reactors using MOx.

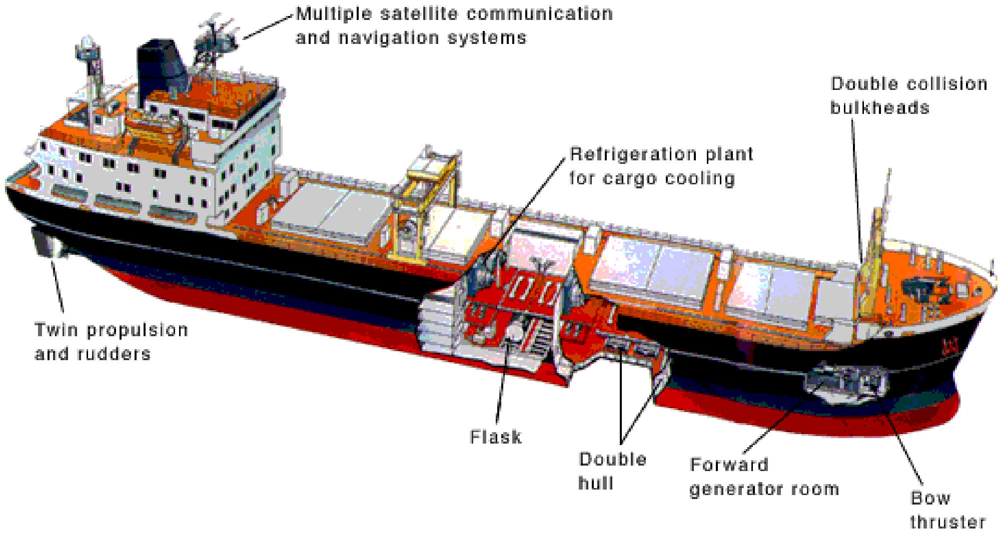
High-level wastes from reprocessing activities, in those countries pursuing reprocessing, are assumed to be “vitrified” with borosilicate glass into glass “logs”. Vitrified wastes are placed in interim storage facilities pending decisions on and construction of final disposal facilities.

Spent Fuel Transport

In instances where spent fuel must be transported from reactor sites to other facilities for reprocessing, interim storage, or permanent storage/disposal, we assume that spent fuel is packed into special shipping casks, and travels by truck, rail, or ship. Where ship transport is required, vessels specially built for transport of spent fuel and similar nuclear materials (such as vitrified high-level wastes and MOx fuel) are currently used, and we assume they will be used in the future. Figures 4-2 provides a schematic of such a vessel, and a photo of a ship in operation is provided in Figure 4-3[66]. Figure 4-4 shows a vehicle used for road transport of spent fuel in Japan[67].

Figure 4-2:

Purpose-built vessel for transport of spent nuclear fuel



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[66] Figures from World Nuclear Association (2010), "Japanese Waste and MOX Shipments From Europe”, available as http://www.world-nuclear.org/info/inf39.html, updated January, 2010.

[67] Figure from World Nuclear Transport Institute (2008), “Picture Libraries”, available from http://www.wnti.co.uk/media-centre/picture-library/.

Figure 4-3: Photo of Ship Used for Transport of Spent Nuclear Fuel

Figure 4-4: Photo of Vehicles Used for Road Transport of Spent Nuclear Fuel

Permanent Disposal of Nuclear Wastes

In this National Enrichment, National Reprocessing scenario, it is assumed that none of the countries of the region, independently or collectively, develop facilities for permanent disposal of spent fuel or high-level wastes from nuclear activities that would being operation before 2050. Facilities for permanent disposal here means facilities in stable geological strata deep underground where it is judged that nuclear materials can remain safely isolated from populations and the biosphere indefinitely. It is possible, even likely, that some countries in the region will advance the planning for and even construction of such facilities before 2050, but any costs for those activities are not counted here. Interim storage is therefore used through 2050 in all countries for materials produced by the nuclear fuel cycle, with the exception of low-level wastes, which are disposed of in landfills in accordance with current practice in each country.

4.3.3. Regional Center(s) Case: Regional Cooperation for Uranium Enrichment and Waste Management

In the "**Regional Center(s)**" scenario, as described briefly above, the countries of the region agree to cooperate in the development and use of one or more regional centers for enrichment of uranium, reprocessing of spent fuel, and the management of nuclear wastes. This center or centers—the location of which is not specified in this scenario, but would likely be in one of the physically larger countries of the region—would be drawn upon and shared by all of the nuclear energy users of the region. As such, the center(s) would, when complete, become the supplier of nuclear fuel for each country, and all spent fuel would be returned to the center(s) for reprocessing or storage. Presumably, at least for some activities, the center(s) would provide economies of scale relative to each country effectively "going it alone" as in the National

Enrichment, National Reprocessing case above. This case does, however, raise thorny policy issues, include how to set up management of a multilateral facility on the sovereign soil of one of the participants in the region so as that it is operated to the satisfaction of all parties and maintains control of large stocks and flows of enriched uranium, separated plutonium and/or mixed-oxide fuel. Presumably, the center(s) would be operated by an international consortium in such a way that costs are shared based on the fraction of the center(s) services used by each country, but it is conceivable that the center(s) could be run by contracting firms under the oversight of the cooperating governments and/or the nuclear utilities using the services.

The following provides a description of the approach to each of the elements of the fuel cycle under this scenario.

Uranium Mining and Milling

In the Regional Center(s) scenario, the countries of the region share enrichment capacity. Though this scenario is compatible with a situation in which each country buying its own uranium (either as ore or refined), then providing its ore to the one or more regional enrichment facilities, we assume that uranium procurement is coordinated among countries. For this scenario, then, we assume that a consortium formed by the uranium users in the region (which could be operated by governments and/or the utilities using uranium) purchases refined uranium on the international market—including, as available, from the countries of the region—and supplies it to the enrichment facility or facilities, charging each country for the amount of uranium used to enrich LEU reactor fuel on its behalf.

With the fuel consortium purchasing fuels, it is assumed that those countries that do not currently have significant uranium production—including Japan, the ROK, the DPRK, Indonesia, and Vietnam—do not extract their reserves or resources (those countries that have them) and that China, with significant mining currently but with ore that is of relatively poor quality, limits its own production (which it provides to the enrichment consortium) to only slightly more than current (2008-2010) levels of output (about 1400 tonnes yellowcake per year[68]). For the sake of convenience (reduced transport distance for nuclear fuel, despite Western Russia's fuel production capacity), it is assumed that RFE nuclear plants also participate in the fuel consortium.

The fuel consortium arrangement means that in this case, relative to the National Enrichment, National Reprocessing case, somewhat more uranium will be purchased from major suppliers—including, for example, Australia, Canada, Russia, emerging Central Asian suppliers, and perhaps others. Representing a considerable portion of the world's reactors, the consortium could have significant market power, but as the number of major suppliers of uranium is also small, this market power is assumed to have a modest impact on price. We assume that the price of yellowcake paid by the consortium is on average about 5 percent less that paid, on average, by uranium consumers under the National Enrichment, National Reprocessing scenario, with the reduction reflecting mostly a reduction in the cost of shipping due to economies of scale (since suppliers can ship larger quantities of uranium to the regional enrichment facility or facilities than to national enrichment plants).

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[68] Rough estimate based on reports of production capacity and near-term capacity additions in China by the World Nuclear Association, "China's Nuclear Fuel Cycle" (last updated 9/18/09, and available as http://www.world-nuclear.org/info/inf63b_china_nuclearfuelcycle.html) of 840 tonnes U per year, plus about 300 tonnes/yr in near-term planned additions. The total has been rounded and converted to tones of U_3O_8.

The concentration of uranium mining and milling in major producer countries in this scenario means that, relative to the National Enrichment, National Reprocessing case, less uranium mine spoils are produced in the region (with the exception of Australia).

Uranium Transport

Processed uranium (yellowcake) transport in the Regional Center(s) scenario largely—with the exception of some domestic transport in China—takes place between major uranium supplier countries and the site(s) of the regional enrichment facility/facilities, traveling mostly by sea.

Uranium Conversion and Enrichment

As noted in the introduction to this scenario, it is assumed that uranium is enriched at one or more facilities in the region operated by a consortium of nuclear power users. It is assumed that conversion of U_3O_8 to uranium hexafluoride for use in gas centrifuge enrichment also takes place at the location(s) where uranium is enriched, though there is no particular reason why under this scenario (natural) UF_6 couldn't also be purchased by the consortium, when available, from international suppliers.

The overall amount of enrichment capacity located at the regional center(s) is assumed to be sufficient to meet the total year-by-year enrichment needs shown in Table 4-2 after the year 2025 (adjusted for MOx use), with capacity in the regional enrichment center(s) ramping up to that level after first operation starts in (we assume) 2018. In practice some enrichment could be purchased from existing facilities (for example, in Europe or the United States) even after the regional center(s) start meeting regional demand in 2025, depending on year-by-year variations in enrichment supply and demand in the region. The three countries currently enriching uranium—Japan, China, and the RFE (Russia)—are assumed to continue enriching fuel at current levels (about 5 percent of requirements—about 300,000 SWU/yr—for Japan, 1.5 million SWU/yr for China[69]) through 2018, when they begin to depend on the regional center(s) for enrichment, winding down their own enrichment activities, and sourcing all of their enrichment from the center(s) by 2025. For China, this effectively means that enrichment capacity additions planned for between 2010 and 2015 are not built (or are not operated at full capacity).

Fuel Fabrication

Fabrication of LEU fuel in the Regional Center(s) case is assumed to take place at the regional centers themselves. To the extent that different reactor types use different fuel types, this will oblige the enrichment facility/facilities to be capable of producing fuel in different configurations.

To the extent that mixed-oxide (MOx) fuels are used by the countries of the region, the Regional Center(s) is/are also assumed responsible for fabricating MOx fuel pellets, fuel rods, and fuel assemblies. We make no specific assumption as to whether this fuel fabrication takes place at regional enrichment or regional reprocessing facilities (if not co-located), though in practice it seems likely that the fuel fabrication would take place where reprocessing takes place in order to reduce the transport of fully- or partially-separated plutonium.

Transportation of Fresh Reactor Fuel

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[69] Estimates based on World Nuclear Association (2010 and 2009), "Nuclear Power in Japan", available at http://www.world-nuclear.org/info/inf79.html, and "Uranium Enrichment", available as http://www.world-nuclear.org/info/inf28.html.

Reactor fuel is assumed to be transported mostly by ship from a central enrichment plant or plants to nuclear plants around the region where they are consumed, with the possible exception of the nation where the plant(s) is/are located. Depleted uranium from regional enrichment activities, again either as UF_6 or in the form of uranium metal or oxide, will need to be transported to locations where it will be stored and ultimately disposed of or used.

Electricity Generation

As in the National Enrichment, National Reprocessing scenario, electricity generation using nuclear fuels—meaning evolution of nuclear capacity and electricity production by nuclear power plants—follows the Business as Usual, Maximum Nuclear, and Minimum Nuclear paths for each country as described in Chapter 3 of this report.

We assume that the use of MOx fuels by the countries of the region in this Regional Center(s) scenario parallels that described for the National Enrichment, National Reprocessing case above in terms of timing and fraction of MOx fuel used.

Spent Fuel Management, Including Reprocessing

As in the National Enrichment, National Reprocessing scenario, we assume that in all countries, spent reactor fuel, including spent MOx fuel, will be stored in spent fuel pools at reactor sites for at least six years before being moved to other storage or reprocessing. In the same countries that are assumed to reprocess spent fuel under the National Enrichment, National Reprocessing Scenario (Japan, the ROK/DPRK, and China), the same 80 percent, 60 percent, and 50 percent, respectively of cooled spent fuel is assumed to be reprocessed by 2030. In this Regional Center(s) case, however, reprocessing will take place not in the countries of origin, but at a regional reprocessing center or centers. Reprocessing at the regional center(s) will start in 2025. In Japan, reprocessing at Rokkasho is assumed to ramp up to full capacity as in the National Enrichment, National Reprocessing case, and to remain at that level until the regional center(s) open in 2025. As in the National Enrichment, National Reprocessing case, 25 percent of spent fuel (suitably cooled) from RFE reactors is assumed to be reprocessed in the regional center(s). In addition, 50 percent of spent fuel from other countries (Taiwan, Indonesia, Vietnam, and Australia) is assumed to be reprocessed at the center(s), starting in 2025 and increasing to the 50 percent level in 2050, after cooling for the requisite six years.

The amount of reprocessed fuel used to make MOx fuel elements and subsequently used in LWRs is the same maximum 20 percent of total fuel use as assumed in the National Enrichment, National Reprocessing case. In years where insufficient reprocessing takes place to provide 20 percent of fuel input to reactors, existing stocks of plutonium and MOx fuel are drawn down to bring total use up to 20 percent. In years where the amount of fuel reprocessed is greater than the equivalent of 20 percent of required fuel input to reactors, excess reprocessed plutonium (either pure or mixed with depleted uranium to reduce proliferation potential) is placed in storage.

It is assumed that the remaining spent fuel from each of the countries is shipped to one or more regional center(s), which might or might not be the same locations where fuel is reprocessed, where the fuel is held in an interim dry-cask-type storage facility, pending the development of regional permanent storage (see below). It is assumed that all spent fuel in each of the countries, including spent fuel produced before the regional facility opens, is ultimately shipped to the regional center or centers.

High-level wastes from reprocessing activities in regional center(s), are assumed, as in the National Enrichment, National Reprocessing case, to be concentrated through evaporation of water and other solvents, then "vitrified" with borosilicate glass into glass "logs". Vitrified wastes are placed in interim storage facilities pending construction of final regional disposal facilities.

Spent Fuel Transport

Shipping of spent fuel, as in the National Enrichment, National Reprocessing scenario is done largely by sea, in dedicated ships, though some shipments will travel at least part of the way to the regional center(s) by road and/or rail.

Permanent Disposal of Nuclear Wastes

In this Regional Center(s) scenario, it is assumed that the countries of the region join together to develop a single facility, or possibly a very small number (2 or 3) of facilities, for permanent disposal of spent fuel or high-level wastes from nuclear activities. It is assumed, however, based on the time that would likely be required to identify and agree on sites, agree on sharing of the burden for facility construction, agree on safety and environmental protocols, and actually construct the facility or facilities, that such a waste repository would not being operations before 2050. The regional repository (or repositories) for permanent disposal would, as in the National Enrichment, National Reprocessing case, be located in stable geological strata deep underground, and designed so that nuclear materials can remain safely isolated from populations and from the biosphere indefinitely.

Low-level wastes are assumed to be the exception to the regional treatment rule for this scenario. As in the National Enrichment, National Reprocessing case, these wastes are assumed to be disposed of in the countries where they are generated, in landfills in accordance with current practice in each country.

4.3.4. "Fuel Stockpile/Market Reprocessing" Case

In this scenario, as described in the summary above, the countries of the region purchase natural and enriched uranium internationally, but cooperate to create a fuel stockpile that the nations of the region can draw upon under specified market conditions. Reprocessing services are purchased from international sources, but remaining spent fuel continues to be stored at generation sites.

The following provides a description of the approach to each of the elements of the fuel cycle under this scenario.

Uranium Mining and Milling

In the **Fuel Stockpile/Market Reprocessing** scenario, though the countries of the region do not share enrichment capacity in the same way as in the Regional Center(s) case, uranium procurement is still coordinated among countries. As in the Regional Center(s) case, a consortium formed by the uranium users in the region (operated by governments and/or utilities) again purchases refined uranium on the international market—including, as available, from the countries of the region—and supplies it to existing international enrichment facilities and to existing facilities in the countries of the region. Each country pays for the amount of enriched uranium it uses, and by extension, for the amount of refined natural uranium used to enrich fuel on its behalf.

In order to provide a more assured supply of uranium at a less volatile price to the countries of the region, the consortium that purchases enrichment services and natural uranium starts in 2015 to purchase uranium at a rate larger than the aggregate needs of its member nations. Additional purchases are made at a rate such that by 2020, the consortium has built up a stockpile of one year's worth of natural uranium. We do not explicitly define the physical location of this stockpile. It could be in a single location, but more likely would be located in a number of different places, probably on the premises of uranium millers and/or enrichment plants.

Except for the stockpiling feature just described, the operation of the fuel consortium in terms of purchases of natural uranium is assumed similar to that in Regional Center(s) case. That is, those countries that do not currently have significant uranium production do not extract their reserves or resources, and China limits its own production to current levels of output. As a result, as in the Regional Center(s) case, more uranium than in the National Enrichment, National Reprocessing case will be purchased from major suppliers. The impact of the consortium on the uranium market is that the consortium achieves an effective 5 percent "discount" relative to the prices paid in the National Enrichment, National Reprocessing scenario, largely due to economies of scale in shipping to large market enrichment facilities..

As in the Regional Center(s) case, the concentration of uranium mining and milling in major producer countries means that, relative to the National Enrichment, National Reprocessing case, less uranium mine spoils are produced in the region (with the exception of Australia).

Uranium Transport

In the Fuel Stockpile/Market Reprocessing scenario, processed uranium (yellowcake) transport largely—with the exception of some domestic transport in China—takes place between major uranium supplier countries and the site(s) of the international enrichment facility/facilities, and travels mostly by sea.

Uranium Conversion and Enrichment

As noted above, we assume that uranium is enriched by international facilities (for example, in the United States, Europe, Russia, and possibly, in the future, elsewhere). The exception to this is that enrichment facilities in Japan and China that are currently extant or under construction will also continue to be used. To quantify these assumptions, we assume that Japan will continue to supply approximately 5 percent of its enrichment needs using its existing enrichment plants (approximately equivalent to the level of recent production as reported by the World Nuclear Association[70]), and that China's enrichment production will ramp up to approximately the level reported by the World Nuclear Association as planned for 2015 (about 3 million kg SWU/yr), but not increase further[71]. These facilities will nominally be part of the regional enrichment consortium, but in practical terms would likely be controlled by, and provide enriched fuel for, the countries in which they are located. For all of the enrichment used in this scenario, uranium conversion from U_3O_8 to uranium hexafluoride for use in gas centrifuge enrichment also takes place at the location(s) where uranium is enriched, though there is no

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[70] Estimate based on World Nuclear Association (2010), "Nuclear Power in Japan", available at http://www.world-nuclear.org/info/inf79.html.

[71] World Nuclear Association (2009), "Uranium Enrichment", available as http://www.world-nuclear.org/info/inf28.html.

particular reason why under this scenario, as in the Regional Center(s) case, non-enriched UF_6 couldn't also be purchased by the consortium, when available, from international suppliers.

Market enrichment services are assumed to cost an average of 160 USD per SWU. The overall amount of enrichment capacity available for use by the consortium in international facilities and in existing or currently under-construction facilities in China and Japan is assumed to be sufficient to meet the total year-by-year enrichment needs shown in Table 4-2, suitably adjusted for MOx use.

Under this scenario the countries of the region cooperate to stockpile enriched fuel as well as natural uranium. We assume that enriched uranium, stored as LEU or in the form of fuel rods, is equal to one year's worth of overall usage by the reactors in the region. Again, we do not specify the location where enriched fuel is stored. A combination of storage at enrichment facilities, intermediate depots in the region, and at reactors themselves could conceivably be used.

Fuel Fabrication

Fabrication of LEU fuel in the Fuel Stockpile/Market Reprocessing case is assumed to take place at the international centers where enrichment is carried out. As in the Regional Center(s) case, to the extent that different reactor types use different fuel types, this will oblige the enrichment facility/facilities to be capable of producing fuel in different configurations.

Where MOx fuels are used by the countries of the region, the international center(s) that handle fuels—including LEU fresh reactor fuel and spent fuels—from the region are also assumed responsible for fabricating MOx fuel pellets, fuel rods, and fuel assemblies. We make no specific assumption as to whether this fuel fabrication takes place at international enrichment or international reprocessing facilities (if not co-located), though in practice, as in the Regional Center(s) case, it seems likely that the fuel fabrication would take place where reprocessing takes place in order to reduce the transport of fully or partially separated plutonium.

Transportation of Fresh Reactor Fuel

Reactor fuel is assumed to be transported mostly by ship from international enrichment plants (and, in the case of MOx fuel, from international reprocessing plants) to nuclear plants around the region where they are consumed, with the possible exception of the nation(s) where the enrichment plant(s) is/are located. Depleted uranium from enrichment activities, again either as UF_6 or in the form of uranium metal or oxide, will need to be transported to locations where it will be stored and ultimately disposed of or used.

Electricity Generation

As in the other scenarios, electricity generation using nuclear fuels—meaning the pattern of evolution of nuclear capacity and electricity production by nuclear power plants—follows the Business as Usual, Maximum Nuclear, and Minimum Nuclear paths for each country as described in Chapter 3 of this report.

We assume that the use of MOx fuels by the countries of the region in this Fuel Stockpile/Market Reprocessing scenario parallels that described for the National Enrichment, National Reprocessing and Regional Center(s) cases above in terms of timing and amount of MOx fuel used.

Spent Fuel Management, Including Reprocessing

As in the National Enrichment, National Reprocessing and Regional Center(s) scenarios, we assume that in all countries, spent reactor fuel, including spent MOx fuel, will be stored in spent fuel pools at reactor sites for at least six years before being moved to other storage or reprocessing. In the same countries (Japan, the ROK/DPRK, and China) that are assumed to reprocess spent fuel under the two scenarios discussed above, the same 80 percent, 60 percent, and 50 percent, respectively of cooled spent fuel is assumed to be reprocessed by 2030. In this case, however, reprocessing will take place not in the countries of origin, but at an international reprocessing center or centers. Reprocessing of spent fuel from the region at the international center(s) will continue from 2009 for Japan (which has had fuel reprocessed in Europe for many years), and will start in 2015 for other nations. In Japan, commercial reprocessing at Rokkasho is assumed NOT to occur (Rokkasho has, as of this writing, operated in a pilot testing mode only[72]), as in this path Japan, like other countries, uses capacity at (mostly existing) international centers to accomplish its reprocessing. .

As in the National Enrichment, National Reprocessing and Regional Center(s) cases, 25 percent of spent fuel (suitably cooled) from RFE reactors is assumed to be reprocessed in international reprocessing center(s). In addition, 50 percent of spent fuel from other countries (Taiwan, Indonesia, Vietnam, and Australia) is ultimately assumed to be reprocessed at international center(s), after cooling for the requisite six years.

It is assumed that the remaining spent fuel from each of the countries is shipped to one or more international center(s), which might or might not be the same locations where fuel is reprocessed, and which might or might not be located in the Asia/Pacific region. At this center or centers, the spent fuel not reprocessed (and spent MOx fuel) is held in interim dry-cask-type storage, pending the development of regional permanent storage (see below). Shipping of spent fuel, as in the Regional Center(s) case, is done largely by sea, in dedicated ships, though some shipments will travel at least part of the way to their destinations by road and/or rail.

High-level wastes from reprocessing activities in international center(s) are assumed, as in the National Enrichment, National Reprocessing and Regional Center(s) cases, to be concentrated through evaporation of water and other solvents, then “vitrified” with borosilicate glass into glass “logs”. Vitrified wastes are placed in international interim storage facilities pending construction of final disposal facilities.

Permanent Disposal of Nuclear Wastes

Similar to the Regional Center(s) scenario, in the Fuel Stockpile/Market Reprocessing case it is assumed that ultimately the countries of the region join together with other nations outside the region to develop a small number (3 to 5?) of international facilities for permanent disposal of spent fuel or high-level wastes from nuclear activities. It is assumed, however, as in the Regional Center(s) case, that the highly involved and complex (and controversial) nature of agreements needed to develop the facilities, in addition to the technical challenges in constructing the facilities, would mean that the centers would not begin operations before 2050. The international repositories for permanent disposal would, as in the National Enrichment, National Reprocessing case, be located in stable geological strata deep underground, and

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[72] Recent news reports suggest that full commercial operations at the Rokkasho plant may not start until late 2010 at the earliest (See, for example, Citizens' Nuclear Information Center (2009), “Rokkasho Reprocessing Plant: 14 Month Delay” available as http://cnic.jp/english/newsletter/nit132/nit132articles/rokkasho.html.), though the plant has undergone several years of pilot testing with spent nuclear fuel, meaning that key operational infrastructure at the plant has now been rendered radioactive.

designed so that nuclear materials can remain safely isolated from populations and from the biosphere indefinitely[73]. Some of the repositories could be located inside the region, or all might be located elsewhere.

As in other cases, low-level and solid wastes from the nuclear fuel cycle are assumed to be disposed of in the countries where they are generated, in landfills in accordance with current practice in each country. This is assumed to be the case whether the wastes are generated in the course of operations of nuclear power plants (in which case they are assumed to be disposed of relatively near the reactors), or associated with international enrichment or reprocessing facilities (in which case are they disposed of in the countries that would host the facilities).

4.3.5. "Market Enrichment/Dry Cask Storage" Case

In the "**Market Enrichment/Dry Cask Storage**" case, the overarching assumption for nuclear fuel supply is that the countries in the region, as in the "Fuel Stockpile/Market Reprocessing" case, continue (or in the cases of countries new to nuclear power, arrange) to purchase at least most of their combined requirements of enrichment services from international suppliers in Europe, North America, or elsewhere. A short list of possible additional suppliers would probably include Russia, and possibly China. All spent fuel, after cooling in ponds at reactor sites, would be put into dry cask storage either at reactor sites or at national or sub-national intermediate storage facilities. In this case, reprocessing does not take place or is rapidly phased out, and MOx fuel is not used in reactors.

The following describes the approach to the nuclear fuel cycle elements under this scenario.

Uranium Mining and Milling

In the Market Enrichment/Dry Cask Storage case the countries of the region use international enrichment capacity in the same way as in the Fuel Stockpile/Market Reprocessing case. A consortium formed by the uranium users in the region begins to purchase refined uranium on the international market in 2015—including, as available, from the countries of the region—and supplies it to existing international enrichment facilities and to existing facilities in the countries of the region (in Japan, China, and Russia). Under this scenario, Japan and China cease expanding their enrichment facilities, but continue to use existing facilities until the end of their operating lives. We make no specific assumption about changes in enrichment capacity in Russia (outside of the RFE); Russia will likely continue to be a key supplier of enrichment services globally. As in the Fuel Stockpile/Market Reprocessing scenario, the consortium purchases uranium at a rate larger than the aggregate needs of its member nations. Additional purchases are made at a rate such that by 2020, the consortium has built up a stockpile of one year's worth of natural uranium. The stockpile could be in a single location, but more likely would be located in a number of different places, probably on the premises of uranium millers and/or enrichment plants.

As in the two previous cases described, those countries that do not currently have significant uranium production do not extract their reserves or resources, and China limits its own production to current levels of output. The concentration of uranium mining and milling in

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[73] See, for example, W. Pickard (2009), "Finessing the fuel: Revisiting the challenge of radioactive waste disposal", Energy Policy, Volume 38, Issue 2, February 2010, Pages 709-714. Abstract available as http://dx.doi.org/10.1016/j.enpol.2009.11.022.

major producer countries means that, relative to the National Enrichment, National Reprocessing case, less uranium mine spoils are produced in the region (with the exception of Australia).

Uranium Transport

As in the Fuel Stockpile/Market Reprocessing and Regional Center(s) scenarios, processed uranium transport largely—with the exception of some domestic transport in China—takes place between major uranium supplier countries and the site(s) of the international enrichment facility/facilities, and travels largely by sea.

Uranium Conversion and Enrichment

As noted above, we assume that uranium is enriched by international facilities (for example, in the United States, Europe, Russia, and possibly, in the future, elsewhere). The exception to this is that enrichment facilities in China that are currently extant or under construction will also continue to be used, and existing enrichment facilities in Japan will be used through 2020, when they will be decommissioned. New enrichment facilities currently under construction in Japan are not completed in this scenario. Chinese facilities will nominally be part of the regional enrichment consortium, but in practical terms would likely be controlled by and provide enriched fuel for China. For all of the enrichment used in this scenario, uranium conversion from U_3O_8 to uranium hexafluoride also is assumed to take place at the location(s) where uranium is enriched, or non-enriched UF_6 is purchased from international suppliers.

As in previous scenarios, market enrichment services are assumed to cost an average of 160 USD per SWU, and the overall amount of enrichment capacity available for use by the regional consortium is assumed to be sufficient to meet the total year-by-year enrichment needs as described earlier (Table 4-2).

As in the previous scenario, the countries of the region cooperate to stockpile enriched fuel as well as natural uranium. Enriched uranium is stored as LEU or in the form of fuel rods, and the stockpile is equal to one year’s worth of overall usage by the reactors in the region. A combination of storage at enrichment facilities, intermediate depots in the region, and at reactors themselves could be used. As a result, with regard to fuel enrichment and related activities (“Yellowcake” conversion to uranium hexafluoride, and transport of natural uranium) the only difference between this scenario and the "Fuel Stockpile/Market Reprocessing" scenario is that the existing enrichment capacity in Japan is actually shut down in 2021.

Fuel Fabrication

Fabrication of LEU fuel in the Market Enrichment/Dry Cask Storage case is assumed to take place at the international centers where enrichment is carried out. To the extent that different reactor types use different types of fuel rods, this will oblige the enrichment facility/facilities to be capable of producing fuel in different configurations.

MOx fuels are not used by the countries of the region in this scenario, with the exception of the small amount of MOx fuel use now (as of 2010) underway at the Genkai plant in Japan, which is assumed to be phased out by 2013.

Transportation of Fresh Reactor Fuel

Reactor fuel is assumed to be transported from international enrichment plants to nuclear plants around the region mostly by ship. Depleted uranium from enrichment activities, again either as UF_6 or in the form of uranium metal or oxide, will need to be transported to locations where it will be stored and ultimately disposed of or used.

Electricity Generation

As in the other scenarios, electricity generation using nuclear fuels—meaning the pattern of evolution of nuclear capacity and electricity production by nuclear power plants—follows the Business as Usual, Maximum Nuclear, and Minimum Nuclear paths for each country as described in Chapter 3 of this report.

Spent Fuel Management, Including Reprocessing

In the Market Enrichment/Dry Cask Storage case, we assume that those countries of the region that do not reprocess or have not reprocessed their spent reactor fuel do not reprocess in the future, and that the remaining countries of the region—Japan and China—cease reprocessing activities by 2015. In Japan, this means that Rokkasho is not brought to commercial operation, and that the pilot reprocessing activities at the Lanzhou plant in China is shut down by 2015. Reactor fuel from power plants in the Russian Far East is likewise not reprocessed (the scenario does not specify the fate of spent fuel from elsewhere in Russia).

In the absence of regional/international reprocessing or regional/international spent fuel management, each of the countries of the region is obliged to store its own spent fuel, likely in dry casks, and either at reactor sites or in national or sub-national interim storage facilities. For the purposes of this scenario, we assume that dry cask storage takes place at reactor sites through 2050 in all countries except Japan, where interim national storage is used (the Mustu facility and perhaps an additional similar facility developed later). This minimizes the shipping required to shipping exclusively within countries, though in some nations (such as Japan and Indonesia) this could mean that some spent fuel could travel by sea, as well as road and/or rail, to reach where it will be stored. Dry cask storage at these facilities is assumed to be for an indefinite period.

Dry cask storage facilities in all countries, though local, are assumed to be administered by an international consortium of the nations of the region, possibly the same consortium that purchases enriched uranium for the region's reactors. This administration might in part, for example, take the form of a handful of monitoring staff from the countries of the region, employed by the consortium, at each site where spent fuel is stored. The costs for maintaining dry cask storage facilities in each country could be (and, in this scenario, are assumed to be) paid for by a cost adder for each kWh of electricity from nuclear power sold in each country, and collected by the regional consortium. The amount of these "adders" collected would be set so as to be sufficient to fund a kind of "annuity" or "trust fund" that would pay for monitoring (and, for example, replacing of casks) in perpetuity, assuming some rate of interest on collected and invested funds, an average rate of inflation, and, to ensure that collections are adequate to support spent fuel management even if costs rise in real terms, assuming an average rate of escalation of spent fuel management costs beyond inflation.

High-level wastes from past reprocessing activities in international center(s), and plutonium (suitably mixed with other elements to deter proliferation) from reprocessing activities already undertaken (or completed by 2015) are assumed to be concentrated through evaporation of water and other solvents, then "vitrified" borosilicate glass into glass "logs". Vitrified wastes are placed in international interim storage facilities pending construction of final disposal facilities.

Permanent Disposal of Nuclear Wastes

In the Market Enrichment/Dry Cask Storage scenario, it is assumed that international facilities for permanent disposal of spent fuel and high-level wastes from nuclear activities will NOT be developed by 2050. Such facilities may be investigated by the international community, but at a very deliberate pace, allowing technologies for waste isolation (and for identifying safe sites for waste isolation) to develop over time, while spent fuel and other high-level wastes are held in dry casks and other interim storage designed to last 100 years or more. . As in other cases, low-level wastes are assumed to be disposed of in the countries where they are generated, in landfills in accordance with current practice in each country.

4.4. Common Assumptions

Annex C provides details on the parameters—such as costs, waste production per unit uranium used, conversion losses, energy input to fuel cycle processes, and other quantities—used in evaluating the Scenarios described above. The literature sources, derivation, and/or guesswork behind these parameters, some of which have little uncertainty associated with them, and some of which are the roughest of assumptions, are also listed in Annex C. A brief listing of some of the key assumptions used in analyzing the scenarios follows.

- Uranium Cost/Price: $120/kg in 2009, escalating at 0.5%/yr in real terms through 2050.
- Average uranium concentration in ore from international market sources: 3.2%[74].
- International enrichment fractions by type: 30% gaseous diffusion in 2007, declining to 0% by 2030, with the remainder being provided by centrifuge-based enrichment.
- Enrichment costs: $160/kg SWU in 2009, with no real escalation in costs through 2050.
- Raw uranium transport costs set at roughly container freight (ship) transport rates, with non-shop uranium transport costs at average bulk freight rail rates in the United States.
- Cost of U_3O_8 conversion to UF_6: $6.2/kg U.
- Cost of UOx fuel fabrication: $270/kg heavy metal (HM).
- Cost of MOx fuel blending/fabrication: $1800/kg HM.
- Fraction of Pu in MOx fuel: 7%.
- Spent fuel transport costs by ship at about $40/tHM-km.
- Cost of reprocessing: $1200/kg HM (except in Japan, where it is assumed to be $3400/kg HM, based roughly on the costs of Rokkasho).
- The effective average lag between the placement of nuclear fuel in service and its removal cooled from spent fuel pools is taken to be 8 years.

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[74] 3.2 percent represents an estimated 2008 global weighted-average ore grade (% as U) for countries where grade estimates were available (see Annex C for derivation and sources used to prepare this estimate). This figure is substantially inflated by the existence of a single very high ore grade, very productive mine in Canada (MacArthur River) with an ore grade over 20%. Taking Canadian production out of the calculation, the average ore grade for uranium produced worldwide in 2008 was about 0.11 percent.

- Cost of treatment and disposal of high-level wastes: $150/kg HM reprocessed.
- Mass of Pu separated during reprocessing: 11 kg/t HM.
- Cost of storage/safeguarding Pu: $3000/kg Pu-yr.
- Capital cost of dry casks (UOx or MOx): $0.8 million/cask.
- Average capacity of dry casks: 10 tonnes spent fuel (heavy metal content).
- Operating cost of dry cask storage: $10,000/cask-yr.
- Cost of interim spent fuel storage (total): $360/kg HM.
- Cost of permanent storage of spent fuel: $1000/kg HM (but not implemented or charged to any scenario by 2050).

5. Evaluation of Fuel Cycle Options—Material Flows, Costs, Other Energy Security Costs and Benefits, and Legal/Political Constraints

5.1. Introduction

In the Chapter that follows we present the results of the analysis of the regional cooperation scenarios described in Chapter 4 of this report, in the context of the nuclear capacity expansion paths by country described in Chapter 3. In so doing, we describe in general the methods used to estimates key parameters of national and regional nuclear fuel cycles—including material flows, energy requirements, and costs—for the different facets of the fuel cycle, and present summary results. Additional details regarding the inputs/assumptions used and their sources, the calculations used in these analyses, and detailed analytical results by nuclear energy path, regional scenario, and country can be found in the workbook printouts provided as Annexes B and C to this Report. The sections of the remainder of this Chapter therefore describe and discuss:

- Estimates of the amount of uranium enrichment capacity required for each nuclear capacity path and for each regional scenario.
- Estimates of the amount of spent fuel and related materials implied by each combination of nuclear capacity expansion paths and regional cooperation scenarios, including implications for spent fuel storage/disposal, reprocessing, and related capacities required.
- Estimates of other parameters of the nuclear fuel cycle, from uranium mining and milling through nuclear waste management, including nuclear materials transport requirements, and energy and water needs for key parts of the fuel cycle.
- Rough, initial estimates of the relevant costs of nuclear fuel cycle activities under each combination of nuclear path and region scenario. Note that these costs do not at present include the capital and non-fuel operating and maintenance costs nuclear reactors, and as a result costs across nuclear paths (for example, between "maximum nuclear" and "minimum nuclear" paths) are not strictly comparable. In future work, we intend to include estimates of nuclear reactor costs, and of the costs of other types of generation needed to satisfy national power demand, in order to offer a more complete cost comparison between nuclear paths.
- A summary evaluation of the relative energy security costs and benefits associated with each of the regional nuclear fuel cycle scenarios, using the broad definition of energy security summarized in Chapter 1 of this Report and detailed in previous Nautilus publications.
- An overview of some of the legal and political constraints on regional nuclear fuel cycle options in East Asia and the Pacific. These constraints constitute challenges that would need to be overcome or worked around in devising a strategy of nuclear fuel cycle cooperation in the region that enhances security but can be practically applied.

5.2. Estimate of Uranium Enrichment Requirements

Below we describe the results of our analysis of uranium enrichment requirements—both within and outside of the East Asia and the Pacific region. We provide an overview of the methods used to generate these estimates, followed by a summary of results.

5.2.1. Needs by Country and by Path: Methods

Starting with the assumptions as to nuclear reactor capacity and electricity output by country described in Chapter 3 of this report, we estimated requirements for uranium enrichment capacity by assuming an average rate of fuel "burn-up" of 50,000 MW-days (thermal) per tonne of heavy metal in nuclear fuel, and an average level of uranium enrichment of 4.51 percent U_{235}, for years after 2007. We recognize that some current reactors will have different levels of fuel burn-up, and some advanced LWRs deployed in the future may achieve higher levels of burn-up, thus the values chosen are meant to be representative averages. The 4.51 percent average enrichment level implies an average requirement for separative work units (SWU) in enrichment after 2007 of 7.04 kg SWU per kg U in the enriched product fuel. We assume that all new (in-region) enrichment takes place in gas centrifuge enrichment plants, and that the more energy-cosumptive gaseous diffusion plants are phased out of use (at least for enriching fuel used in the region) by 2030. These parameters were combined with assumptions as to the timing and extent (fraction of required enriched fuel) of in-country enrichment operations by regional cooperation scenario, as described in Chapter 4, to generate required levels of enrichment by country, nuclear capacity expansion path, and cooperation scenario for the years 2000 through 2050. Since some of the scenarios involve the use of MOx fuel, which reduces enriched uranium requirements, the overall requirements for enriched fuel were adjusted downward in those scenarios to account for the fraction of reactor fuel that is MOx fuel in each year.

5.2.2. Needs by Country and by Path: Results

In the BAU nuclear capacity expansion path, total regional annual requirements for uranium enrichment rise from just over 1000 metric tones enriched U (about 8.3 million kg SWU) in 2000 to nearly about 6400 (just under 45 million SWU) for those scenarios in which MOx fuel is used to 7000 tonnes (just under 50 million SWU) when MOx is not heavily used, in 2050 (Figures 5-1 and 5-2). In the National Enrichment, National Reprocessing Scenario (Scenario1), the bulk of this enrichment occurs in-country, with China developing capacity sufficient to supply, after use of MOx fuel is accounted for, about 3400 tonnes of enriched uranium annually be 2050, Japan producing 1100 tonnes, the ROK 700 tonnes, and the Russian Far East somewhat over 100 tonnes, though the RFE's uranium requirements would most likely be supplied from facilities in other regions of Russia. In Scenario 2, the "Regional Center(s)" Scenario (Scenario 2), very little enrichment at national facilities is used in the countries of the region, with most (all, by 2015) enrichment done at regionally-operated facilities. In the other two scenarios, "Fuel Stockpile/Market Reprocessing" Scenario (Scenario 3) and "Market Enrichment/Dry Cask Storage" Scenario (Regional Scenario 4), only modest in-country enrichment for domestic purposes takes place, most of it (all, by 2022) in China. The remainder of enriched uranium and enrichment services in Scenarios 3 and 4 are purchased on the international market, which could include purchases from facilities in the region.

Figure 5-1: Requirements for Enriched Uranium by Scenario, Adjusted for MOx Use, BAU Nuclear Capacity Expansion Path

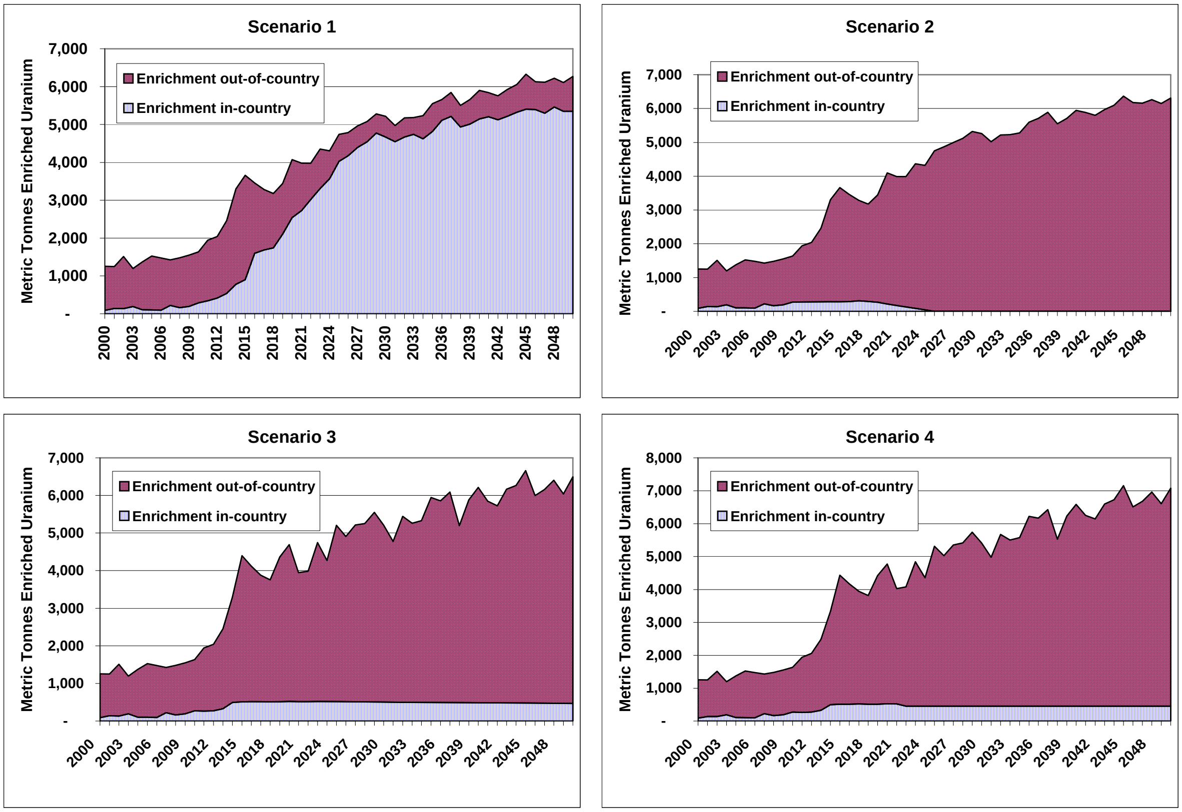
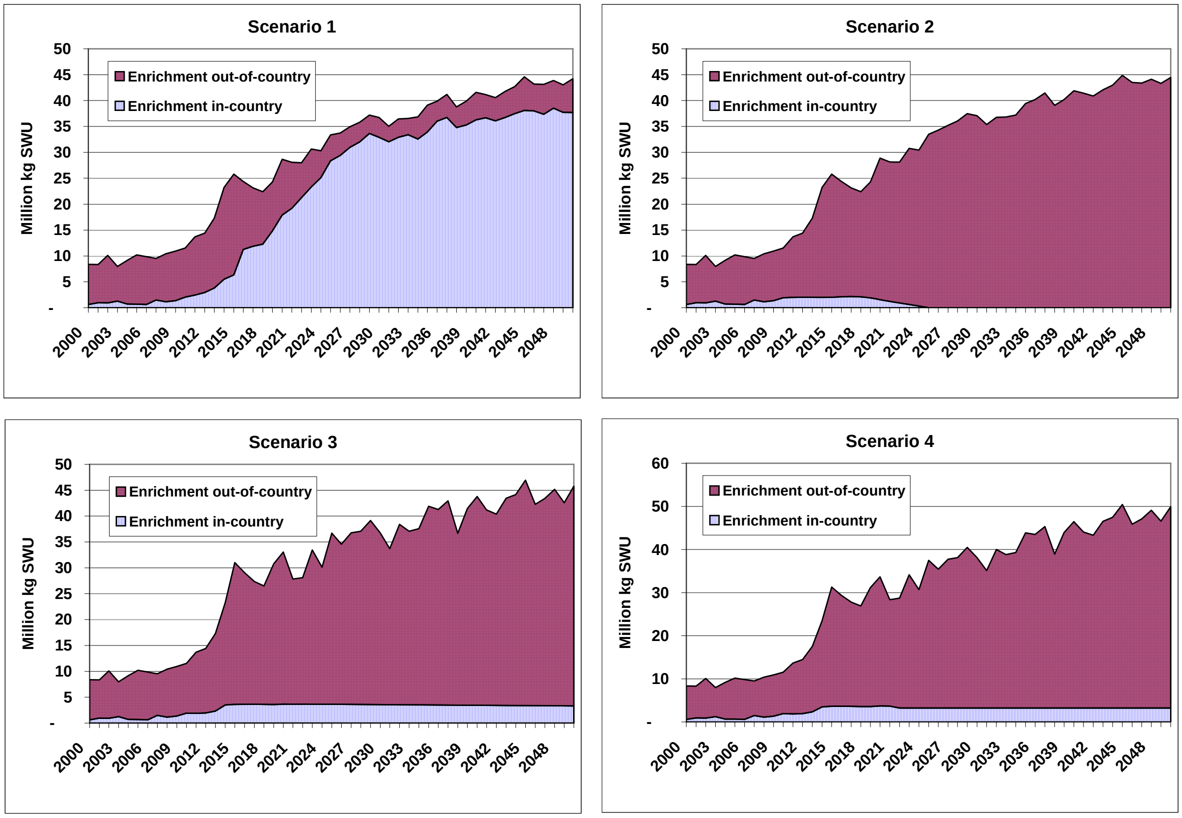


Figure 5-2: Estimated Enrichment Services by Scenario, Adjusted for MOx Use, BAU Nuclear Capacity Expansion Path



Figures 5-3 through 5-6 present the enrichment services requirements results shown in Figure 5-2 differentiated by country, but not by source of enrichment services. In all scenarios, not surprisingly, growth in enrichment services needs in China dominate, with needs for enricument in countries new to nuclear power, most notably Vietnam, increasing becoming significant in the 2030 to 2050 period. In Figures 5-5 and 5-6, the volume of enrichment services required to build a regional stockpile is significant initially (in about 2015 to 2020), though in practice such a stockpile might be built up more gradually than is modeled here.

Figure 5-3: Estimated Enrichment Services by Country for Scenario 1, Adjusted for MOx Use, BAU Nuclear Capacity Expansion Path

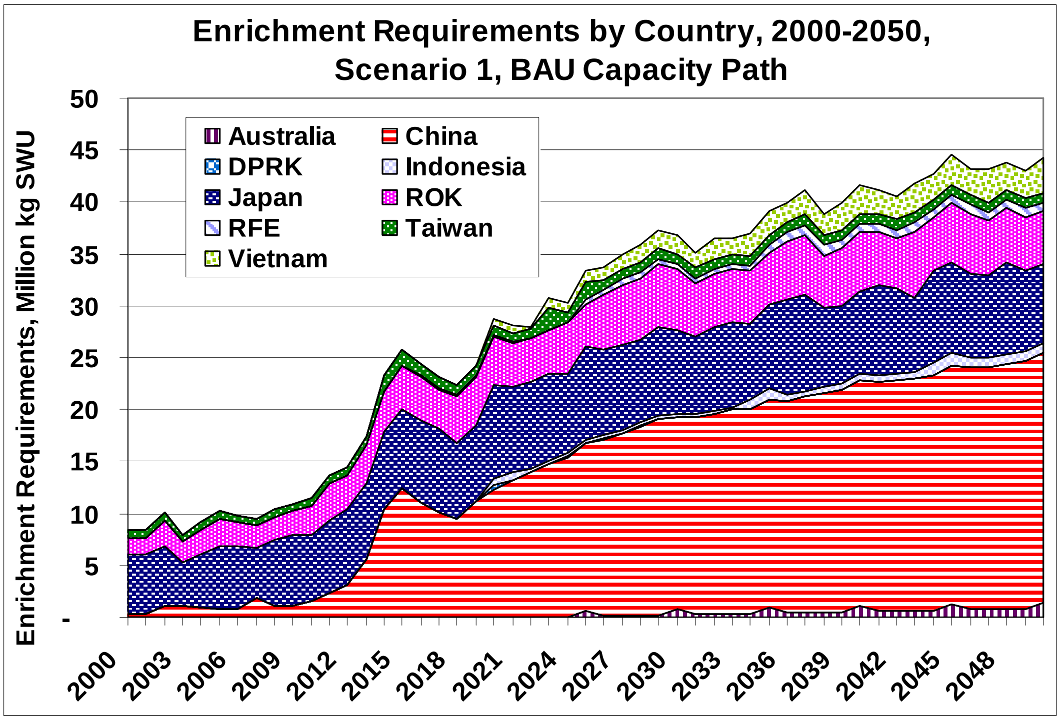


Figure 5-4: Estimated Enrichment Services by Country for Scenario 2, Adjusted for MOx Use, BAU Nuclear Capacity Expansion Path

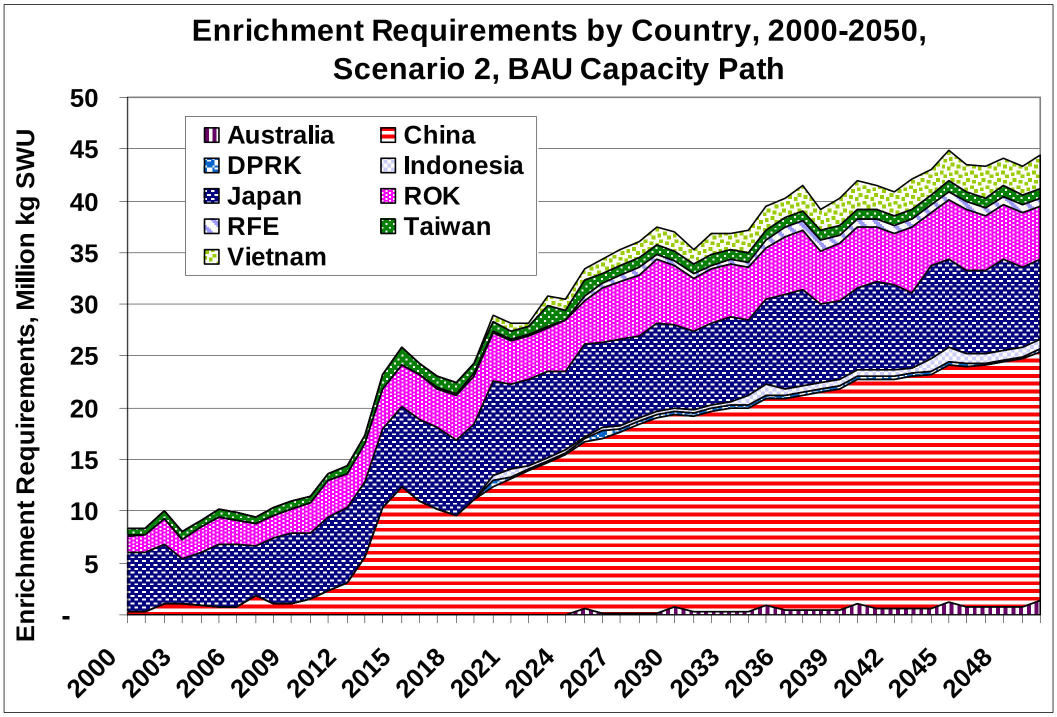


Figure 5-5: Estimated Enrichment Services by Country for Scenario 3, Adjusted for MOx Use, BAU Nuclear Capacity Expansion Path

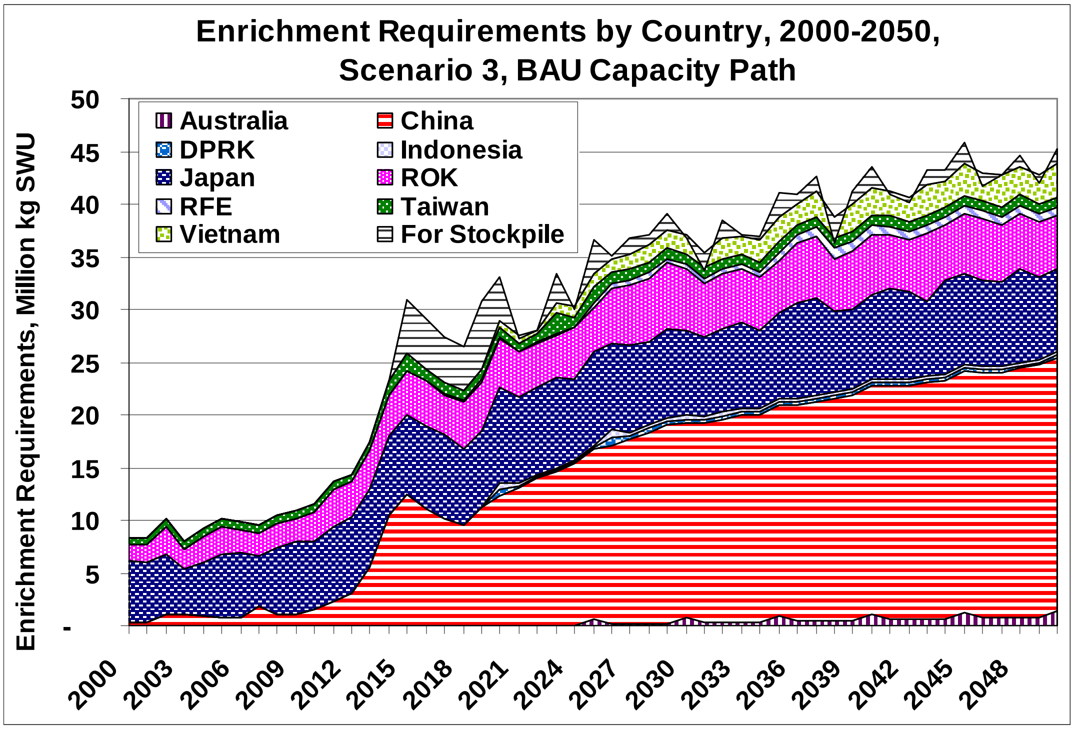
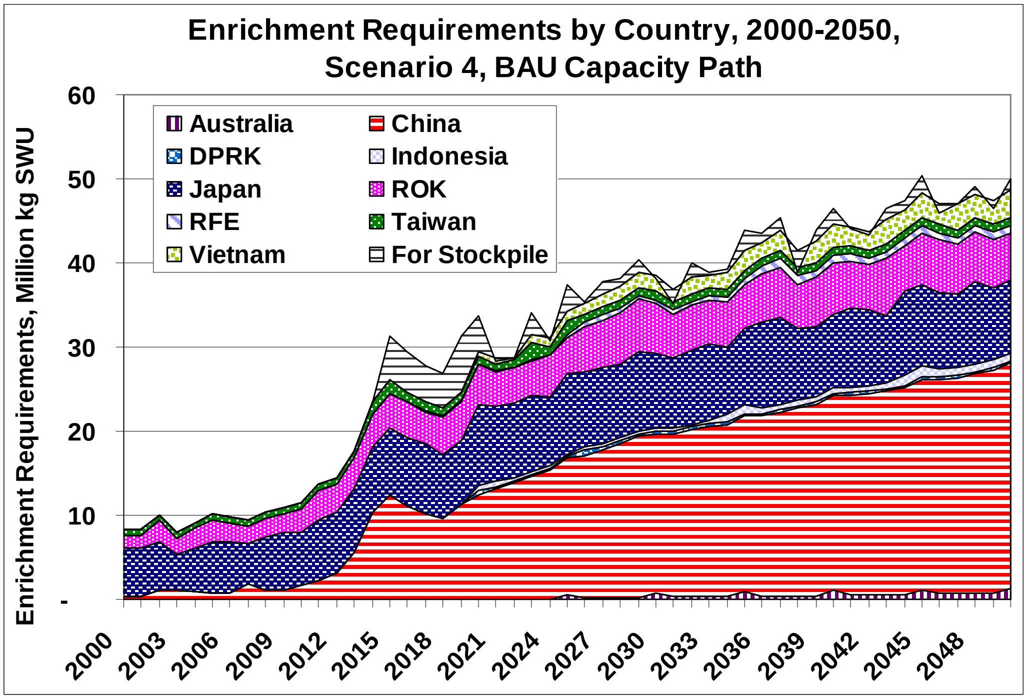


Figure 5-6: Estimated Enrichment Services by Country for Scenario 4, Adjusted for MOx Use, BAU Nuclear Capacity Expansion Path



Similar patterns of in-country enrichment for use in domestic reactors and enrichment in regional or international centers are shown if maximum (MAX) or minimum (MIN) nuclear capacity expansion paths are assumed, but the ultimate enrichment requirements by 2050 are quite different. In scenarios using MAX path, enrichment needs rise to over 10,000 metric tones enriched U annually by 2050 (about 70 million SWU) in scenarios without substantial MOx use, and about 10 percent less than that in scenarios with MOx use, with annual requirements in the MIN path falling from a maximum of about 3000 te enriched U (about 20 million SWU) in the 2020s to about 2100 te (about 15 million SWU) in 2050.

Under Scenario 1, additional enrichment capacity in the countries of the region will need to be developed under any nuclear capacity expansion path. Under the other regional cooperation scenarios, estimated global enrichment capacity by 2015 (about 69 million SWU; as described by the World Nuclear Association[75], and including 3.3 million SWU in China, 33 million SWU in Russia, and 0.75 million SWU in Japan) would likely need to be expanded significantly by 2050 to meet the combination of regional and out-of-region enrichment demand under the BAU or MAX nuclear capacity expansion paths. Under the MAX expansion path and Scenario 1, China would be obliged to build by 2050 new enrichment capacity approximately equal to 60 percent of today's **global** capacity for production of enriched uranium. Under the MIN nuclear capacity expansion path, international enrichment facilities as of 2015 seem likely to be sufficient to meet regional and out-of-region demand without significant expansion, though some facilities decommissioned before 2050 might need to be replaced, depending on trends in nuclear power in other regions of the globe. Figures

5.3. Estimate of Required Spent Fuel Storage/Disposal/Reprocessing Capacity, and Production of Related Wastes

An essential set of results to compare across scenarios are those related to the "back-end" of the nuclear fuel cycle, namely reprocessing and/or storage/permanent disposal of spent nuclear fuels and their major co-products. Below we summarize the methods used to estimate spent fuel arisings and related co-products and waste products.

5.3.1. Needs by Country and by Path: Methods

In estimating spent fuel arisings, we first calculate the amount of fuel consumed in each country, each nuclear energy capacity expansion path, and each scenario, as described above. Then we estimate the total spent fuel (including MOx spent fuel) that emerges from at-reactor spent fuel pools cooled and ready for further processing in each year. This estimate is prepared by simply lagging the quantity of reactor fuel input by a number of years—our initial assumption has been to assume eight years—to account for the amount of time nuclear fuel spends in the reactor itself plus time spent cooling in spent fuel pools. After eight years, we count the spent fuel as available for reprocessing or ready to be placed in at-reactor dry-cask storage, domestic interim away-from-reactor storage, domestic permanent storage/disposal, regional interim away-from-reactor storage, or regional permanent storage/disposal. For the fraction of cooled spent

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[75] World Nuclear Association, "Uranium Enrichment, dated January 27, 2010, and available as http://www.world-nuclear.org/info/inf28.html.

fuel that is reprocessed, we track the production of plutonium, uranium, high-, mid-, and low-level wastes, and solid wastes. The amount of plutonium blended to MOx fuel is deducted from the amount produced, and the rest is assumed to remain in storage.

As a rough comparison, we estimate the amount of capacity in spent fuel pools at reactors in the region, using published figures of capacity for existing reactors to estimate capacity of pools at reactors to be built in the future. We then assume that when pools are 90 percent full in each country, spent fuel must be placed in some other kind of storage (dry-cask, interim, or permanent).

The result is that we have two "metrics" of spent fuel sent to storage—the amount of spent fuel (less the quantity reprocessed) that emerges from spent fuel pools each year, and the amount deemed to be needed to be discharged from spent fuel pools once pools are 90 percent fuel. Neither is a perfect metric: some spent fuel can be expected to remain in pools far longer than five or six years; and national spent fuel capacity is not an ideal measure of remaining space at reactors, since it is often not easy to move fuel from reactor to reactor (for physical, political, or legal reasons, for example). These metrics nonetheless provide a means of comparing different spent fuel management scenarios.

5.3.2. Needs by Country and by Path: Results

Given the assumptions outlined above, Figure 5-7 presents an estimate of the amount of uranium oxide (UOx, that it, not MOx) spent fuel that has been cooled in spent fuel pools and is ready for reprocessing or for some type of storage/disposal. This figure presents results for the BAU nuclear capacity expansion path under Scenario 1, and shows that the total annual spent fuel available for disposal rises to about 5000 tonnes heavy metal (tHM) by 2050. Similar results for the MAX and MIN nuclear capacity expansion paths are not shown, but annual UOx spent fuel in the MAX case rises to about 7000 tHM by 2050, while reaching a maximum of aobut 2600 tHM/yr in the MIN case by the 2030s, falling to about 2000 tHM/yr by 2050. As shown in Figure 5-8, an additional 400 tHM/yr of cooled MOx fuel would need to be stored or disposed of by 2050 in the BAU nuclear expansion path and regional cooperation Scenario 1 (about 140 tonnes/yr under the MIN path, and 540 tonnes/yr under the MAX path). On a cumulative basis (Figure 5-9) UOx fuel to be reprocessed, stored, or disposed of in the BAU path rises to about 140,000 tonnes (including spent fuel from reactors installed before 2000) by 2050.under the BAU path, as compared with 174,000 in the MAX path, and 99,000 in the MIN path. Regional Scenario 4, in which very little reprocessing takes place, produces more UOx spent fuel, but only a few percent more. Figure 5-10 shows cumulative MOx spent fuel cooled and ready for storage/disposal in the National Enrichment, National Reprocessing regional Scenario 1 with the BAU nuclear capacity expansion path. As noted earlier in this report, however, spent MOx fuel and spent UOx fuel have different radiological properties, and thus might not, ultimately, be managed in the same way, though this analysis to date has assumed that UOx and MOx spent fuel **would** be managed similarly.

Figure 5-7: Estimated Cooled Spent Cooled UOx Fuel Produced Annually, By Country, BAU Nuclear Capacity Expansion Path, and Regional Scenario 1 (tonnes heavy metal in fuel)

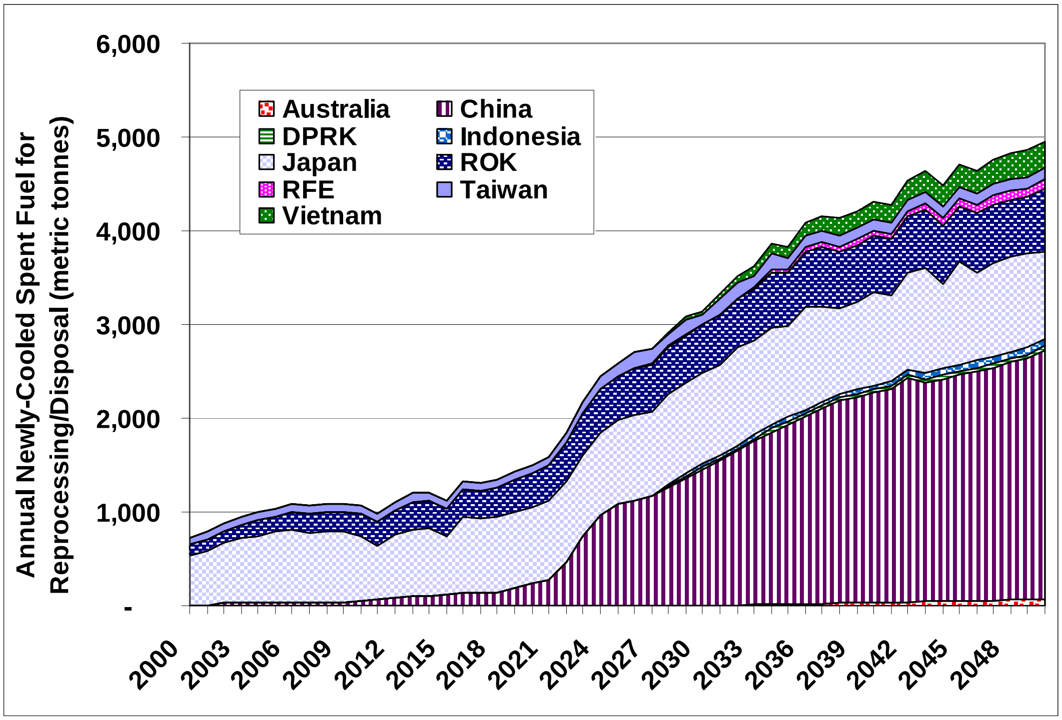


Figure 5-8: Estimated Cooled Spent Cooled MOx Fuel Produced Annually, By Country, BAU Nuclear Capacity Expansion Path and Regional Scenario 1 (tonnes heavy metals in fuel)

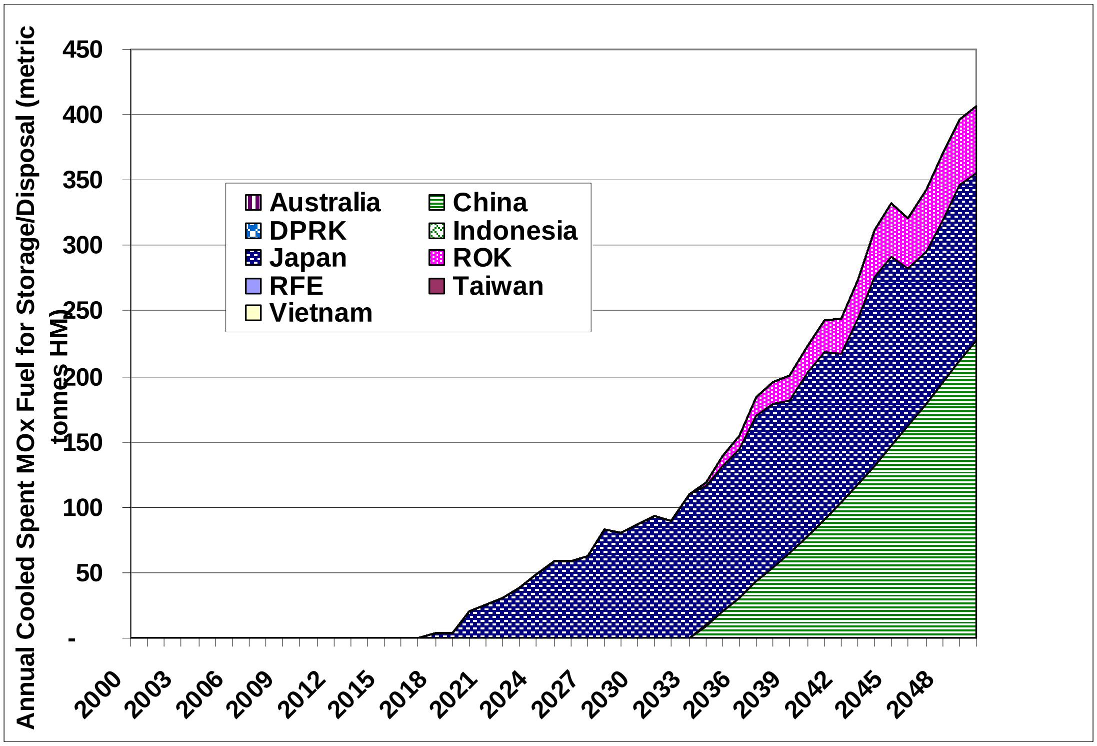


Figure 5-9: Cumulative Estimated Cooled Spent Cooled UOx Fuel Produced, By Country, BAU Nuclear Capacity Expansion Path and Regional Scenario 1 (tonnes heavy metals in fuel)

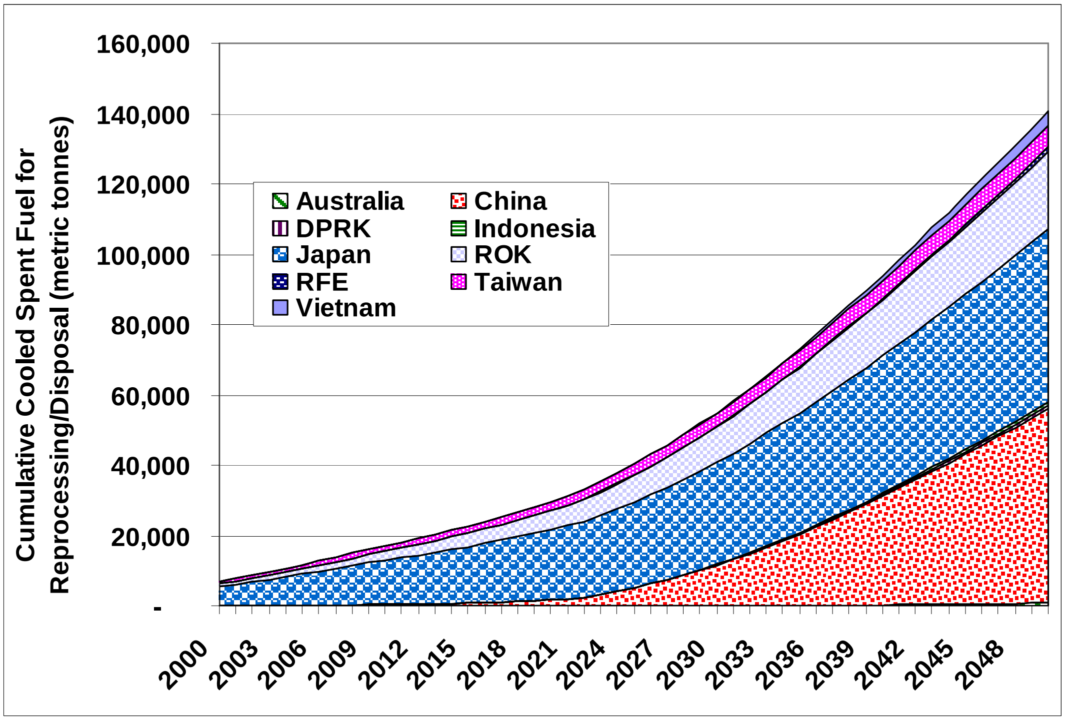


Figure 5-10: Cumulative Estimated Cooled Spent Cooled MOx Fuel Produced, By Country, BAU Nuclear Capacity Expansion Path and Regional Scenario 1 (tonnes heavy metals in fuel)

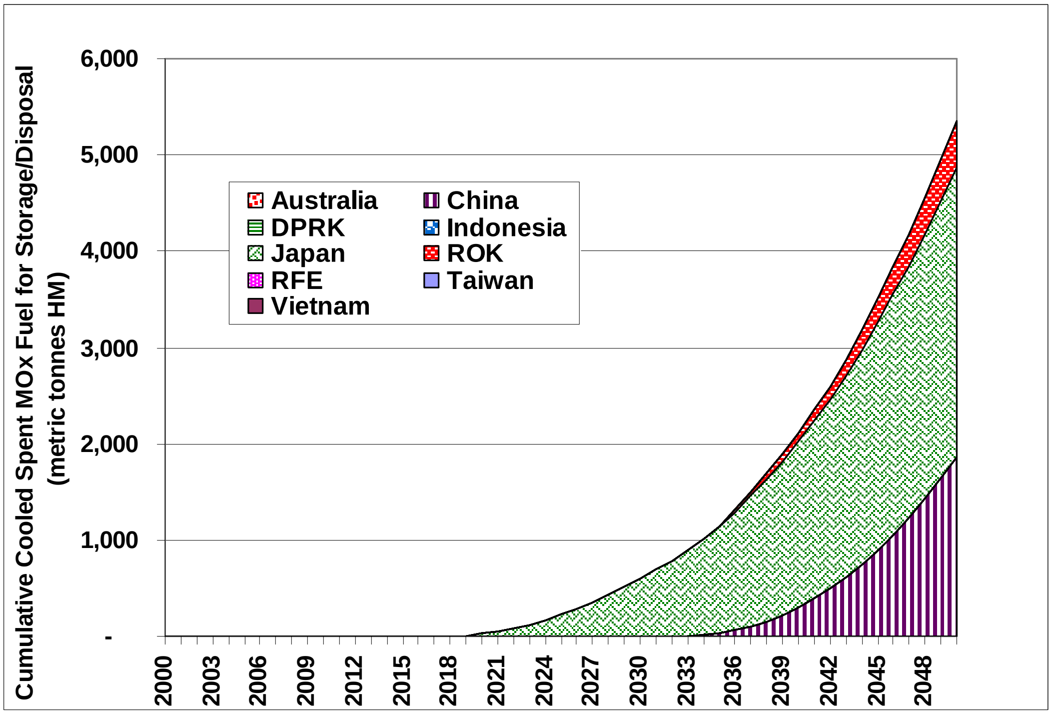


Figure 5-11 offers a comparison, albeit a rather complicated one, between the amount of spent fuel pool capacity available (again, with the very rough assumption that cooled fuel must be moved to some other kind of storage or disposal when spent fuel pools in a nation are 90 percent full). This graph indicates that under the BAU nuclear capacity expansion path and Regional Scenario 1, China would have to find storage for about 36,000 tonnes of spent fuel by 2050, Japan would need storage for over 20,000 tonnes, and the ROK would need about 13,000 tonnes of storage. Because Taiwan has a policy of having extra spent fuel storage in its at-reactor pools, in part through re-racking, and we have assume that this policy continues for replacement reactors built in the future (at existing sites), Taiwan continues to have spent fuel capacity sufficient to store all of its spent fuel output under the BAU path, though in practice the composition of fuel rods may limit the amount of time spent fuel assemblies can be stored in spent fuel pools.

Figure 5-11: Cumulative Difference between 90% of LWR Spent Fuel (including MOx) Capacity in Spent Fuel Pools at Domestic Reactors, and Cumulative Amount of Spent Fuel Produced, by Country, BAU Nuclear Capacity Expansion Path and Regional Scenario 1 (tonnes heavy metals in fuel)

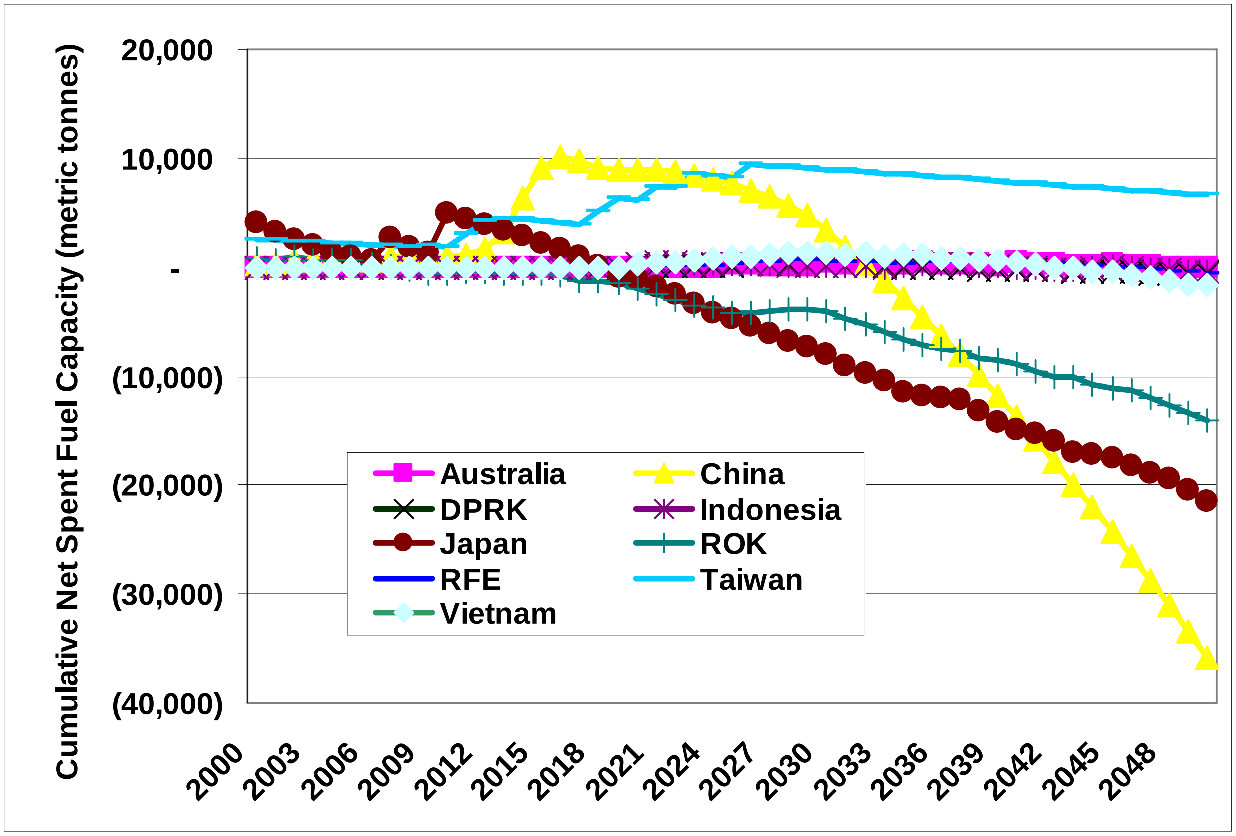
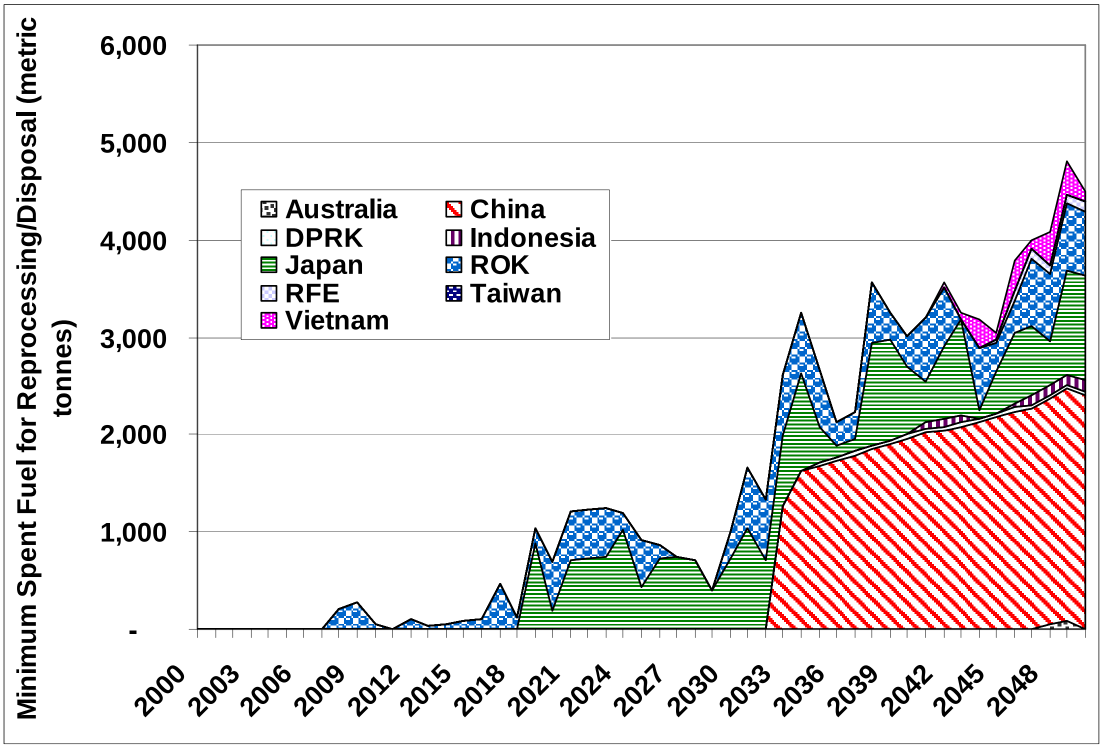


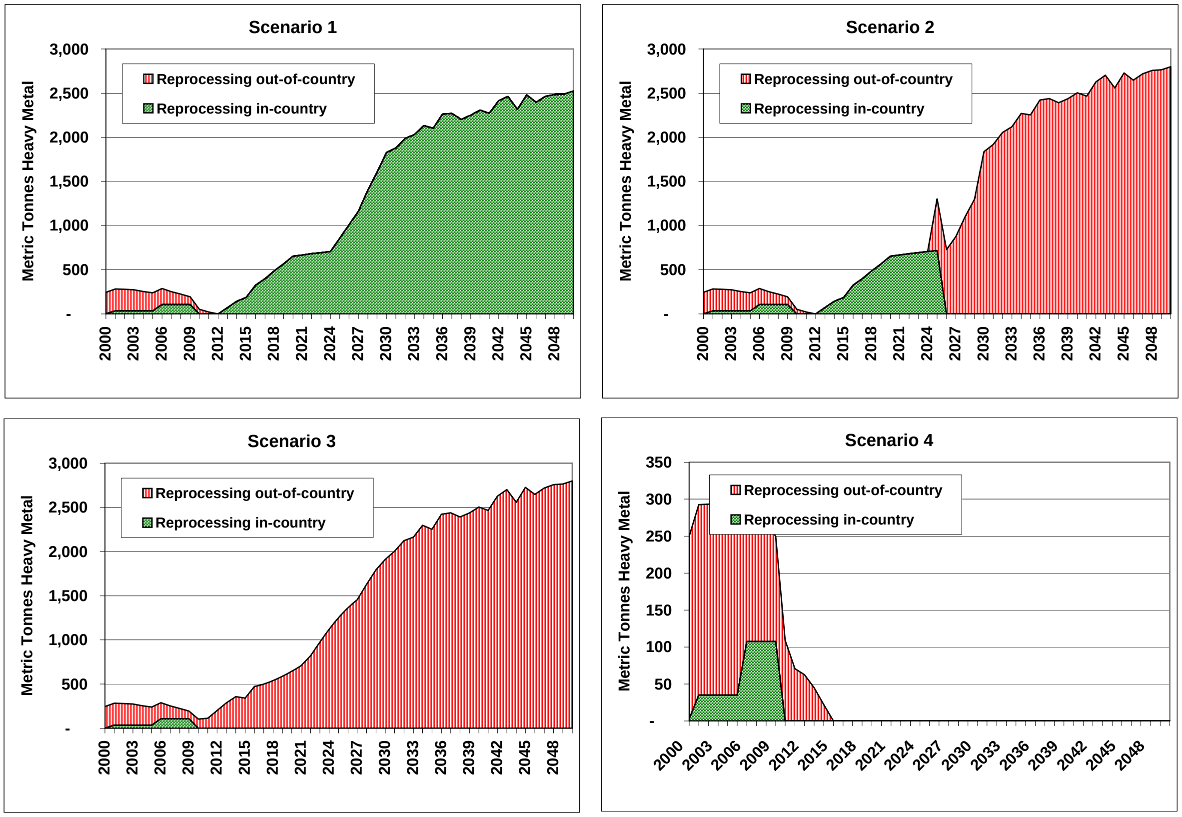
Figure 5-12 presents another angle on the sufficiency of spent fuel pool capacity, in this case showing the amount of annual spent fuel, by country, that would need to be reprocessed, stored, or otherwise disposed of due to spent fuel pools in each country reaching 90 percent of capacity. The 2050 total shown here, again for the BAU nuclear path and Regional Scenario 1, is about 4500 tonnes HM, or only about 10 percent less than the total cooled spent fuel shown as ready for reprocessing/storage/disposal in Figure 5-7. Though these figures show different trends by country, and different shapes, particularly in the early years of the period (while spent fuel pools are filling up), their relatively consistent results in later years suggest that tracking spent fuel that is cooled and ready for further processing is a reasonable basis for quantifying future spent fuel management needs.

Figure 5-12: Implied Minimum Annual Requirements for Out-of-reactor-pool Storage, Disposal, or Reprocessing (Metric tonnes heavy metal), Based on Maximum 90 Percent Fraction of Spent Fuel Capacity, by Country, BAU Nuclear Capacity Expansion Path and Regional Scenario 1 (tonnes heavy metals in fuel)



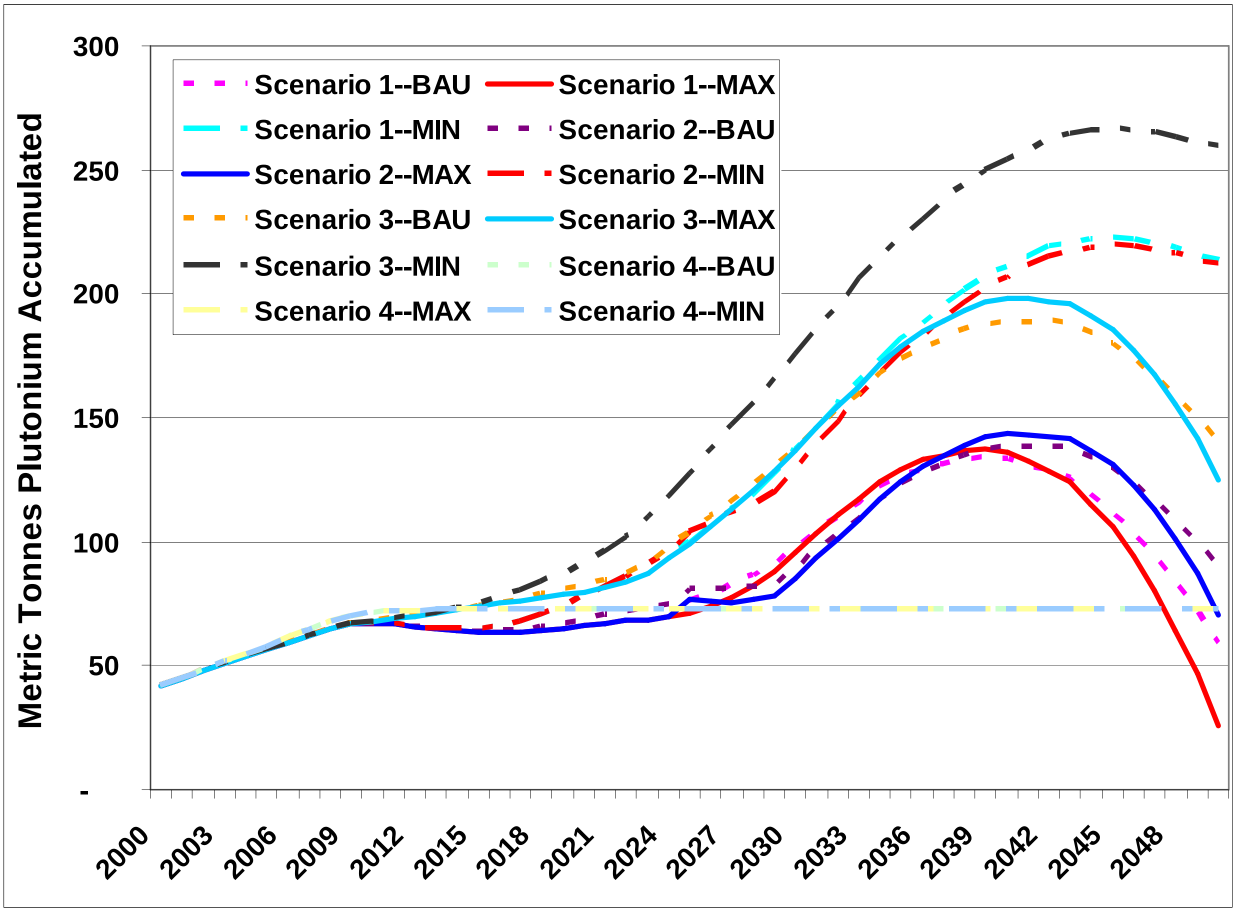
The estimated quantities of spent fuel reprocessed under each of the four regional scenarios (assuming BAU-path nuclear capacity expansion) are shown in Figure 5-13. Here reprocessing is mostly in-country in Scenario 1, mostly out of country (but of similar magnitude—about 3000 tonnes HM per year by 2050) in Scenarios 2 and 3, and of a much lower magnitude (a few hundred tones per year, based on a rough estimate of Japanese spent fuel reprocessed in Europe) and falling rapidly to zero, in Scenario 4. These findings are driven by the scenario assumptions described in Chapter 4.

Figure 5-13: Implied Amount of Cooled Spent LWR Fuel (UOx only) Reprocessed In-country and Out-of-country from Regional Spent Fuel, by Scenario, BAU Nuclear Capacity Expansion Path (tonnes heavy metals in fuel)



Reprocessing of spent fuel produces plutonium, some of which, in amounts varying depending on the scenario, is blended with uranium (from various possible sources) and then used in MOx fuel (producing spent MOx fuel), and some of which must be placed in secured storage. Figure 5-14 shows compares the total plutonium accumulated by the countries of the region from 2000 through 2050 under each combination of cooperation scenario and nuclear capacity expansion path. Under that combination of Scenario 1 (National Enrichment, National Reprocessing) and the MAX nuclear path, plutonium stocks rise to about 125 tonnes by about 2040, then fall to about 20 tonnes by 2050 as more MOx is consumed, primarily in the large Chinese reactor fleet. This assumes that plutonium produced in other countries, in this case, especially Japan, could be used to blend MOx fuel for use elsewhere. Scenarios 1, 2, and 3, in combination with MIN nuclear capacity scenarios, result in the largest accumulations of plutonium, at over 200 tonnes by the 2040s, as a result of the combination of aggressive reprocessing and limited use of MOx fuel (because reactor fleets are smaller).

***Figure 5-14: Total Cumulative Implied Mass of Plutonium Separated from Cooled Spent LWR Fuel (UOx only) Reprocessed Domestically and Internationally, Less Plutonium Used to make MOx Fuel (metric tonnes heavy metal) by Regional Scenario and Nuclear Expansion Path* (Note: Includes Pu stocks accumulated by Japan by 2000, mostly from fuel reprocessed internationally)**



Reprocessing yields a range of waste products, of which the most complex and expensive to manage, as well as the most radioactive, are high-level wastes. Table 5-1 shows the variation in high-level waste production—counted as cubic meters of vitrified (made into glass) product, implied by each of the Regional Scenarios. Scenarios 1 through 3 produce a cumulative 6800 to 7900 cubic meters of vitrified high-level waste over the period from 2000 through 2050, and about 300 cubic meters per year by 2050. These quantities are not particularly large, given the size of the nuclear industry in the region, but the high-level wastes are sufficiently radioactive that special very long term storage will be required.

Table 5-1: Production of Vitrified High-level Wastes from Reprocessing (cubic meters) by Nuclear Fuel Cycle Scenario (BAU Nuclear Capacity Expansion Path)

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
YEAR	Reprocessing in-country	Reprocessing out-of-country	Reprocessing in-country	Reprocessing out-of-country	Reprocessing in-country	Reprocessing out-of-country	Reprocessing in-country	Reprocessing out-of-country
2010	-	6	-	6	-	12	-	13
2030	210	-	-	211	-	220	-	-
2050	290	-	-	322	-	322	-	-
Cumulative, 2000-2050	6,877	231	796	6,672	70	7,926	70	291

Table 5-2 summarizes the amount of spent fuel required for storage/disposal, after reprocessing has been taken into account. The Regional Scenario without reprocessing, (Scenario 4, the “Market Enrichment/Dry Cask Storage” Scenario) produces about twice as much spent fuel for storage, on a cumulative basis, as the other scenarios. Storing this additional spent fuel, if done (as in Scenario 4), would require about 8000 additional dry casks over the 2000-2050 period (in addition to the approximately 9000 dry casks needed in Scenario 1, for example). These casks would occupy on the order of 20 additional hectares of land for storage, which is a modest area when one considers that it is likely to be spread over dozens of sites region-wide. For Scenario 4, a MAX nuclear capacity expansion path results in an estimated 171,000 cumulative tonnes of spent fuel for disposal by 2050. Using MIN capacity assumption estimates, a cumulative regional inventory of 92,000 t HM of spent fuel are implied.

Table 5-2: Annual Total Spent Fuel for Storage/Disposal, Excluding Reprocessed Fuel (tHM) by Nuclear Fuel Cycle Scenario (BAU Nuclear Capacity Expansion Path)

	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
YEAR	UOx Fuel Only	MOx Fuel Only	UOx Fuel Only	MOx Fuel Only	UOx Fuel Only	MOx Fuel Only	UOx Fuel Only	MOx Fuel Only
2010	1,017	-	1,017	-	966	-	962	-
2030	1,313	87	1,301	87	1,227	87	3,226	-
2050	2,426	406	2,147	409	2,147	409	5,355	-
Cumulative, 2000-2050	72,460	5,352	69,302	5,379	64,709	5,379	136,467	12

5.4. Evaluation of Materials Flows in Regional Scenarios

The nuclear fuel cycle consists of a number of steps, each with its own set of costs, impacts, and material flows. Though virtually all forms of energy extraction and conversion also include a number of steps to extract fuels and ready them for human use, nuclear fuels are perhaps unique in the combination of the number of steps required from resource to consumable energy product (and for waste management), and in the technical complexity of many of those steps. We have attempted to track the flow of the major nuclear materials—including forms of uranium and the by-products of nuclear electricity generation—through the nuclear fuel cycle, and have also tried to account for key inputs such as fossil fuels, electricity, water, and money (discussed in Section 5.5). In so doing, we have necessarily made rough estimates of many parameters, and made judgment calls as to which parameters were likely to be of lesser importance to the analysis as a whole. As of this writing (April, 2010), some parameters in the analysis are merely "placeholders" awaiting research to provide reasonable estimates. The sources and methods used to estimate key input parameters to the analysis are provided in the Workpapers volume (Annex C) to this Report.

Although we have relied, whenever possible, on estimates of key parameters from trusted sources of information, it is necessary to acknowledge that many parameters used in this analysis are quite uncertain. Our analysis can be easily updated to incorporate additional information, but at present there are some major elements, such as the trends of costs of nuclear fuel cycle facilities, that may have a significant bearing on the ultimate cost of different regional fuel cycle options as the future unfolds.

Below we provide our current estimates of key materials flows, by regional cooperation scenario, for the major parts of the nuclear fuel cycle. We focus on regional totals and on analyses using the BAU nuclear capacity expansion paths. Results by country and for other nuclear expansion paths are available in Workpapers volumes accompanying this Report (see Annexes B and C). Although some of the tables provided below present results to what appear to be many significant figures of precision, this is for convenience only in transferring results from our modeling workbook to this document. The reader is encouraged to remember that the results below are typically precise to at best two or three significant figures, due to significant uncertainties in many parameters.

5.4.1. Uranium Mining and Milling

To model uranium mining and milling, we separate uranium mined in the region for domestic reactors from uranium mined for sale internationally (whether in the region or not) account for uranium produced by in-situ leaching separately from other uranium production, and track surface-mined and underground-mined uranium separately. Start with estimates of natural U requirements by country, path, and regional scenario, and estimate uranium ore production implied, energy and water use in uranium production, radioactivity in mill tailings implied, and costs (see section 5.5 for costs results). Tables 5-3 through 5-8 present summary results for nuclear fuel cycle activities related to mining and milling of uranium. All tables shown in this Section focus on the BAU nuclear capacity paths. As with the results above (and as described in Chapter 4), the Scenarios referred to the tables below are as follows:

- "Scenario 1": National Enrichment, National Reprocessing Scenario
- "Scenario 2": Regional Center(s) Scenario
- "Scenario 3": Fuel Stockpile/Market Reprocessing Scenario
- "Scenario 4": Market Enrichment/Dry Cask Storage

Highlights of the tables presented below include:

- Natural uranium requirements will reach about 55 to 60 thousand tones (as U) by 2050, or about 1.9 to 2.0 million tones over the period 2000-2050. About 10 percent less uranium is needed annually in 2050 in those scenarios that include reprocessing (scenarios 1 through 3), with those scenarios requiring less than 5 percent less natural U from 2000 through 2050.

- On the order of 2.7 to 14 million tonnes of uranium ore are required annually by 2050 to supply the reactors of the region, or about 77 to 350 million tonnes over 2000 – 2050. Note that these figures vary in part because they in situ leaching—a process requiring little ore removal—is used to different degrees in the different scenarios, but largely because in scenarios where most uranium is sourced internationally (Scenarios 2 through 4), the average grade of ore is much higher, at 3.2 percent (see section 4.5 and Annex B), than it is for uranium sourced from mines in the region—typically 0.05 to 0.2 percent. Excluding Canada, the world average concentration of uranium in mined ore in 2008 was about 0.11 percent. Some major uranium deposits worldwide have average U concentrations lower than this level, and some have higher concentrations (especially some notable deposits in Canada, with uranium concentrations in the 10-20 percent level). We hope to refine our estimates of U concentrations, including better estimates for resources in each of the countries of the region, as analysis continues. At millions or tens of millions of tonnes annually, the amount of material that must be processed to power the region's reactors is considerable, though still probably two to three orders of magnitude less than the mass of coal that is used in the region annually. In open-cast uranium mines, removal of overburden adds to the total amount of material that is moved, perhaps by a factor up to 60[76].
- Electricity use in mining and milling by 2050 totals about 0.5 to 1.3 TWh per year, region-wide, varying by scenario. This is less then 0.1 percent of total regional nuclear output under the BAU nuclear capacity expansion path in 2050.
- Fossil fuel use in mining and milling by 2050 totals about 1.5 to 2.1 PJ (petajoules, or thousand terajoules) per year, region-wide, varying by scenario. This is on the order of 0.002 percent of China's estimated oil products use in 2050 (as include in draft China LEAP analysis).
- Water use in mining and milling by 2050 totals about 57 to 64 million cubic meters per year, regionwide, varying by scenario.
- Radioactivity in uranium mill tailings produced in 2050 to supply uranium for the region's reactors totals about 0.3 to 2.2 peta becquerel[77] (PBq), with cumulative radioactivity of 7.3 to 55 PBq over the 2000 – 2050 period.

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[76] Wise Uranium Project (2002; "Uranium Mine and Mill Resident Individual Dose Calculator – HELP", available as http://www.wise-uranium.org/rdcmrh.html) notes "At conventional uranium mines, overburden and waste rock has to be removed to get access to the uranium ore. The waste-to-ore ratio can range between 1 and 5 for underground mines and between 1 and 60 for open pit mines." The Larimer County Environmental Advisory Board (2008; Report on In Situ Leach and Open-Pit Mining, Prepared for the Larimer County [Colorado, USA] Commissioners, available as www.wpcva.com/content/current/chatham/uranium/pdf/4.pdf), cites an average overburden to ore ratio of 30 to one, presumably for the United States, and presumably based on U.S. Environmental Protection Agency Data. The World Nuclear Association ("Environmental Aspects of Uranium Mining", dated September, 2009, and available as http://www.world-nuclear.org/info/inf25.html) gives an overburden to ore ratio for one part of one mine in Australia of "slightly over 2:1". Clearly, the amount of overburden that must be removed per unit of ore, especially in open-cast mines, is highly significant, but highly variable from mine to mine.

[77] A Becquerel (Bq)is s unit of radioactivity corresponding to one nuclear disintegration per second.

Table 5-3: Natural Uranium Requirements

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Metric Tons Natural Uranium (as U) Mined In-country for Use in Domestic Reactors	2010	1,125	1,137	1,137	1,137
	2030	14,908	2,006	2,005	2,082
	2050	21,033	2,622	2,628	2,865
	Cumulative, 2000-2050	539,031	70,164	70,221	73,206

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Metric Tons Natural Uranium (as U) Imported for Use in Domestic Reactors	2010	14,342	14,329	14,329	14,329
	2030	32,836	45,745	45,303	47,033
	2050	36,162	54,567	56,231	61,309
	Cumulative, 2000-2050	1,372,771	1,841,697	1,904,154	1,987,886

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Metric Tons Natural Uranium (as U) Imported plus Domestic Production	2010	15,467	15,467	15,467	15,467
	2030	47,743	47,750	47,308	49,115
	2050	57,194	57,188	58,859	64,174
	Cumulative, 2000-2050	1,911,802	1,911,862	1,974,375	2,061,092

Table 5-4: Uranium Ore Requirements

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Thousand te Uranium Ore to Supply Uranium Mined In-country for Use in Domestic Reactors	2010	651	658	658	658
	2030	9,141	1,217	1,217	1,264
	2050	13,019	1,616	1,620	1,767
	Cumulative, 2000-2050	325,422	41,721	41,755	43,556

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Thousand Metric Tons Uranium Ore (from In-country and outside mines) to Supply All Domestic Uranium Needs	2010	928	935	935	935
	2030	9,775	2,102	2,093	2,173
	2050	13,718	2,671	2,707	2,952
	Cumulative, 2000-2050	351,967	77,333	78,575	81,994

Table 5-5: Electricity Requirements for Mining and Milling

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used (Mining and Milling) for Uranium Produced In-country for Use in Domestic Reactors (GWh)	2010	54	54	54	54
	2030	693	57	57	59
	2050	969	57	57	62
	Cumulative, 2000-2050	25,439	2,569	2,570	2,662

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used (Mining and Milling) for Uranium Imported In-country for Use in Domestic Reactors (GWh)	2010	124	124	124	124
	2030	284	395	391	406
	2050	312	472	486	530
	Cumulative, 2000-2050	11,863	15,915	16,455	17,178

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used (Mining and Milling) for Domestic and Imported Production (GWh)	2010	177	178	178	178
	2030	977	452	448	465
	2050	1,281	529	543	592
	Cumulative, 2000-2050	37,301	18,484	19,025	19,841

Table 5-6: Fossil Fuel Requirements for Mining and Milling

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Fossil Fuel (likely mostly diesel) Used (Mining and Milling) for Uranium Produced In-country for Use in Domestic Reactors (TJ)	2010	55	55	55	55
	2030	955	304	304	315
	2050	1,422	487	488	532
	Cumulative, 2000-2050	30,928	7,495	7,502	7,913

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Total Fossil Fuel (likely mostly diesel) Used (Mining and Milling) for Uranium Imported In-country for Use in Domestic Reactors (TJ)	2010	275	275	275	275
	2030	630	877	869	902
	2050	694	1,047	1,079	1,176
	Cumulative, 2000-2050	26,331	35,326	36,524	38,130

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Total Fossil Fuel (likely mostly diesel) Used (Mining and Milling) for Domestic and Imported Uranium Production (TJ)	2010	330	330	330	330
	2030	1,585	1,181	1,173	1,217
	2050	2,116	1,533	1,566	1,708
	Cumulative, 2000-2050	57,259	42,821	44,026	46,043

Table 5-7: Water Use for Mining and Milling

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Water Use for Milling (including in-situ leaching) of Uranium Produced In-country for Use in Domestic Reactors (million cubic meters)	2010	1	1	1	1
	2030	15	2	2	2
	2050	21	3	3	3
	Cumulative, 2000-2050	539	70	70	73

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Water Use for Milling (including in-situ leaching) of Uranium Imported In-country for Use in Domestic Reactors (million cubic meters)	2010	14	14	14	14
	2030	33	46	45	47
	2050	36	55	56	61
	Cumulative, 2000-2050	1,373	1,842	1,904	1,988

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Water Use for Milling (including in-situ leaching) for Production of Domestic and Imported Uranium (million cubic meters)	2010	15	15	15	15
	2030	48	48	47	49
	2050	57	57	59	64
	Cumulative, 2000-2050	1,912	1,912	1,974	2,061

Table 5-8: Radioactivity from Uranium Mill Tailings

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Radioactivity in Mill Tailings from Uranium Produced In-country for Use in Domestic Reactors (TBq)	2010	111	113	113	113
	2030	1,546	216	216	224
	2050	2,204	290	290	317
	Cumulative, 2000-2050	55,400	7,291	7,297	7,615

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Radioactivity in Mill Tailings from Uranium Imported for Use in Domestic Reactors (TBq)	2010	1,267	1,268	1,268	1,268
	2030	4,193	3,903	3,867	4,015
	2050	5,119	4,688	4,823	5,258
	Cumulative, 2000-2050	166,045	155,732	160,772	167,838

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Radioactivity in Mill Tailings from Uranium Produced Domestically and Imported for Use in Reactors in the Region (TBq)	2010	1,379	1,380	1,380	1,380
	2030	5,739	4,119	4,083	4,239
	2050	7,323	4,977	5,113	5,575
	Cumulative, 2000-2050	221,445	163,023	168,068	175,453

5.4.2. Uranium Transportation and Enrichment

Our calculations of uranium transportation and enrichment requirements start with the calculated requirements for nuclear fuels described above. These requirements are multiplied by factors, varying by scenario and sometimes country, that express the distance from uranium mining and milling sites to domestic or foreign enrichment facilities, the mode (rail/road—which are assumed to have similar costs, or ship, which is assumed to cost less) and the of transport. Requirements for enrichment are calculated assuming a rate of fuel burn-up that can vary across countries (though we have assumed a constant rate after 2007 for now), which translates into a fixed rate of SWU requirements per unit of enriched fuel output (assuming a constant fraction of U_{235} in the "tails" of the reprocessing operations). We estimate the cost of transport, uranium conversion to UF_6, and enrichment using literature values and recent market costs. We assume a constant real cost of enrichment at present ($160/kg SWU), but have included a means of easily exploring different cost trajectories. We calculate liquid and solid wastes from uranium conversion and enrichment, output of depleted uranium, and electricity and fossil fuel inputs to conversion and enrichment based on literature values.

Tables 5-9 through 5-18 provide results of the analysis of the four scenarios for parameters related to uranium transportation and enrichment. Highlights of these results include:

- Requirements for input to uranium enrichment (adjusted for reductions in requirements due to MOx use) ranging from just under 57 to over 64 thousand tonnes per year by 2050, and a cumulative total of about 1.9 million tonnes to over 2 million tonnes (Scenario 4) for the period from 2000 through 2050.

- Fossil fuel use for U_3O_8 conversion to uranium hexafluoride ranging from under 140 to over 150 TJ/yr by 2050.
- Electricity used for uranium enrichment for nuclear fuel used region-wide totals about 2.2 to 2.5 TWh per year, or about 0.1 percent of annual regional electricity output from nuclear power in that year.
- Annual solid and liquid wastes from uranium conversion are about 40,000 metric tonnes and 400,000 cubic meters annually by 2050, respectively.
- Annual production of depleted uranium from enrichment facilities of 51 to 57 thousand metric tonnes annually in 2050.

Table 5-9: Uranium Enrichment

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Metric Tons Natural Uranium (as UF6, but expressed as U) Enriched In-country for Use in Domestic Reactors	2010	2,581	2,479	2,479	2,479
	2030	42,546	-	4,548	4,142
	2050	49,259	-	4,307	4,142
	Cumulative, 2000-2050	1,419,689	43,956	189,687	180,318

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Metric Tons Natural Uranium (as UF6, but expressed as U) Enriched Outside the Country for Use in Domestic Reactors	2010	12,258	12,360	12,360	12,360
	2030	4,784	47,730	42,741	44,953
	2050	7,650	57,277	54,633	60,120
	Cumulative, 2000-2050	468,195	1,855,977	1,772,436	1,868,560

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Metric Tons Natural Uranium (as UF6, but expressed as U) Enriched Inside and Outside the Country for Use in Domestic Reactors	2010	14,840	14,840	14,840	14,840
	2030	47,329	47,730	47,288	49,095
	2050	56,909	57,277	58,940	64,262
	Cumulative, 2000-2050	1,887,885	1,899,933	1,962,123	2,048,878

Table 5-10: Natural Uranium Transport to Enrichment Facilities

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Million Tonne-km U3O8 Transport to In-country Enrichment for Use in Domestic Reactors	2010	1.1	1.1	1.1	1.1
	2030	13.0	-	4.0	4.2
	2050	17.7	-	3.8	4.2
	Cumulative, 2000-2050	488	31	160	167

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Million Tonne-km U3O8 Transport to Out-of-country Enrichment for Use in Domestic Reactors	2010	123	124	124	124
	2030	48	480	430	446
	2050	77	576	549	599
	Cumulative, 2000-2050	4,719	18,653	17,813	18,610

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Million Tonne-km U3O8 Transport to In-country and Out-of-country Enrichment for Use in Domestic Reactors	2010	124	125	125	125
	2030	61	480	434	450
	2050	95	576	553	603
	Cumulative, 2000-2050	5,207	18,684	17,974	18,777

Table 5-11: Fossil Fuel Use in Conversion of U_3O_8 to UF_6

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Fossil Fuel Used in Converting U3O8 to UF6 for Uranium Enriched In-country (TJ)	2010	6	6	6	6
	2030	102	-	11	11
	2050	119	-	10	11
	Cumulative, 2000-2050	3,417	106	457	475

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Fossil Fuel Used in Converting U3O8 to UF6 for Uranium Enriched Out-of-country (TJ)	2010	30	30	30	30
	2030	12	115	103	107
	2050	18	138	131	143
	Cumulative, 2000-2050	1,130	4,467	4,266	4,456

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Fossil Fuel Used in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (TJ)	2010	36	36	36	36
	2030	114	115	114	118
	2050	137	138	142	155
	Cumulative, 2000-2050	4,547	4,573	4,722	4,931

Table 5-12: Electricity Fuel Use in Conversion of U_3O_8 to UF_6

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used in Converting U3O8 to UF6 for Uranium Enriched In-country (GWh)	2010	3	2	2	2
	2030	43	-	5	5
	2050	50	-	4	5
	Cumulative, 2000-2050	1,427	44	191	198

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used in Converting U3O8 to UF6 for Uranium Enriched Out-of-country (GWh)	2010	12	12	12	12
	2030	5	48	43	45
	2050	8	58	55	60
	Cumulative, 2000-2050	472	1,865	1,781	1,861

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country	2010	15	15	15	15
	2030	48	48	48	49
	2050	57	58	59	65
	Cumulative, 2000-2050	1,899	1,909	1,972	2,059

Table 5-13: Solid Waste Produced in Conversion of U_3O_8 to UF_6

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched In-country (metric tons)	2010	1,816	1,744	1,744	1,744
	2030	29,932	-	3,199	3,322
	2050	34,654	-	3,030	3,304
	Cumulative, 2000-2050	998,777	30,924	133,448	138,717

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched Out-of-country (metric tons)	2010	8,624	8,696	8,696	8,696
	2030	3,365	33,579	30,069	31,218
	2050	5,382	40,295	38,435	41,906
	Cumulative, 2000-2050	330,362	1,305,713	1,246,940	1,302,704

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (metric tons)	2010	10,440	10,440	10,440	10,440
	2030	33,297	33,579	33,268	34,539
	2050	40,036	40,295	41,465	45,210
	Cumulative, 2000-2050	1,329,139	1,336,636	1,380,388	1,441,422

Table 5-14: Liquid Waste in Conversion of U_3O_8 to UF_6

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched In-country (cubic meters)	2010	16,863	16,195	16,195	16,195
	2030	277,936	-	29,708	30,843
	2050	321,790	-	28,137	30,678
	Cumulative, 2000-2050	9,274,354	287,147	1,239,160	1,288,090

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched Out-of-country (cubic meters)	2010	80,079	80,747	80,747	80,747
	2030	31,250	311,807	279,211	289,878
	2050	49,974	374,171	356,898	389,126
	Cumulative, 2000-2050	3,067,649	12,124,476	11,578,729	12,096,539

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liguid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (cubic meters)	2010	96,942	96,942	96,942	96,942
	2030	309,186	311,807	308,919	320,721
	2050	371,764	374,171	385,035	419,805
	Cumulative, 2000-2050	12,342,002	12,411,623	12,817,889	13,384,629

Table 5-15: Enriched Fuel Requirements

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enriched Fuel Requirements for Uranium Enriched In-country for Domestic Use (metric tons enriched fuel as U)	2010	284	273	273	273
	2030	4,689	-	501	520
	2050	5,428	-	475	518
	Cumulative, 2000-2050	156,496	4,888	20,947	21,773

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enriched Fuel Requirements for Uranium Enriched Out of-country for Domestic Use (metric tons enriched fuel as U)	2010	1,351	1,362	1,362	1,362
	2030	527	5,260	4,710	4,890
	2050	843	6,312	6,021	6,564
	Cumulative, 2000-2050	52,154	204,937	195,731	204,466

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enriched Fuel Requirements for Uranium Enriched In-country or Out-of-country for Domestic Use (metric tons enriched fuel as U)	2010	1,635	1,635	1,635	1,635
	2030	5,216	5,260	5,211	5,410
	2050	6,271	6,312	6,495	7,082
	Cumulative, 2000-2050	208,650	209,825	216,678	226,239

Table 5-16: Enrichment Services Requirements

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enrichment Requirements for Uranium Enriched In-country for Domestic Use (Million kg SWU)	2010	2.0	1.9	1.9	1.9
	2030	33.0	-	3.5	3.7
	2050	38.3	-	3.3	3.6
	Cumulative, 2000-2050	1,103	34	147	153

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enrichment Requirements for Uranium Enriched Out-of-country for Domestic Use (Million kg SWU)	2010	10	10	10	10
	2030	4	37	33	34
	2050	6	44	42	46
	Cumulative, 2000-2050	364	1,441	1,376	1,437

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Enrichment Requirements for Uranium Enriched In-country or Out-of-country for Domestic	2010	12	12	12	12
	2030	37	37	37	38
	2050	44	44	46	50
	Cumulative, 2000-2050	1,466	1,475	1,523	1,590

Table 5-17: Electricity Requirements for Enrichment

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used for Uranium Enrichment In-country for Fuel Used in Domestic Reactors (GWh)	2010	100	96	96	96
	2030	1,652	-	177	183
	2050	1,913	-	167	182
	Cumulative, 2000-2050	55,129	1,703	7,362	7,653

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used for Uranium Enrichment Out-of-country for Fuel Used in Domestic Reactors (GWh)	2010	6,313	6,365	6,365	6,365
	2030	186	1,854	1,660	1,723
	2050	297	2,224	2,122	2,313
	Cumulative, 2000-2050	149,669	263,573	263,814	268,814

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Electricity Used for Uranium Enrichment In-country or Out-of-country for Fuel Used in Domestic Reactors (GWh)	2010	6,413	6,462	6,462	6,462
	2030	1,838	1,854	1,836	1,907
	2050	2,210	2,224	2,289	2,496
	Cumulative, 2000-2050	204,798	265,275	271,176	276,467

Table 5-18: Depleted Uranium Production from Enrichment

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Depleted Uranium Produced from Uranium Enrichment In-country for Fuel Used in Domestic Reactors (metric tons U)	2010	2,297	2,206	2,206	2,206
	2030	37,857	-	4,047	4,201
	2050	43,830	-	3,833	4,179
	Cumulative, 2000-2050	1,263,193	39,068	168,739	175,404

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Depleted Uranium Produced from Uranium Enrichment Out-of-country for Fuel Used in Domestic Reactors (metric tons U)	2010	10,907	10,998	10,998	10,998
	2030	4,256	42,470	38,031	39,484
	2050	6,807	50,965	48,612	53,002
	Cumulative, 2000-2050	417,432	1,651,040	1,576,705	1,647,235

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Depleted Uranium Produced from Uranium Enrichment In-country or Out-of-country for Fuel Used in Domestic Reactors (metric tons U)	2010	13,204	13,204	13,204	13,204
	2030	42,113	42,470	42,077	43,685
	2050	50,637	50,965	52,445	57,181
	Cumulative, 2000-2050	1,680,625	1,690,108	1,745,445	1,822,639

5.4.3. Fuel Fabrication and Transport

Our calculations of reactor fuel fabrication and transport requirements start with the calculated requirements for enriched nuclear fuels as described above. These requirements, split into UOx (fuel made of oxides of uranium enriched for U235) and MOx fuel including (plutonium blended with uranium) are multiplied by factors, varying by scenario and sometimes country, that express the distance from fuel fabrication sites (assumed the same as or very near enrichment sites) to reactors where they are used, and the mode of reactor fuel transport. We used factors from the literature to estimate the solid and liquid wastes production from fuel fabrication, using, until more specific data are available, the same waste production factors for both UOx and MOx fuels (though some differences are likely). Similarly, we use factors from the literature that describe fossil fuel and electricity use per unit of fuel produced to calculate the overall use of those inputs for fuel fabrication, again, for the moment, using the same factors for both MOx and UOx fuel. We assume costs for fuel fabrication, per unit, of $272 per kg heavy metal for UOx, and $1,800 per kg heavy metal for MOx. We assume that fabricated MOx fuel is 7 percent plutonium (fraction of HM). As with other parameters included in the calculations described in this report, the sources of these assumptions can be found in the Workpapers volume provided as an Annex.

Tables 5-19 through 5-29 provide results of the analysis of the four scenarios for parameters related to uranium oxide (UOx) and MOx fuel fabrication and transportation to reactor sites. Highlights of these results include:

- Annual fabricated UOx fuel requirements of 6200 to 7000 tonnes (t HM) in 2050, with Scenario 4 requiring the higher end of this range.
- Annual fabricated MOx fuel requirements of just under 600 tonnes (t HM) per year in Scenarios 1 through 3. No MOx fuel is used in Scenario 4 in 2050, and just 12 tonnes (versus 9000 tonnes in the other scenarios) of MOx fuel are used in Scenario 4 over 2000 - 2050.
- Forty tonnes of plutonium is used annually in fabricating MOx fuel in Scenarios 1 through 3 by 2050.
- Fabrication of UOx fuel produces 3100 to 3500 tonnes of solid waste annually region-wide by 2050, and fabrication of MOx fuel produces about 290 tonnes of wastes annually by 2050 in Scenarios 1 through 3. Wastes from MOx fuel fabrication may be of particular concern, because they contain plutonium manufacturing wastes and in MOx fuel pellets that are not of high enough quality for fuel rods, and thus, if not handled and secured properly, represent a radiotoxicity and proliferation risk[78].
- Fuel fabrication requires about 2 TWh per year regionwide by 2050.

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[78] Mycle Schneider, personal communication, March, 2010.

Table 5-19: Requirements for UOx Fuel Fabrication

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	282	271	271	271
	2030	4,622	-	500	452
	2050	5,297	-	461	452
	Cumulative, 2000-2050	153,931	4,858	20,768	19,717

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated Outside the Country for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	1,337	1,348	1,348	1,348
	2030	542	5,207	4,659	4,904
	2050	912	6,249	5,969	6,559
	Cumulative, 2000-2050	52,633	202,869	193,743	204,259

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Requirements for UOx Fuel (excluding MOx) from All Sources (Metric tonnes heavy metal in fabricated fuel)	2010	1,619	1,619	1,619	1,619
	2030	5,164	5,207	5,159	5,356
	2050	6,209	6,249	6,430	7,011
	Cumulative, 2000-2050	206,564	207,726	214,511	223,976

Table 5-20: Requirements for MOx Fuel Fabrication

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for MOx Fuel Blended and Fabricated In-Country for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	0	0	0	0
	2030	196	-	15	-
	2050	576	-	51	-
	Cumulative, 2000-2050	9,141	26	788	1

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for MOx Fuel Blended and Fabricated Out-of-Country for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	3	3	3	3
	2030	0	197	182	-
	2050	0	581	529	-
	Cumulative, 2000-2050	277	9,450	8,688	11

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Requirements for MOx Fuel Blended and Fabricated from All Sources for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	4	4	4	4
	2030	196	197	197	-
	2050	576	581	581	-
	Cumulative, 2000-2050	9,419	9,477	9,477	12

Table 5-21: Use of Plutonium in MOx Fuel Fabrication

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Use of Plutonium for MOx Fuel Blended and Fabricated In-Country for Use in Domestic Reactors (Metric tonnes Pu in fabricated fuel)	2010	0.0	0.0	0.0	0.0
	2030	13.7	-	1.1	-
	2050	40.3	-	3.6	-
	Cumulative, 2000-2050	639.9	1.8	55.2	0.0

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Use of Plutonium for MOx Fuel Blended and Fabricated Out-of-Country for Use in Domestic Reactors (Metric tonnes Pu in fabricated fuel)	2010	0.2	0.2	0.2	0.2
	2030	0.0	13.8	12.7	-
	2050	0.0	40.6	37.1	-
	Cumulative, 2000-2050	19	662	608	1

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Use of Plutonium for MOx Fuel Blended and Fabricated from All Sources for Use in Domestic Reactors (Metric tonnes Pu in fabricated fuel)	2010	0.3	0.3	0.3	0.3
	2030	13.7	13.8	13.8	-
	2050	40.3	40.6	40.6	-
	Cumulative, 2000-2050	659	663	663	0.8

Table 5-22: Solid Wastes Production from UOx Fuel Fabrication

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated In-country (metric tons)	2010	141	135	135	135
	2030	2,311	-	250	226
	2050	2,648	-	231	226
	Cumulative, 2000-2050	76,965	2,429	10,384	9,859

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated Out-of-country (metric tons)	2010	668	674	674	674
	2030	271	2,604	2,330	2,452
	2050	456	3,124	2,985	3,280
	Cumulative, 2000-2050	26,317	101,434	96,871	102,130

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated, All Sources (metric tons)	2010	809	809	809	809
	2030	2,582	2,604	2,580	2,678
	2050	3,104	3,124	3,215	3,506
	Cumulative, 2000-2050	103,282	103,863	107,256	111,988

Table 5-23: Liquid Wastes Production from UOx Fuel Fabrication

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated In-country (cubic meters)	2010	2,538	2,438	2,438	2,438
	2030	41,597	-	4,498	4,067
	2050	47,670	-	4,150	4,067
	Cumulative, 2000-2050	1,385,376	43,721	186,916	177,453

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated Out-of-country (cubic meters)	2010	12,033	12,133	12,133	12,133
	2030	4,875	46,866	41,935	44,139
	2050	8,208	56,240	53,723	59,032
	Cumulative, 2000-2050	473,698	1,825,817	1,743,687	1,838,334

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated, All Sources (cubic meters)	2010	14,571	14,571	14,571	14,571
	2030	46,472	46,866	46,432	48,206
	2050	55,878	56,240	57,873	63,099
	Cumulative, 2000-2050	1,859,074	1,869,538	1,930,603	2,015,787

Table 5-24: Solid Wastes Production from MOx Fuel Fabrication

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated In-country (metric tons)	2010	0.1	0.1	0.1	0.1
	2030	98.1	-	7.7	-
	2050	288.1	-	25.6	-
	Cumulative, 2000-2050	4,570.7	13.1	394.2	0.3

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated Out-of-country (metric tons)	2010	1.7	1.7	1.7	1.7
	2030	0.0	98.6	90.9	-
	2050	0.0	290.3	264.7	-
	Cumulative, 2000-2050	139	4,725	4,344	6

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Solid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated, All Sources (metric tons)	2010	1.8	1.8	1.8	1.8
	2030	98.1	98.6	98.6	-
	2050	288.1	290.3	290.3	-
	Cumulative, 2000-2050	4,709	4,738	4,738	5.9

Table 5-25: Liquid Wastes Production from MOx Fuel Fabrication

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated In-country (cubic meters)	2010	2	2	2	2
	2030	1,766	-	138	-
	2050	5,186	-	461	-
	Cumulative, 2000-2050	82,272	236	7,096	5

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated Out-of-country (cubic meters)	2010	30	31	31	31
	2030	0	1,774	1,636	-
	2050	0	5,226	4,765	-
	Cumulative, 2000-2050	2,495	85,054	78,194	100

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Liquid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated, All Sources (cubic meters)	2010	32	32	32	32
	2030	1,766	1,774	1,774	-
	2050	5,186	5,226	5,226	-
	Cumulative, 2000-2050	84,768	85,290	85,290	106

Table 5-26: Fossil Fuel Use in UOx Fuel Fabrication

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating UOx Fuel for Fuel Enriched and Fabricated In-country (TJ)	2010	764	734	734	734
	2030	12,521	-	1,354	1,224
	2050	14,349	-	1,249	1,224
	Cumulative, 2000-2050	416,998	13,160	56,262	53,413

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating UOx Fuel for Fuel Enriched and Fabricated Out-of-country (TJ)	2010	3,622	3,652	3,652	3,652
	2030	1,468	14,107	12,622	13,286
	2050	2,471	16,928	16,171	17,769
	Cumulative, 2000-2050	142,583	549,571	524,850	553,339

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating UOx Fuel, All Sources (TJ)	2010	4,386	4,386	4,386	4,386
	2030	13,988	14,107	13,976	14,510
	2050	16,819	16,928	17,420	18,993
	Cumulative, 2000-2050	559,581	562,731	581,111	606,752

Table 5-27: Electricity Use in UOx Fuel Fabrication

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating UOx Fuel for Fuel Enriched and Fabricated In-country (GWh)	2010	85	82	82	82
	2030	1,391	-	150	136
	2050	1,594	-	139	136
	Cumulative, 2000-2050	46,318	1,462	6,249	5,933

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating UOx Fuel for Fuel Enriched and Fabricated Out-of-country (GWh)	2010	402	406	406	406
	2030	163	1,567	1,402	1,476
	2050	274	1,880	1,796	1,974
	Cumulative, 2000-2050	15,837	61,043	58,297	61,462

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating UOx Fuel for Fuel Enriched and Fabricated, All Sources (GWh)	2010	487	487	487	487
	2030	1,554	1,567	1,552	1,612
	2050	1,868	1,880	1,935	2,110
	Cumulative, 2000-2050	62,155	62,505	64,546	67,394

Table 5-28: Fossil Fuel Use in MOx Fuel Fabrication

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating MOx Fuel for Fuel Enriched and Fabricated In-country (TJ)	2010	0.6	0.5	0.5	0.5
	2030	531.5	-	41.6	-
	2050	1,560.9	-	138.8	-
	Cumulative, 2000-2050	24,764.0	70.9	2,135.8	1.6

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating MOx Fuel for Fuel Enriched and Fabricated Out-of-country (TJ)	2010	9.1	9.2	9.2	9.2
	2030	0.0	534.0	492.4	-
	2050	0.0	1,573.0	1,434.2	-
	Cumulative, 2000-2050	751.1	25,601.4	23,536.5	30.2

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Fossil Fuel Use in Fabricating MOx Fuel, All Sources (TJ)	2010	10	10	10	10
	2030	532	534	534	-
	2050	1,561	1,573	1,573	-
	Cumulative, 2000-2050	25,515	25,672	25,672	32

Table 5-29: Electricity Use in MOx Fuel Fabrication

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating MOx Fuel for Fuel Enriched and Fabricated In-country (GWh)	2010	0	0	0	0
	2030	59	-	5	-
	2050	173	-	15	-
	Cumulative, 2000-2050	2,751	8	237	0

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating MOx Fuel for Fuel Enriched and Fabricated Out-of-country (GWh)	2010	1.0	1.0	1.0	1.0
	2030	0.0	59.3	54.7	-
	2050	0.0	174.7	159.3	-
	Cumulative, 2000-2050	83.4	2,843.7	2,614.3	3.4

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Electricity Used in Fabricating MOx Fuel from All Sources (GWh)	2010	1	1	1	1
	2030	59	59	59	-
	2050	173	175	175	-
	Cumulative, 2000-2050	2,834	2,852	2,852	4

5.4.4. Reprocessing and Spent Fuel Management

Our calculations of results for each scenario associated with reprocessing and spent fuel management start with production of spent fuel related to the amounts of UOx and MOx fuel input to reactors. We then assume an average lag of 8 years between the time that fuel enters the reactor and when it is available for further processing after cooling. This can be interpreted as assuming an average of about 2 years of fuel use in reactors, followed by about 6 years of cooling in spent fuel pools. In practice, depending on available capacity in spent fuel pools and the type of fuel used (MOx fuel can require longer cooling), this lag may vary. To these “spent fuel arisings”, we then apply factors, which vary by Scenario, to describe the fraction of spent fuel reprocessed, and where it is reprocessed (in-country, in regional centers, or in international centers that may be within or outside of the region) over time. This allows the calculation of reprocessing activity over time, to which are applied factors to calculate the costs, wastes (high-, low- and mid-level, and solid wastes) exiting reprocessing, as well as the amount of plutonium separated from spent fuels. We then apply factors for to calculate the costs of management of each type of waste (at present, only the factor for high-level wastes is used). The fraction of UOx spent fuel not reprocessed (and all MOx spent fuel) must be stored or disposed of, in ways that vary by scenario. We calculate the number of storage casks required to transport the spent fuel to storage sites (interim or permanent), and estimate the number of dry casks needed to store spent fuel in Scenario 4. Cost factors are applied to calculate the overall costs of each of these spent fuel management options.

As with other parameters included in the calculations described in this report, the sources of these assumptions can be found in the Workpapers volume provided as an Annex.

Tables 5-30 through 5-42 provide results of the analysis of the four scenarios for parameters related to uranium oxide (UOx) and MOx spent fuel management, including transportation, reprocessing and/or storage disposal, and management of wastes from reprocessing. Highlights of these results include:

- Nuclear energy programs in the region through 2050 imply the need to manage 135,000 to 140,000 t HM of spent fuel, and up to 5,400 tonnes of MOx spent fuel.
- Ten to 20 annual ocean voyages of spent fuel transport vessels will be required in Scenarios 1 through 3 (none in Scenario 4).
- Reprocessing of spent fuels in Scenarios 1 through 3 produce, over the period from 2000 through 2050, 7000 to 8000 tonnes of high-level wastes that will require long-term management.

Note that as with other tables in this chapter, unless otherwise noted, the results presented below are all for the BAU nuclear capacity expansion path, though results for other paths are available in the Workpapers volumes (compiled results are presented in Annex B).

Table 5-30: Cooled UOx Spent Fuel Available for Further Processing

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual New Spent LWR Fuel Cooled and Available for Reprocessing, Storage, or Disposal (excluding MOx spent fuel), Metric Tonnes Heavy Metal	2010	1,071	1,071	1,071	1,071
	2030	3,139	3,139	3,139	3,226
	2050	4,949	4,946	4,946	5,355
	Cumulative, 2000-2050	134,266	134,238	134,238	139,606

Table 5-31: Cooled MOx Spent Fuel Available for Storage/Disposal

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Spent MOx Fuel Cooled and Available for Storage or Disposal, Metric Tonnes Heavy Metal	2010	-	-	-	-
	2030	87	87	87	-
	2050	406	409	409	-
	Cumulative, 2000-2050	5,352	5,379	5,379	12

Table 5-32: Cooled UOx Spent Fuel Reprocessed

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Amount of Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (Metric tonnes heavy metal; based on annual amount of newly-cooled spent fuel available by year)	2010	-	-	-	-
	2030	1,826	-	-	-
	2050	2,523	-	-	-
	Cumulative, 2000-2050	59,800	6,917	608	608

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Amount of Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (Metric tonnes heavy metal; based on annual amount of newly-cooled spent fuel available by year)	2010	54	54	105	109
	2030	-	1,838	1,912	-
	2050	-	2,798	2,798	-
	Cumulative, 2000-2050	2,005	58,019	68,922	2,531

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Amount of Spent LWR Fuel (UOx only) Reprocessed in Total for Use in Domestic Reactors (Metric tonnes heavy metal)	2010	54	54	105	109
	2030	1,826	1,838	1,912	-
	2050	2,523	2,798	2,798	-
	Cumulative, 2000-2050	61,805	64,936	69,529	3,139

Table 5-33: Ocean Transport of UOx Spent Fuel for Reprocessing

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Number of Ocean Voyages Annually for Transport of Cooled Spent LWR Fuel (UOx only) to In-country Reprocessing Centers	2010	-	-	-	-
	2030	8.07	-	-	-
	2050	8.54	-	-	-
	Cumulative, 2000-2050	259.66	51.53	4.53	4.53

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Number of Ocean Voyages Annually for Transport of Cooled Spent LWR Fuel (UOx only) to Out-of-country Reprocessing Centers	2010	0.40	0.40	0.78	0.81
	2030	-	13.69	14.24	-
	2050	-	20.84	20.84	-
	Cumulative, 2000-2050	14.94	432.17	513.38	18.85

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Number of Ocean Voyages Annually for Transport of Cooled Spent LWR Fuel (UOx only) to All Reprocessing Centers	2010	0.4	0.4	0.8	0.8
	2030	8.1	13.7	14.2	-
	2050	8.5	20.8	20.8	-
	Cumulative, 2000-2050	274.6	483.7	517.9	23.4

Table 5-34: Volume of High-level Wastes from Reprocessing

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of High-level Waste (as vitrified) from Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (cubic meters)	2010	-	-	-	-
	2030	210	-	-	-
	2050	290	-	-	-
	Cumulative, 2000-2050	6,877	796	70	70

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of High-level Waste (as vitrified) from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (cubic meters)	2010	6	6	12	13
	2030	-	211	220	-
	2050	-	322	322	-
	Cumulative, 2000-2050	231	6,672	7,926	291

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of High-level Waste (as vitrified) from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	6	6	12	13
	2030	210	211	220	-
	2050	290	322	322	-
	Cumulative, 2000-2050	7,108	7,468	7,996	361

Table 5-35: Electricity Use for High-level Wastes Management (Vitrification)

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Electricity Use for Treatment of High-level Wastes from Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (GWh)	2010	-	-	-	-
	2030	6.3	-	-	-
	2050	8.7	-	-	-
	Cumulative, 2000-2050	206.3	23.9	2.1	2.1

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Electricity Use for Treatment of High-level Wastes from Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (GWh)	2010	0.2	0.2	0.4	0.4
	2030	-	6.3	6.6	-
	2050	-	9.7	9.7	-
	Cumulative, 2000-2050	6.9	200.2	237.8	8.7

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Electricity Use for Treatment of High-level Wastes from All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Use in Domestic Reactors (GWh)	2010	0.2	0.2	0.4	0.4
	2030	6.3	6.3	6.6	-
	2050	8.7	9.7	9.7	-
	Cumulative, 2000-2050	213.2	224.0	239.9	10.8

Table 5-36: Volume of Medium-level Wastes from Reprocessing

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Medium-level Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (cubic meters)	2010	-	-	-	-
	2030	365	-	-	-
	2050	505	-	-	-
	Cumulative, 2000-2050	11,960	1,383	122	122

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Medium-level Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (cubic meters)	2010	11	11	21	22
	2030	-	368	382	-
	2050	-	560	560	-
	Cumulative, 2000-2050	401	11,604	13,784	506

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Medium-level Waste from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	11	11	21	22
	2030	365	368	382	-
	2050	505	560	560	-
	Cumulative, 2000-2050	12,361	12,987	13,906	628

Table 5-37: Volume of Low-level Wastes from Reprocessing

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Low-level Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (cubic meters)	2010	-	-	-	-
	2030	2,557	-	-	-
	2050	3,532	-	-	-
	Cumulative, 2000-2050	83,720	9,684	851	851

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Low-level Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (cubic meters)	2010	75	75	146	153
	2030	-	2,574	2,677	-
	2050	-	3,917	3,917	-
	Cumulative, 2000-2050	2,807	81,226	96,490	3,543

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Low-level Waste from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	75	75	146	153
	2030	2,557	2,574	2,677	-
	2050	3,532	3,917	3,917	-
	Cumulative, 2000-2050	86,527	90,911	97,341	4,394

Table 5-38: Volume of Solid Wastes from Reprocessing

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Solid Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (cubic meters)	2010	-	-	-	-
	2030	274	-	-	-
	2050	378	-	-	-
	Cumulative, 2000-2050	8,970	1,038	91	91

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Solid Waste from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (cubic meters)	2010	8	8	16	16
	2030	-	276	287	-
	2050	-	420	420	-
	Cumulative, 2000-2050	301	8,703	10,338	380

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Volume of Solid Waste from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	8	8	16	16
	2030	274	276	287	-
	2050	378	420	420	-
	Cumulative, 2000-2050	9,271	9,740	10,429	471

Table 5-39: Mass of Plutonium Separated During Reprocessing

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from Cooled Spent LWR Fuel (UOx only) Reprocessed in Domestic Plants, Less Plutonium Used to make MOx Fuel (metric tonnes heavy metal)	2010	(0.02)	(0.01)	(0.01)	(0.01)
	2030	6.35	-	(1.07)	-
	2050	(12.58)	-	(3.59)	-
	Cumulative, 2000-2050	17.90	74.26	(48.50)	6.64

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally, Less Plutonium Used to make MOx Fuel (metric tonnes heavy metal)	2010	0.36	0.35	0.91	0.96
	2030	(0.00)	6.42	8.31	-
	2050	(0.00)	(9.87)	(6.28)	-
	Cumulative, 2000-2050	2.65	(23.33)	149.96	27.06

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from All Cooled Spent LWR Fuel (UOx only) Reprocessed, Less Plutonium Used to make MOx Fuel (metric tonnes heavy metal)	2010	0.34	0.34	0.90	0.95
	2030	6.35	6.42	7.24	-
	2050	(12.58)	(9.87)	(9.87)	-
	Cumulative, 2000-2050	20.55	50.93	101.46	33.70

Table 5-40: Mass of Plutonium Separated During Reprocessing, Less Plutonium Used for MOx

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from Cooled Spent LWR Fuel (UOx only) Reprocessed in Domestic Plants (metric tonnes heavy metal)	2010	-	-	-	-
	2030	20.09	-	-	-
	2050	27.75	-	-	-
	Cumulative, 2000-2050	657.80	76.09	6.69	6.69

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally (metric tonnes heavy metal)	2010	0.59	0.59	1.15	1.20
	2030	-	20.22	21.04	-
	2050	-	30.78	30.78	-
	Cumulative, 2000-2050	22.06	638.21	758.14	27.84

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Mass of Plutonium Separated from All Cooled Spent LWR Fuel (UOx only) Reprocessed (metric tonnes heavy metal)	2010	0.59	0.59	1.15	1.20
	2030	20.09	20.22	21.04	-
	2050	27.75	30.78	30.78	-
	Cumulative, 2000-2050	679.86	714.30	764.82	34.52

Table 5-41: Mass of Uranium Separated During Reprocessing

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Implied Mass of Uranium Separated during Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Domestically for Domestic Reactors (metric tonnes)	2010	-	-	-	-
	2030	1,717	-	-	-
	2050	2,371	-	-	-
	Cumulative, 2000-2050	56,212	6,502	571	571

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Implied Mass of Uranium Separated during Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Domestic Reactors (metric tonnes)	2010	50	50	98	102
	2030	-	1,728	1,798	-
	2050	-	2,630	2,630	-
	Cumulative, 2000-2050	1,885	54,538	64,786	2,379

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Implied Mass of Uranium Separated during All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Domestic Reactors (metric tonnes)	2010	50	50	98	102
	2030	1,717	1,728	1,798	-
	2050	2,371	2,630	2,630	-
	Cumulative, 2000-2050	58,097	61,040	65,358	2,950

Table 5-42: Number of Storage Casks Required for Spent Fuel Not Reprocessed

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Number of Casks Required for Dry Cask Storage of Cooled Spent LWR Fuel (UOx only) for Storage/Disposal, Net of Reprocessing (units)	2010	102	102	97	96
	2030	131	130	123	323
	2050	243	215	215	535
	Cumulative, 2000-2050	7,246	6,930	6,471	13,647

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Number of Casks Required for Dry Cask Storage of Cooled Spent LWR MOx Fuel for Storage/Disposal (units)	2010	-	-	-	-
	2030	9	9	9	-
	2050	41	41	41	-
	Cumulative, 2000-2050	535	538	538	1

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Number of Casks Required for Cooled Spent LWR Fuel, UOx and MOx, for Domestic Reactors (units)	2010	102	102	97	96
	2030	140	139	131	323
	2050	283	256	256	535
	Cumulative, 2000-2050	7,781	7,468	7,009	13,648

5.5. Evaluation of Costs in Regional Scenarios

Along with the inputs to and outputs of nuclear fuel cycle facilities, we have attempted to track the costs of the nuclear fuel cycle through its various elements. In general, though not in every case, we have used "levelized" costs, expressed, for example, on a per-tonne-heavy metal processed basis, to include a multitude of operating and maintenance and capital costs, often for very long-lived facilities. In other cases we have extrapolated market trends in prices, for example, for uranium prices and enrichment services, while providing for the option of modeling different price trends. All costs in the tables in this section are provided in 2009 dollars. Costs summed over 2000-2050 are not discounted. We focus on the results of the BAU nuclear capacity expansion path, though summary results for other paths are also available in the Workpapers volume (Annex B) attached to this report. Note that, as with other parameters, though we have tried to use the best estimates available for nuclear fuel cycle costs, these estimates are in many cases by their very nature quite speculative, as they often specify costs for technologies that have not yet been commercialized (permanent waste storage, for example), or are commercialized but practiced in only a few places in the world (reprocessing and high-level waste vitrification, for example), or are subject to regulatory oversight with the potential to considerably change costs, or for which specific costs were not immediately available for this analysis (such as most nuclear materials transport costs). As such, the costs estimates provided here should be taken as indicative estimates only, for use primarily in comparing regional scenarios.

Not yet included in the analysis below are the costs of nuclear generation, apart from fuel-related costs. We have omitted these costs (capital costs and O&M costs, for example) at present because a full comparison of different nuclear paths also requires inclusion of the capital costs of other electricity generation sources and of other methods of providing energy services that might be included in a given energy sector development path for a given country. We expect to include nuclear generation-related costs, along with a more complete relative comparison of overall costs of different energy paths, in research pursued in subsequent years of the East Asia Science and Society project (see Chapter 6 of this Report).

Initial highlights of the cost results presented below (Tables 5-43 through 5-61) include:

- Uranium mining and milling costs for the region are estimated at $8.2 to $9.0 billion per year by 2050, with the inclusion of reprocessing in Scenarios 1 through 3 reducing costs only modestly.
- Natural uranium transport costs, at an estimated 1 to 8 million dollars per year in 2050, are a negligible fraction of overall costs.
- Uranium conversion costs range from 360 to 400 million dollars per year by 2050 for the countries of the region.
- Uranium enrichment costs for the region are on the same order of magnitude as mining and milling costs, at an estimated at $7.1 to $8.0 billion per year by 2050, with the inclusion of reprocessing in scenarios again reducing costs only modestly.
- UOx fuel fabrication costs are estimated at $1.7 to $1.9 billion annually by 2050.
- Though the quantity of MOx fuel used is much lower than that of UOx fuel, MOx fabrication costs are estimated at about $1.0 billion annually by 2050 in Scenarios 1 through 3 where MOx is used.
- Reprocessing costs range from $3.4 to 4.7 billion per year in those Scenarios (1 through 3) that feature reprocessing.
- Treatment of high-level wastes from reprocessing adds 380 to 420 million per year to the costs of Scenarios 1 through 3, with treatment of medium-level, low-level, and solid wastes from reprocessing, and of uranium separated from spent fuel during reprocessing (less uranium used for MOx fuel) adding an aggregate $240 to $260 million per year to costs by 2050.
- Plutonium storage costs range from about $170 to $420 million/yr in 2050, with those scenarios that result in higher Pu inventories showing higher costs.
- Interim storage of non-reprocessed spent fuels (and of MOx fuel), in Scenarios 1 through 3, has estimated costs in 2050 of $870 to $920 million per year. In Scenario 4, using Dry Cask Storage, estimated costs in 2050 are about $840 million per year, or just slightly lower, though the amount of spent fuel being handled in Scenario 4 does not include the fuel sent to reprocessing. Estimated costs for transportation of spent fuel in are about $150 million annually in 2050 in Scenario 1, $300 to $310 million/yr in Scenarios 2 and 3, and $33 million/yr in Scenario 4.

Overall, the conclusion from the above—similar to the conclusion that a number of other researchers have reached, using per-unit costs (not from regional scenarios), is that reprocessing of spent fuel results in much higher costs—higher by on the order of $5 billion per year or more, region-wide, in 2050—than using dry-cask storage and not reprocessing spent fuel.

Table 5-43: Mining and Milling Cost Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost (or value) of Uranium Produced In-country for Use in Domestic Reactors (Million 2009 dollars)	2010	$ 135	$ 137	$ 137	$ 137
	2030	$ 1,978	$ 266	$ 266	$ 276
	2050	$ 3,084	$ 384	$ 385	$ 420
	Cumulative, 2000-2050	$ 73,329	$ 9,333	$ 9,340	$ 9,756

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost (or value) of Uranium Imported for Use in Domestic Reactors (Million 2009 dollars)	2010	$ 1,722	$ 1,721	$ 1,721	$ 1,721
	2030	$ 4,357	$ 6,070	$ 5,711	$ 5,929
	2050	$ 5,302	$ 8,001	$ 7,832	$ 8,540
	Cumulative, 2000-2050	$ 179,783	$ 243,787	$ 241,131	$ 252,191

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost (or value) of Uranium Produced Domestically or Imported for Use in Reactors in the Region (Million 2009 dollars)	2010	$ 1,858	$ 1,858	$ 1,858	$ 1,858
	2030	$ 6,336	$ 6,336	$ 5,977	$ 6,206
	2050	$ 8,386	$ 8,385	$ 8,218	$ 8,960
	Cumulative, 2000-2050	$ 253,113	$ 253,120	$ 250,471	$ 261,948

Table 5-44: Natural Uranium Transport Cost Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Cost (Million 2009 USD) of U3O8 Transport to In-country Enrichment for Use in Domestic Reactors	2010	$ 0.02	$ 0.02	$ 0.02	$ 0.02
	2030	$ 0.27	$ -	$ 0.08	$ 0.09
	2050	$ 0.37	$ -	$ 0.08	$ 0.09
	Cumulative, 2000-2050	$ 10.19	$ 0.64	$ 3.35	$ 3.49

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Cost (Million 2009 USD) of U3O8 Transport to Out-of-country Enrichment for Use in Domestic Reactors	2010	$ 1.57	$ 1.58	$ 1.58	$ 1.58
	2030	$ 0.61	$ 6.11	$ 5.47	$ 5.68
	2050	$ 0.98	$ 7.33	$ 6.99	$ 7.62
	Cumulative, 2000-2050	$ 60.07	$ 237.41	$ 226.72	$ 236.86

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Cost (Million 2009 USD) of U3O8 Transport to In-country and Out-of-country Enrichment for Use in Domestic Reactors	2010	$ 1.59	$ 1.60	$ 1.60	$ 1.60
	2030	$ 0.88	$ 6.11	$ 5.55	$ 5.76
	2050	$ 1.35	$ 7.33	$ 7.07	$ 7.71
	Cumulative, 2000-2050	$ 70.26	$ 238.05	$ 230.08	$ 240.35

Table 5-45: Uranium Conversion Cost Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Conversion of U3O8 to UF6 for Uranium Enriched In-country (million dollars)	2010	$ 16	$ 16	$ 16	$ 16
	2030	$ 267	$ -	$ 29	$ 30
	2050	$ 309	$ -	$ 27	$ 29
	Cumulative, 2000-2050	$ 8,903	$ 276	$ 1,190	$ 1,237

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Conversion of U3O8 to UF6 for Uranium Enriched Out-of-country (million dollars)	2010	$ 77	$ 78	$ 78	$ 78
	2030	$ 30	$ 299	$ 268	$ 278
	2050	$ 48	$ 359	$ 343	$ 374
	Cumulative, 2000-2050	$ 2,945	$ 11,639	$ 11,116	$ 11,613

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Conversion of U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (million dollars)	2010	$ 93	$ 93	$ 93	$ 93
	2030	$ 297	$ 299	$ 297	$ 308
	2050	$ 357	$ 359	$ 370	$ 403
	Cumulative, 2000-2050	$ 11,848	$ 11,915	$ 12,305	$ 12,849

Table 5-46: Uranium Enrichment Cost Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Uranium Enrichment In-country for Fuel Used in Domestic Reactors (Million 2009 dollars)	2010	$ 321	$ 308	$ 308	$ 308
	2030	$ 5,287	$ -	$ 565	$ 587
	2050	$ 6,121	$ -	$ 535	$ 584
	Cumulative, 2000-2050	$ 176,093	$ 5,130	$ 23,240	$ 24,170

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Uranium Enrichment Services Imported for Fuel Used in Domestic Reactors (Million 2009 dollars)	2010	$ 1,523	$ 1,536	$ 1,536	$ 1,536
	2030	$ 594	$ 5,932	$ 5,311	$ 5,514
	2050	$ 951	$ 7,118	$ 6,789	$ 7,402
	Cumulative, 2000-2050	$ 55,153	$ 227,442	$ 217,060	$ 226,910

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Annual Total Cost of Uranium Enrichment Services In-country or Imported for Fuel Used in Domestic Reactors (Million 2009 dollars)	2010	$ 1,844	$ 1,844	$ 1,844	$ 1,844
	2030	$ 5,882	$ 5,932	$ 5,877	$ 6,101
	2050	$ 7,072	$ 7,118	$ 7,325	$ 7,986
	Cumulative, 2000-2050	$ 231,247	$ 232,571	$ 240,300	$ 251,081

Table 5-47: Uranium (UOx) Reactor Fuel Transport Cost Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Million dollars)	2010	$ 0.05	$ 0.05	$ 0.05	$ 0.05
	2030	$ 0.64	$ -	$ 0.09	$ 0.09
	2050	$ 0.81	$ -	$ 0.08	$ 0.09
	Cumulative, 2000-2050	$ 22.33	$ 0.80	$ 3.72	$ 3.75

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated Out-of-Country for Use in Domestic Reactors (Million dollars)	2010	$ 1.74	$ 0.81	$ 1.75	$ 1.75
	2030	$ 0.70	$ 3.12	$ 6.06	$ 6.38
	2050	$ 1.19	$ 3.75	$ 7.76	$ 8.53
	Cumulative, 2000-2050	$ 68.42	$ 121.72	$ 251.87	$ 265.54

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated for Use in Domestic Reactors, All Sources (Million dollars)	2010	$ 1.79	$ 0.86	$ 1.80	$ 1.80
	2030	$ 1.35	$ 3.12	$ 6.15	$ 6.47
	2050	$ 2.00	$ 3.75	$ 7.84	$ 8.62
	Cumulative, 2000-2050	$ 90.75	$ 122.53	$ 255.58	$ 269.29

Table 5-47: Mixed Oxide (MOx) Reactor Fuel Transport Cost Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for MOx Fuel for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Million dollars)	2010	$ 0.00	$ 0.00	$ 0.00	$ 0.00
	2030	$ 0.03	$ -	$ 0.00	$ -
	2050	$ 0.13	$ -	$ 0.01	$ -
	Cumulative, 2000-2050	$ 1.66	$ 0.00	$ 0.19	$ 0.00

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for MOx Fuel for Fuel Enriched and Fabricated Out-of-Country for Use in Domestic Reactors (Million dollars)	2010	$ 0.01	$ 0.00	$ 0.01	$ 0.01
	2030	$ 0.00	$ 0.18	$ 0.35	$ -
	2050	$ 0.00	$ 0.52	$ 1.03	$ -
	Cumulative, 2000-2050	$ 0.54	$ 8.51	$ 16.94	$ 0.02

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for MOx Fuel for Fuel Enriched and Fabricated for Use in Domestic Reactors, All Sources (Million dollars)	2010	$ 0.01	$ 0.00	$ 0.01	$ 0.01
	2030	$ 0.03	$ 0.18	$ 0.36	$ -
	2050	$ 0.13	$ 0.52	$ 1.05	$ -
	Cumulative, 2000-2050	$ 2.20	$ 8.51	$ 17.13	$ 0.02

Table 5-48: Uranium (UOx) Reactor Fuel Fabrication Cost Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Million dollars)	2010	$ 77	$ 74	$ 74	$ 74
	2030	$ 1,258	$ -	$ 136	$ 123
	2050	$ 1,442	$ -	$ 126	$ 123
	Cumulative, 2000-2050	$ 41,911	$ 1,323	$ 5,655	$ 5,368

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated Out-of-Country for Use in Domestic Reactors (Million dollars)	2010	$ 364	$ 367	$ 367	$ 367
	2030	$ 147	$ 1,418	$ 1,269	$ 1,335
	2050	$ 248	$ 1,701	$ 1,625	$ 1,786
	Cumulative, 2000-2050	$ 14,330	$ 55,235	$ 52,750	$ 55,613

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated, All Sources, for Use in Domestic Reactors (Million dollars)	2010	$ 441	$ 441	$ 441	$ 441
	2030	$ 1,406	$ 1,418	$ 1,405	$ 1,458
	2050	$ 1,690	$ 1,701	$ 1,751	$ 1,909
	Cumulative, 2000-2050	$ 56,241	$ 56,557	$ 58,405	$ 60,982

Table 5-49: MOx Reactor Fuel Fabrication Cost Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for MOx Fuel for Fuel Enriched and Fabricated In-Country for Use in Domestic Reactors (Million dollars)	2010	$ 0.4	$ 0.3	$ 0.3	$ 0.3
	2030	$ 353	$ -	$ 28	$ -
	2050	$ 1,037	$ -	$ 92	$ -
	Cumulative, 2000-2050	$ 16,454	$ 47	$ 1,419	$ 1.1

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for MOx Fuel for Fuel Enriched and Fabricated Out-of-Country for Use in Domestic Reactors (Million dollars)	2010	$ 6.0	$ 6.1	$ 6.1	$ 6.1
	2030	$ 0	$ 355	$ 327	$ -
	2050	$ 0	$ 1,045	$ 953	$ -
	Cumulative, 2000-2050	$ 499	$ 17,011	$ 15,639	$ 20

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Fuel Fabrication Costs for MOx Fuel, All Sources, for Use in Domestic Reactors (Million dollars)	2010	$ 6	$ 6	$ 6	$ 6
	2030	$ 353	$ 355	$ 355	$ -
	2050	$ 1,037	$ 1,045	$ 1,045	$ -
	Cumulative, 2000-2050	$ 16,954	$ 17,058	$ 17,058	$ 21

Table 5-50: UOx Spent Fuel Transport (to Reprocessing) Cost Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 79.62	$ -	$ -	$ -
	2050	$ 132.03	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 2,657	$ 137	$ 12	$ 12

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (Million dollars)	2010	$ 27.54	$ 10.59	$ 53.71	$ 55.95
	2030	$ -	$ 363.07	$ 982.00	$ -
	2050	$ -	$ 552.64	$ 1,436.85	$ -
	Cumulative, 2000-2050	$ 1,030	$ 11,459	$ 35,391	$ 1,300

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Transport Costs for All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (Million dollars)	2010	$ 27.54	$ 10.59	$ 53.71	$ 55.95
	2030	$ 79.62	$ 363.07	$ 982.00	$ -
	2050	$ 132.03	$ 552.64	$ 1,436.85	$ -
	Cumulative, 2000-2050	$ 3,687	$ 11,595	$ 35,403	$ 1,312

Table 5-51: UOx Spent Fuel Reprocessing Cost Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 3,911	$ -	$ -	$ -
	2050	$ 4,667	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 130,353	$ 23,519	$ 2,067	$ 2,067

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (Million dollars)	2010	$ 64	$ 64	$ 126	$ 131
	2030	$ -	$ 2,206	$ 2,295	$ -
	2050	$ -	$ 3,358	$ 3,358	$ -
	Cumulative, 2000-2050	$ 2,406	$ 69,623	$ 82,706	$ 3,037

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Use in Domestic Reactors (Million dollars)	2010	$ 64	$ 64	$ 126	$ 131
	2030	$ 3,911	$ 2,206	$ 2,295	$ -
	2050	$ 4,667	$ 3,358	$ 3,358	$ -
	Cumulative, 2000-2050	$ 132,759	$ 93,142	$ 84,773	$ 5,103

Table 5-52 Reprocessing High-level Waste Management Cost Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of High-level Wastes from Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed In-country for Use in Domestic Reactors (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 274	$ -	$ -	$ -
	2050	$ 378	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 8,970	$ 1,038	$ 91	$ 91

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of High-level Wastes from Reprocessing of Cooled Spent LWR Fuel (UOx only) Reprocessed Internationally for Use in Domestic Reactors (Million dollars)	2010	$ 8	$ 8	$ 16	$ 16
	2030	$ -	$ 276	$ 287	$ -
	2050	$ -	$ 420	$ 420	$ -
	Cumulative, 2000-2050	$ 301	$ 8,703	$ 10,338	$ 380

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of High-level Wastes from All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Use in Domestic Reactors (Million dollars)	2010	$ 8	$ 8	$ 16	$ 16
	2030	$ 274	$ 276	$ 287	$ -
	2050	$ 378	$ 420	$ 420	$ -
	Cumulative, 2000-2050	$ 9,271	$ 9,740	$ 10,429	$ 471

(Note: Includes in year 2000 and cumulative values costs for HLW stocks accumulated by Japan by 2000, mostly from fuel reprocessed internationally)

Table 5-53 Reprocessing Medium-level Waste Management Cost Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Medium-level Wastes from Reprocessing In-country (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 114	$ -	$ -	$ -
	2050	$ 157	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 3,718	$ 430	$ 38	$ 38

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Medium-level Wastes from Reprocessing Out-of--country (Million dollars)	2010	$ 3	$ 3	$ 7	$ 7
	2030	$ -	$ 114	$ 119	$ -
	2050	$ -	$ 174	$ 174	$ -
	Cumulative, 2000-2050	$ 125	$ 3,608	$ 4,285	$ 157

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Medium-level Wastes from All Reprocessing (Million dollars)	2010	$ 3	$ 3	$ 7	$ 7
	2030	$ 114	$ 114	$ 119	$ -
	2050	$ 157	$ 174	$ 174	$ -
	Cumulative, 2000-2050	$ 3,843	$ 4,038	$ 4,323	$ 195

Table 5-54 Reprocessing Low-level Waste Management Cost Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Low-level Wastes from Reprocessing In-country for Use in Domestic Reactors (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 48	$ -	$ -	$ -
	2050	$ 67	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 1,585	$ 183	$ 16	$ 16

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Low-level Wastes from Reprocessing Out-of-country (Million dollars)	2010	$ 1	$ 1	$ 3	$ 3
	2030	$ -	$ 49	$ 51	$ -
	2050	$ -	$ 74	$ 74	$ -
	Cumulative, 2000-2050	$ 53	$ 1,538	$ 1,826	$ 67

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Low-level Wastes from All Reprocessing (Million dollars)	2010	$ 1	$ 1	$ 3	$ 3
	2030	$ 48	$ 49	$ 51	$ -
	2050	$ 67	$ 74	$ 74	$ -
	Cumulative, 2000-2050	$ 1,638	$ 1,721	$ 1,843	$ 83

Table 5-55 Reprocessing Solid Waste Management Cost Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Solid Wastes from Reprocessing In-country (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 0.3	$ -	$ -	$ -
	2050	$ 0.4	$ -	$ -	$ -
	Cumulative, 2000-2050	$ 8.6	$ 1.0	$ 0.1	$ 0.1

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Solid Wastes from Reprocessing Out-of-country (Million dollars)	2010	$ 0.0	$ 0.0	$ 0.0	$ 0.0
	2030	$ -	$ 0.3	$ 0.3	$ -
	2050	$ -	$ 0.4	$ 0.4	$ -
	Cumulative, 2000-2050	$ 0.3	$ 8.4	$ 9.9	$ 0.4

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Solid Wastes from All Reprocessing (Million dollars)	2010	$ 0.0	$ 0.0	$ 0.0	$ 0.0
	2030	$ 0.3	$ 0.3	$ 0.3	$ -
	2050	$ 0.4	$ 0.4	$ 0.4	$ -
	Cumulative, 2000-2050	$ 8.9	$ 9.4	$ 10.0	$ 0.5

Table 5-56: Cost Estimates for Management of Uranium Separated from Spent Fuel During Reprocessing

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Uranium Separated During from Reprocessing In-country (Million dollars)	2010	$ (0.0)	$ (0.0)	$ (0.0)	$ (0.0)
	2030	$ 13.2	$ -	$ (0.1)	$ -
	2050	$ 15.7	$ -	$ (0.4)	$ -
	Cumulative, 2000-2050	$ 409.0	$ 55.5	$ (1.4)	$ 4.9

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Uranium Separated During from Reprocessing Out-of-country (Million dollars)	2010	$ 0.4	$ 0.4	$ 0.8	$ 0.9
	2030	$ (0.0)	$ 13.2	$ 14.0	$ -
	2050	$ (0.0)	$ 17.9	$ 18.3	$ -
	Cumulative, 2000-2050	$ 13.9	$ 392.1	$ 486.1	$ 20.3

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Costs for Treatment and Disposal/Storage of Uranium Separated During from All Reprocessing (Million dollars)	2010	$ 0.4	$ 0.4	$ 0.8	$ 0.8
	2030	$ 13.2	$ 13.2	$ 13.8	$ -
	2050	$ 15.7	$ 17.9	$ 17.9	$ -
	Cumulative, 2000-2050	$ 422.9	$ 447.7	$ 484.7	$ 25.2

Table 5-57: Plutonium Storage Cost Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost/Benefit of Storage/ safeguarding/ disposal of Plutonium from Reprocessing Operations (fraction not used as MOx) (Million dollars)	2010	$ 202	$ 202	$ 203	$ 213
	2030	$ 293	$ 269	$ 413	$ 218
	2050	$ 179	$ 270	$ 421	$ 218
	Cumulative, 2000-2050	$ 13,023	$ 13,480	$ 17,683	$ 10,615

Table 5-58: Spent Fuel Storage Cask Capital Cost Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost of Casks Required for Dry Cask Storage of Cooled Spent LWR Fuel (UOx only) for Storage/Disposal, Not Including Spent Fuel Reprocessed Domestically or Internationally (Million dollars)	2010	$ 81	$ 81	$ 77	$ 77
	2030	$ 105	$ 104	$ 98	$ 258
	2050	$ 194	$ 172	$ 172	$ 428
	Cumulative, 2000-2050	$ 5,797	$ 5,544	$ 5,177	$ 10,917

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost of Casks Required for Dry Cask Storage of Cooled Spent LWR MOx Fuel for Storage/Disposal (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 6.96	$ 6.96	$ 6.96	$ -
	2050	$ 32.49	$ 32.74	$ 32.74	$ -
	Cumulative, 2000-2050	$ 428.17	$ 430.35	$ 430.35	$ 0.94

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Cost of Casks Required for Dry Cask Storage of Cooled Spent LWR UOx and MOx Fuel for Storage/Disposal (Million dollars)	2010	$ 81	$ 81	$ 77	$ 77
	2030	$ 112	$ 111	$ 105	$ 258
	2050	$ 227	$ 205	$ 205	$ 428
	Cumulative, 2000-2050	$ 6,225	$ 5,975	$ 5,607	$ 10,918

Table 5-59: Spent Fuel Storage Cask O&M Cost Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Operating and Maintenance Cost for Casks Required for Dry Cask Storage of Cooled Spent LWR Fuel (UOx only) for Storage/Disposal, Not Including Spent Fuel Reprocessed Domestically or Internationally (Million dollars)	2010	$ 8	$ 8	$ 8	$ 8
	2030	$ 32	$ 33	$ 29	$ 46
	2050	$ 72	$ 69	$ 65	$ 136
	Cumulative, 2000-2050	$ 1,474	$ 1,456	$ 1,329	$ 2,319

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Operating and Maintenance Cost for Casks Required for Dry Cask Storage of Cooled Spent LWR MOx Fuel for Storage/Disposal (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 0.60	$ 0.60	$ 0.60	$ 0.01
	2050	$ 5.35	$ 5.38	$ 5.38	$ 0.01
	Cumulative, 2000-2050	$ 53.29	$ 53.46	$ 53.46	$ 0.37

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Total Annual Operating and Maintenance Cost for Casks Required for Dry Cask Storage of All Cooled Spent LWR Fuel for Storage/Disposal (Million dollars)	2010	$ 8	$ 8	$ 8	$ 8
	2030	$ 33	$ 34	$ 29	$ 46
	2050	$ 78	$ 75	$ 70	$ 136
	Cumulative, 2000-2050	$ 1,527	$ 1,510	$ 1,383	$ 2,320

Table 5-60: Total Spent Fuel Storage Costs Estimates

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Storage/Disposal of Cooled Spent LWR Fuel (UOx only), Not Including Spent Fuel Reprocessed Domestically or Internationally (Million dollars)	2010	$ 342	$ 366	$ 348	$ 245
	2030	$ 426	$ 468	$ 442	$ 583
	2050	$ 725	$ 773	$ 773	$ 844
	Cumulative, 2000-2050	$ 22,970	$ 24,949	$ 23,295	$ 24,906

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Storage/Disposal of Cooled Spent MOx Fuel (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 31	$ 31	$ 31	$ -
	2050	$ 146	$ 147	$ 147	$ -
	Cumulative, 2000-2050	$ 1,927	$ 1,937	$ 1,937	$ 4

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Storage/Disposal of All Cooled Spent Fuel (Million dollars)	2010	$ 342	$ 366	$ 348	$ 245
	2030	$ 457	$ 500	$ 473	$ 583
	2050	$ 872	$ 920	$ 920	$ 844
	Cumulative, 2000-2050	$ 24,897	$ 26,885	$ 25,232	$ 24,910

Table 5-61: Estimated Cost of Transport of Spent Fuels to Storage/Disposal

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Transport to Storage/Disposal for LWR Fuel (UOx only), Not Including Spent Fuel Reprocessed Domestically or Internationally (Million dollars)	2010	$ 21	$ 121	$ 115	$ 12
	2030	$ 67	$ 155	$ 145	$ 22
	2050	$ 126	$ 257	$ 254	$ 33
	Cumulative, 2000-2050	$ 3,173	$ 8,250	$ 7,668	$ 1,012

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Transport to Storage/Disposal for Cooled Spent MOx Fuel (Million dollars)	2010	$ -	$ -	$ -	$ -
	2030	$ 1.7	$ 10.3	$ 10.3	$ -
	2050	$ 21.5	$ 48.5	$ 48.5	$ -
	Cumulative, 2000-2050	$ 216.4	$ 637.5	$ 637.5	$ 0.2

Parameter	YEAR	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Implied Total Cost of Transport to Storage/Disposal for All Cooled Spent Fuel (Million dollars)	2010	$ 21	$ 121	$ 115	$ 12
	2030	$ 68	$ 165	$ 156	$ 22
	2050	$ 147	$ 306	$ 303	$ 33
	Cumulative, 2000-2050	$ 3,390	$ 8,887	$ 8,305	$ 1,013

Table 5-62, and Figures 5-15 and 5-16 summarize all of the nuclear fuel-cycle costs quantified (if approximately) thus far for the four regional nuclear fuel cycle scenarios analyzed in this Report. Overall costs are dominated by costs for uranium production, enrichment, and reprocessing, with spent fuel storage and disposal a modest (about 4-5%) fraction of costs, and nuclear materials transport costs even smaller[79].

Table 5-62: Summary of Nuclear Fuel Cycle Costs, BAU Nuclear Capacity Expansion Path, for Four Scenarios, Annual Costs in 2050 and Cumulative Costs, 2000-2050

	Annual Costs in 2050				**Cumulative Costs, 2000-2050**			
Cost Category	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Uranium (Yellowcake) Production/Purchase	$ 8,386	$ 8,385	$ 8,218	$ 8,960	$ 253,113	$ 253,120	$ 250,471	$ 261,948
Uranium Transport to Enrichment Plants	$ 1	$ 7	$ 7	$ 8	$ 70	$ 238	$ 230	$ 240
Conversion of U_3O_8 to UF_6 for Enrichment	$ 357	$ 359	$ 370	$ 403	$ 11,848	$ 11,915	$ 12,305	$ 12,849
Uranium Enrichment Services	$ 7,072	$ 7,118	$ 7,325	$ 7,986	$ 231,247	$ 232,571	$ 240,300	$ 251,081
UOx Fuel Transport	$ 2	$ 4	$ 8	$ 9	$ 91	$ 123	$ 256	$ 269
MOx Fuel Transport	$ 0	$ 1	$ 1	$ -	$ 2	$ 9	$ 17	$ 0
UOx Fuel Fabrication	$ 1,690	$ 1,701	$ 1,751	$ 1,909	$ 56,241	$ 56,557	$ 58,405	$ 60,982
MOx Fuel Fabrication	$ 1,037	$ 1,045	$ 1,045	$ -	$ 16,954	$ 17,058	$ 17,058	$ 21
Spent UOx Fuel Transport to Reprocessing	$ 132	$ 553	$ 1,437	$ -	$ 3,687	$ 11,595	$ 35,403	$ 1,312
Reprocessing	$ 4,667	$ 3,358	$ 3,358	$ -	$ 132,759	$ 93,142	$ 84,773	$ 5,103
Treatment/Disposal of HLW from Reprocessing*	$ 378	$ 420	$ 420	$ -	$ 9,803	$ 10,272	$ 10,961	$ 1,003
Storage of Plutonium from Reprocessing*	$ 179	$ 270	$ 421	$ 218	$ 13,023	$ 13,480	$ 17,683	$ 10,615
Disposal of MLW from Reprocessing	$ 157	$ 174	$ 174	$ -	$ 3,843	$ 4,038	$ 4,323	$ 195
Disposal of LLW from Reprocessing	$ 67	$ 74	$ 74	$ -	$ 1,638	$ 1,721	$ 1,843	$ 83
Disposal of Solid Wastes from Reprocessing	$ 0	$ 0	$ 0	$ -	$ 9	$ 9	$ 10	$ 0
Disposal/Use of Depleted U from Reprocessing	$ 16	$ 18	$ 18	$ -	$ 423	$ 448	$ 485	$ 25
Storage/Disposal of UOx Spent Fuel	$ 725	$ 773	$ 773	$ 844	$ 22,970	$ 24,949	$ 23,295	$ 24,906
Storage/Disposal of MOx Spent Fuel	$ 146	$ 147	$ 147	$ -	$ 1,927	$ 1,937	$ 1,937	$ 4
Spent UOx Fuel Transport to Storage/Disposal	$ 126	$ 257	$ 254	$ 33	$ 3,173	$ 8,250	$ 7,668	$ 1,012
Spent MOx Fuel Transport to Storage/Disposal	$ 22	$ 48	$ 48	$ -	$ 216	$ 637	$ 637	$ 0
TOTAL of Above	$ 25,161	$ 24,713	$ 25,849	$ 20,369	$ 763,036	$ 742,068	$ 768,059	$ 631,649

* Note: Includes Pu and HLW stocks accumulated by Japan by 2000, mostly from fuel reprocessed internationally.

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[79] In Table 5-62, HLW, MLW, and LLW are high-level, medium-level radioactive wastes, and low-level radioactive wastes, respectively.

Figure 5-15:

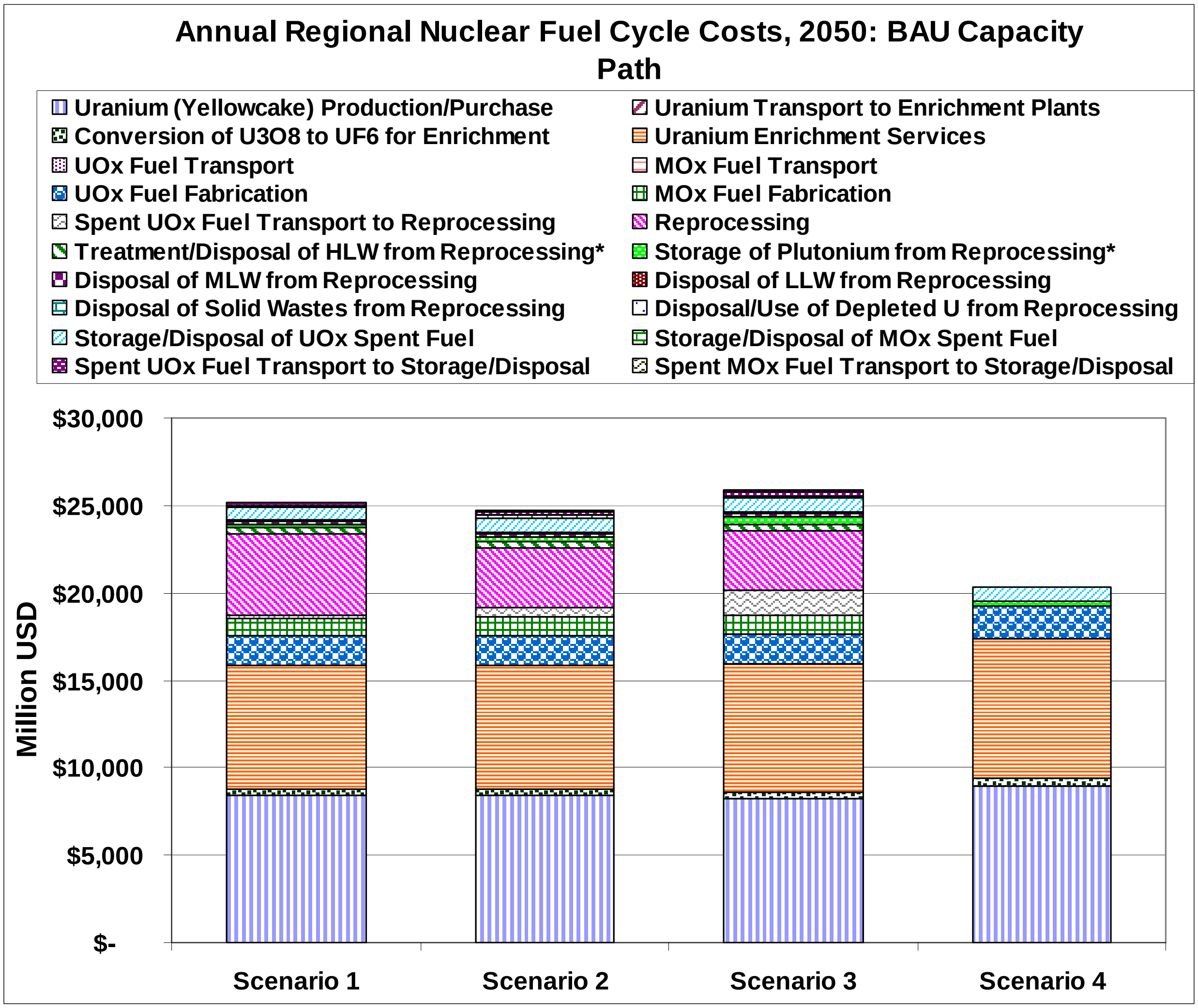
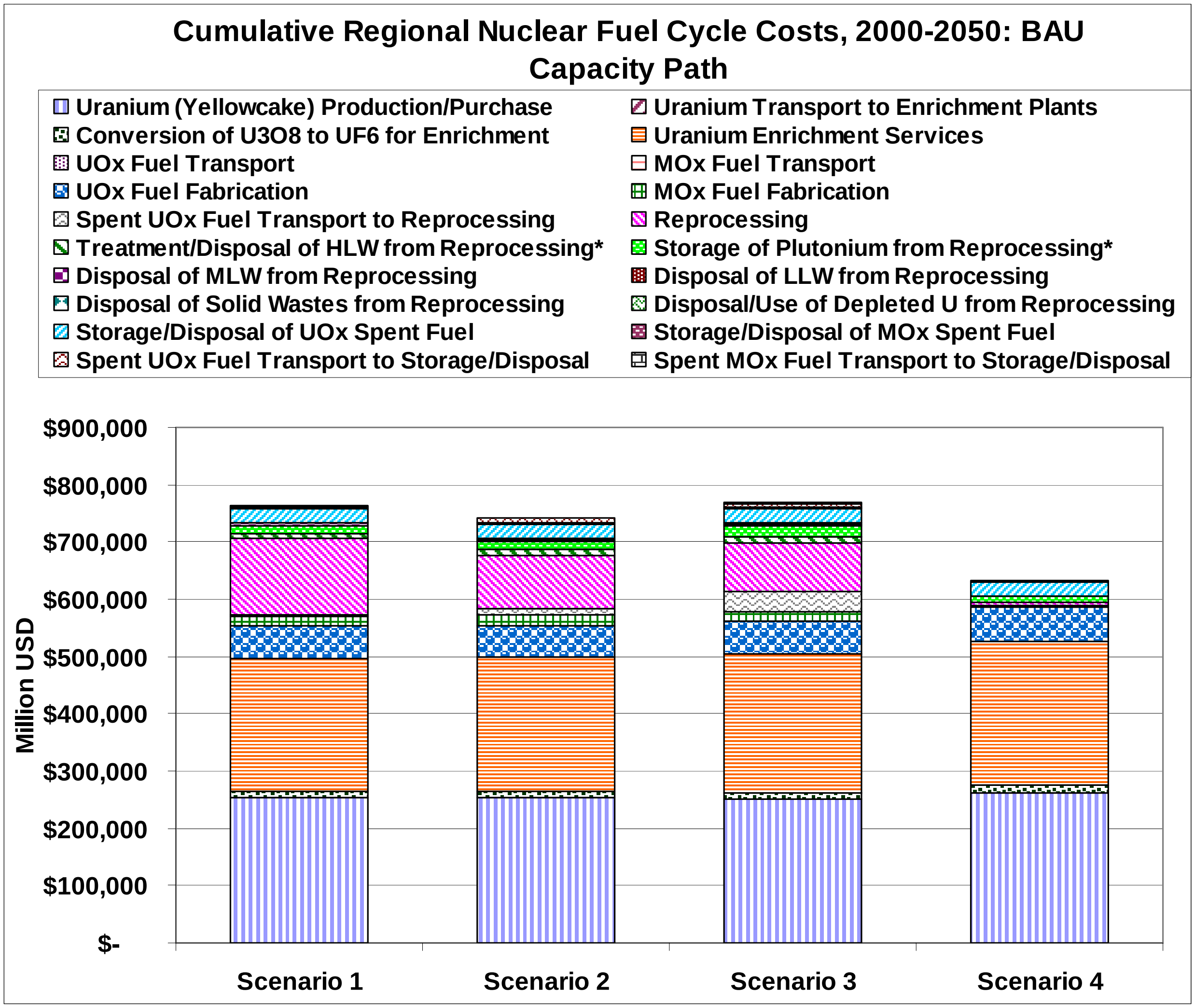

Annual Regional Nuclear Fuel Cycle Costs, 2050: BAU Capacity Path
Uranium (Yellowcake) Production/Purchase
Uranium Transport to Enrichment Plants
Conversion of U3O8 to UF6 for Enrichment
Uranium Enrichment Services
UOx Fuel Transport
MOx Fuel Transport
UOx Fuel Fabrication
MOx Fuel Fabrication
Spent UOx Fuel Transport to Reprocessing
Reprocessing
Treatment/Disposal of HLW from Reprocessing*
Storage of Plutonium from Reprocessing*
Disposal of MLW from Reprocessing
Disposal of LLW from Reprocessing
Disposal of Solid Wastes from Reprocessing
Disposal/Use of Depleted U from Reprocessing
Storage/Disposal of UOx Spent Fuel
Storage/Disposal of MOx Spent Fuel
Spent UOx Fuel Transport to Storage/Disposal
Spent MOx Fuel Transport to Storage/Disposal
Million USD
$30,000
$25,000
$20,000
$15,000
$10,000
$5,000
$-
Scenario 1
Scenario 2
Scenario 3
Scenario 4

Figure 5-16:



5.6. Evaluation of Energy Security Costs and Benefits of Scenarios

Given the multiple dimensions of energy security described briefly in Chapter 1, and the linkages/overlaps between energy security dimensions and the dimensions of sustainability and sustainable development, a framework for evaluating and measuring—or at least comparing—the relative attributes of different approaches to energy sector development is needed. Such a framework should be designed to help to identify the relative costs and benefits of different “energy futures”—which are essentially, future scenarios driven by suites of energy (and other social) policies, and in the case of this Report focus on regional nuclear fuel cycle cooperation “futures”. Below we identify some of the policy issues associated with the dimensions of energy policy presented earlier, and adapt a framework for evaluating energy security, as broadly defined, to the study of nuclear fuel cycle cooperation in East Asia.

5.6.1. Methods for Energy Security Evaluation of Scenarios

"Energy Security" has typically, to those involved in making energy policy, meant mostly securing access to oil, other fossil fuels. With increasingly global, diverse energy markets, however, old energy security rationales are less important, and other issues, including climate change, other environmental, economic, and international considerations are becoming increasingly important. As a consequence, a more comprehensive operating definition of "Energy Security" is needed, along with a workable framework for analysis of which of many possible energy paths or scenarios yield greater Energy Security for the areas considered. Based on work done as a part of the Nautilus Institute "Pacific Asia Regional Energy Security" project, a broad definition of Energy Security was offered in the first chapter of this Report. Below we briefly describe an analytical framework designed to help to comparison the energy security characteristics—both positive and negative—of different of energy future scenarios. Though broadly applicable to many different kinds of energy futures analyses, in this Report we adapt and apply this framework to the study of the energy security implications of the different regional nuclear fuel cycle scenarios described above. The results of the application of the analytical framework to the regional scenarios are briefly summarized in the next section of this Chapter. Additional details on the original work to develop a methodology for energy security analysis—which has been continued as a part of Nautilus Institute's ongoing Asian Energy Security and the current East Asia Science and Security project, can be found in the report A Framework for Energy Security Analysis and Application to a Case Study of Japan[80].

Many of the existing definitions of energy security begin, and usually end, with a focus on maintaining energy supplies. Supplies of oil are a typical, specific focus, but maintaining access to, and controlling costs of, fuels to generate electricity in particular has in part been a major historical driver of the development of nuclear power in East Asia, particularly in Japan and the ROK. This supply-based focus has as its cornerstones reducing vulnerability to foreign threats or pressure, preventing a supply crisis from occurring, and minimizing the economic and military impact of a supply crisis once it has occurred. National energy policies today are being challenged on multiple fronts. The substance of these challenges needs to be incorporated into a new, broader concept of energy security. Current national and international energy policies have been facing many new challenges, and have at their disposal new tools that need to be considered as key components of new energy security concepts. At least five key components—environment, technology, demand side management, social and cultural factors, and post-Cold War international relations—are central additions to the traditional supply-side point of view in a new Comprehensive Energy Security Concept (as presented in Chapter 1, but reprised here in a slightly longer form for convenience):

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[80] This report, dated June, 1998, was prepared by Tatsujiro Suzuki, David Von Hippel, Ken Wilkening, and Dr. James Nickum for the PARES project, representing a group of collaborating energy-sector researchers from the United States and Japan convened by Nautilus Institute and the Institute for Global Communications. The PARES project had as its goals to propose a consensus definition of "energy security", develop an analytical framework to address energy security dimensions of choices in energy sector development, prepare illustrative medium-range energy "paths" for Japan (1995 to 2020), evaluate the energy paths against a suite of energy security criteria using the framework, and review the results for applicability to other countries of the region. The LEAP energy-environment planning software that continues to be used in the EASS project was used as a key tool in PARES research. The full PARES report is available from Nautilus Institute as http://www.nautilus.org/archives/pares/PARES_Synthesis_Report.PDF. Some of the text here is adapted from the PARES report, as well as from a summary article derived from the PARES report, D. von Hippel (2004) "Energy Security Analysis: A New Framework", ReCOMMEND Newsletter, Issue 2, Volume 1, pages 4-7, dated December, 2004, available as http://www.energycommunity.org/reCOMMEND/reCOMMEND2.pdf.

> A nation-state is energy secure to the degree that fuel and energy services are available to ensure: a) survival of the nation, b) protection of national welfare, and c) minimization of risks associated with supply and use of fuel and energy services. The six dimensions of energy security—within attainment of each of these three objectives of energy security should be measured—include **energy supply-related**, **economic**, **technological**, **environmental**, **social and cultural**, and **military/security-related** dimensions.

Energy policies must address the domestic and international (regional and global) implications of each of these dimensions. Thus, national energy policies should be evaluated against each of the three basic objectives as manifested in the domestic and international implications of each dimension. What distinguishes the energy security definition is its emphasis on the imperative to consider extra-territorial implications of the provision of energy and energy services, while recognizing the complexity of actualizing (and measuring) national energy security. The definition of Energy Security provided above is also designed to include emerging concepts of Environmental Security. Dimensions of Environmental Security include the effects of the state of the environment on human security, the effects of the state of the environment on military security, the effects of security institutions on the environment, and the effects of environmental security ideas on prospects for international environmental cooperation.

Testing the Energy Security Impacts of Different Energy Scenarios

Given the broad definition of energy security provided above, how should a framework for evaluation of energy security impacts of different policy approaches be organized? Some of the challenges in setting up such a framework include deciding on manageable but useful level of detail, incorporation of uncertainty, risk considerations, comparison of tangible and intangible costs/benefits, comparing impacts across different spatial levels and time-scales, and balancing analytical comprehensiveness and transparency. In meeting these challenges, a framework was devised that is based on a variety of tools, including the elaboration and evaluation of alternative energy/environmental “paths” or “scenarios” for a nation and/or region (for example, the different nuclear capacity development paths considered for each nation in Chapter 3, or the four regional nuclear cooperation scenarios considered in Chapter 4), followed by application of additional analytical tools such as diversity indices and multiple-attribute (trade-off) analysis. Central to the application of the framework is its application to search for "robust" solutions—that is, a search for sets of policies that meet multiple energy security and other objectives at the same time. The framework for the analysis of Energy Security (broadly defined) includes the following steps:

1. Define objective and subjective measures of energy (and environmental) security to be evaluated.

2. Collect data, and develop candidate energy paths/scenarios that yield roughly consistent energy services.

3. Test the relative performance of paths/ scenarios for each energy security measure included in the analysis.

4. Incorporate elements of risk

5. Compare path and scenario results
6. Eliminate paths that lead to clearly sub-optimal or unacceptable results, and iterate the analysis as necessary to reach clear conclusions.

Each of these steps necessarily include both qualitative and quantitative components that must be addressed and compared—sometimes subjectively, and sometimes objectively—as consistently as possible. Some of the possible measures of energy security, and dimensions and attributes for energy security analyses in general are summarized in Table 5-63, below. The list of measures used for any given analysis, however, can and should change depending on the particular policy scenarios being evaluated, though it is important for any analysis to remain comprehensive across energy security attributes so as not to risk overlooking important points of view.

Table 5-63: Dimensions and Attributes of Energy Security

Dimension of Energy Security	**Attributes**	**Interpretation**
Energy Supply	Total Primary Energy	Higher = indicator of other impacts
	Fraction of Primary Energy as Imports	Lower = preferred
	Diversification Index (by fuel type, primary energy)	Lower index value preferred
	Diversification Index (by supplier, key fuel types)	Lower index value preferred
	Stocks as a fraction of imports (key fuels)	Higher = greater resilience to supply interruption
Economic	Total Energy System Internal Costs	Lower = preferred
	Total Fuel Costs	Lower = preferred
	Import Fuel Costs	Lower = preferred
	Economic Impact of Fuel Price Increase (as fraction of GNP)	Lower = preferred
Technological	Diversification Indices for key industries (such as power generation) by technology type	Lower = preferred
	Diversity of R&D Spending	Qualitative—Higher preferred
	Reliance on Proven Technologies	Qualitative—Higher preferred
	Technological Adaptability	Qualitative—Higher preferred

Table 5-63 (continued): Dimensions and Attributes of Energy Security

Dimension of Energy Security	**Attributes**	**Interpretation**
Environmental	GHG emissions (tonnes CO_2, CH_4	Lower = preferred
	Acid gas emissions (tonnes SOx, NOx)	Lower = preferred
	Local Air Pollutants (tonnes particulates, hydrocarbons, others?)	Lower = preferred
	Other air and water pollutants (including marine oil pollution)	Lower = preferred
	Solid Wastes (tonnes bottom ash, fly ash, scrubber sludge)	Lower = preferred (or at best neutral, with safe re-use)
	Nuclear waste (tonnes or Curies, by type)	Lower = preferred, but qualitative component for waste isolation scheme
	Ecosystem and Aesthetic Impacts	Largely Qualitative—Lower preferred
	Exposure to Environmental Risk	Qualitative—Lower preferred
Social and Cultural	Exposure to Risk of Social or Cultural Conflict over energy systems	Qualitative—Lower preferred
Military/Security	Exposure to Military/Security Risks	Qualitative—Lower preferred
	Relative level of spending on energy-related security arrangements	Lower = preferred

An energy path or scenario describes the evolution—or potential evolution—of a country or region's energy sector (or a portion of same) assuming that a specific set of energy policies are (or are not) put in place. The level of detail with which an energy path/scenario is described is a function of the degree of realism required to make the path analysis plausible to an audience of policy-makers, as well as the analytical resources (person-time) and data available to do the analysis. "Bottom-up" quantitative description of energy paths, like the ones typically assembled in LEAP as a part of the EASS project, offer the possibility to specify fuels and technologies used, as well as energy system costs, and key environmental emissions, in some detail, but can require a considerable amount of work. Simpler models, such the Excel-based model of regional nuclear cooperation scenarios that produced the results above, can also be used, providing that model outputs can include measures of energy security like those presented in Table 5-63. A major criterion to keep in mind, when developing energy paths/scenarios, is that the paths chosen should be both reasonably plausible, yet different enough from each other to yield, when their attributes are compared, significant insight into the ramifications of the energy policy choices that the paths describe.

Once attribute values (and qualitative assessments) have been compiled for each of the energy paths/scenarios considered, the next step is to compare the values of measures across paths. Here, it is possible to ascribe weights to each attribute and thus devise one or more overall indices of "energy security", but the most straightforward approach is probably to simply line up the attributes values for each path side by side, and review the differences between paths, focusing on differences that are truly significant. For example, if the difference in net present value (NPV) cost of plan "A" is one billion dollars greater than that of plan "B", the difference must be examined relative to the overall cost of the energy system, or to the cost of the economy as a whole. To an energy system with costs of, say, one trillion (10^{12}) dollars in capital, operating and maintenance, and fuel costs over 20 years, a difference between plans of one billion (10^9) dollars is not only trivial, it is dwarfed by the uncertainties in even the most certain elements of the analysis. The key, then, is to search for differences between the attributes of the plans—taking care to include both qualitative and quantitative attributes—that are truly meaningful.

The side-by-side comparison of candidate paths/scenarios should, if the original set of paths considered was sufficiently broad, allow the identification and elimination of paths that are clearly worse, in several (or key) attribute dimensions, than other candidates. The process of elimination of paths, should, however, be approached in a systematic, transparent, and well-documented way.

5.6.2. Energy Security Evaluation of Scenarios

Below we follow—in a summary fashion—the general energy security analysis procedure described above to compare energy security attributes for the four regional nuclear fuel cycle scenarios developed in this Report. It should be emphasized that while many different attributes and measures could be chosen for this analysis, the approach taken here has generally been to focus on attributes that are significantly different between scenarios, in order to provide guidance on the key policy trade-offs involved in choosing one scenario over another. Additional scenario results were presented earlier in this chapter, and more detailed results are available in the Annexes to this Report.

Table 5-64 provides a side-by-side comparison of the four nuclear fuel cycle cooperation scenarios. In some cases, comparisons between scenarios are combined convenience, since some of the scenarios share attributes. The results in Table 5-64 compare the results of the four scenarios under the "BAU" nuclear generation capacity expansion path, as this provides the most straightforward point of comparison between the paths. In some cases, results of other nuclear expansion paths are provided to note how the different scenarios might diverge in their performance under varying capacity expansion cases (and the related implications for policy). For reference, the designations of the scenarios considered are:

- "Scenario 1": National Enrichment, National Reprocessing Scenario
- "Scenario 2": Regional Center(s) Scenario
- "Scenario 3": Fuel Stockpile/Market Reprocessing Scenario
- "Scenario 4": Market Enrichment/Dry Cask Storage

Except as noted, the quantitative results presented in Table 5-64 are cumulative for the period 2000-2050. Costs are presented in undiscounted 2009 US dollars.

The judgments presented in the table below are not absolute. In many cases, readers will find points of view on specific attribute that we have not reflected in the comparisons provided, or indeed, have not thought of. In those cases, we would be most interested to hear other perspectives on the comparisons we provide.

Table 5-64: Energy Security Comparison of Regional Nuclear Fuel Cycle Cooperation Scenarios

Dimension of Energy Security	**Attributes**	**Scenario 1 Result**	**Scenario 2 Result**	**Scenario 3 Result**	**Scenario 4 Result**
Energy Supply	Total natural uranium use	1.91 Mt (57.2 kt/yr in 2050)	1.91 Mt (57.2 kt/yr in 2050)	1.97 Mt (58.9 kt/yr in 2050)	2.07 Mt (64.2 kt/yr in 2050)
	Fraction uranium use imported	63.2% in 2050	95.4% in 2050	95.5% in 2050	95.5% in 2050
	Diversification of uranium supply	Scenario 1, in that it spurs domestic uranium production in many countries, arguably provides more diversification in uranium supply than the other scenarios, but uranium from the international market already comes from many source countries, and the implementation of an international consortium to purchase uranium in Scenarios 2 through 4 provides the market power to potentially obtain favorable pricing and consistent deliveries from uranium suppliers.			
	Total enrichment services use	1,466 M kg SWU (44 M kg SWU in 2050)	1,475 M kg SWU (44 M kg SWU in 2050)	1,523 M kg SWU (46 M kg SWU in 2050)	1,590 M kg SWU (50 M kg SWU in 2050)
	Fraction of enrichment services imported	13.4% in 2050	100% in 2050	92.7% in 2050	92.7% in 2050
	Diversification of enrichment supplies	Scenario 1 includes more enrichment facilities, but since a plant in one nation of the region may not be available for use by another nation, the effect may be to increase dependence of each country on a single plant. In scenario 2, with regional enrichment, use of a single large regional plant would decrease diversity of supply, but use of several regional plants would improve diversity. In scenarios 3 and 4, potential use of several international suppliers could increase diversity of enrichment supplies, to the extent that available international capacity exists. Supplies from some international suppliers (N. America, EU) might be vulnerable to disruption of sea lanes from Asia, but supplies from Russia may not.			
	Fuel Stockpiles	No stockpile, but more mining, enrichment in-country	No stockpile, but enrichment in-region (thus under regional control)	Stockpile held by region as buffer against supply, price disruption	Stockpile held by region as buffer against supply, price disruption

Dimension of Energy Security	**Attributes**	**Scenario 1 Result**	**Scenario 2 Result**	**Scenario 3 Result**	**Scenario 4 Result**
Economic	Total uranium, enrichment, fabrication, transport costs	$570 billion	$572 billion	$579 billion	$587 billion
	Total nuclear fuel cycle costs (except generation)	$763 billion	$742 billion	$768 billion	$632 billion
	Cost of Imported nuclear fuels/services	Lowest due to concentration of mining, enrichment, reprocessing in-country.	Higher than scenarios 1 and 4, but possibly lower than scenario 3, depending on cost of new regional facilities.	Likely highest due to combination of imported enrichment plus reprocessing and stockpiles, but possible savings over scenario 2 by using mostly existing international facilities.	Higher than scenario 1 but lower than other scenarios due to lower costs for spent-fuel management.
	Economic impacts of nuclear fuel cycle arrangements	In aggregate, the difference between scenarios—at about 1.5 billion dollars per year maximum by 2050 spread over the region, is trivial relative to regional GDP Locally and nationally, the costs of the national and regional facilities needed in scenarios 1 through 3, and the benefit to local and national economies of running those facilities, will be spread unevenly over the region. Overall higher costs of nuclear power will be higher in scenarios 1 through 3 than in scenario 4, with related impacts on spending in the overall economy, but since the relative change in electricity costs is likely to be small, the overall impacts of the change will likewise be small. Scenario 1, with more facilities at the national scale, may have slightly higher costs per unit nuclear material output than in the other scenarios (though such cost difference are largely not reflected to date in the analysis). Scenario 1 may also offer arguably higher economic risks to individual nations, if facilities do not work as planned or have higher-than-expected costs. Scenario 1 also is likely to offer more variable impacts on different countries than in Scenarios 2 and 3, where financial risks are diffused over the region. Scenarios 1 and, to a possibly similar extent, 2, also may require sufficient capital to build new national and regional nuclear fuel cycle facilities as to affect the availability of capital for other types of investments, but the relative impact of this type of effect needs to be judged in the context of all types of nuclear, electricity, and energy sector investments region-wide, as well as the types of and amounts of financing available for different types of investments.			

Dimension of Energy Security	Attributes	Scenario 1 Result	Scenario 2 Result	Scenario 3 Result	Scenario 4 Result
Technological	Diversification in key industries by technology type	Of the four scenarios, scenario 1 is likely to build national capacity in nuclear fuel cycle technologies of different types more than any of the other scenarios.			
	Diversity of R&D Spending	Within the nuclear fuel cycle area, scenario 1 will likely build national R&D spending more than other scenarios. Taking a broader view, scenario 1 may serve to limit R&D in other (non-nuclear) areas of science and technology, relative to the other scenarios, by focusing national R&D investment on nuclear fuel cycle activities, possibly to the detriment of other energy and non-energy technology R&D investments.			
	Reliance on proven technologies (technological risk)	For most parts of the fuel cycle, all scenarios rely primarily on technologies that are already commercialized. In some cases, however, countries in the region have had difficulty with some of the technologies involved (Japan’s problems in commissioning Rokkasho, for example), thus it could be argued that scenario 1 offers the highest technological risk to individual nations, scenario 2 has higher technological risk for the region as a whole (to the extent that the fuel cycle of the region largely depends on one or a few key plants), and scenario 4, which relies on dry-cask storage, offers the most reliance on proven technologies.			
	Technological Adaptability	Scenario 4 probably offers higher technological adaptability than the other scenarios because the use of dry-cask storage defers the need to make decisions on permanent storage or other disposition of spent fuel, allowing disposal and possibly other fuel reprocessing technologies time to mature.			

Dimension of Energy Security	**Attributes**	**Scenario 1 Result**	**Scenario 2 Result**	**Scenario 3 Result**	**Scenario 4 Result**
Environmental	Greenhouse gas (GHG) emissions	As all scenarios involve the same amount of nuclear generation, the direct emissions of GHGs from the electricity sector from each scenario will be nearly the same, though there could be an indirect effect if investments in nuclear fuel cycle infrastructure affect other investments in the electricity sector. Scenario 4 likely results in the highest consumption of electricity, at least, and possibly other energy (likely fossil fuels) for fuel cycle activities, because of higher electricity use for uranium enrichment, though this comparison is not complete. Overall, the difference in GHG emissions between scenarios is likely to be insignificant on the scale of national GHG emissions (perhaps on the order of 0.1 percent or less).			
	Acid gas emissions and local air pollutants	Scenario 1, with more mining, milling, conversion, enrichment, and reprocessing facilities at the national level, will likely produce more air pollutant emissions from nuclear fuel cycle activities nationally than other scenarios, though the national hosts of the facilities shared in scenario 2 will also bear the burden of increased emissions. Scenario 4 offers the least in-region emissions. In all cases, however, the incremental emissions from nuclear fuel cycle activities are likely to be very small when compared to overall national/regional acid gas and local air pollutant emissions.			
	Other air and water pollutants (including marine oil pollution)	Assuming proper disposal of wastes from nuclear fuel cycle operations, other routine air pollutants and water pollutants should vary little across scenarios, though scenario 1, with more in-country facilities, offers greater risk of accidental releases than other scenarios. Conversely, greater transport of nuclear materials by ship in scenarios 2 and 3 (and, to a lesser extent, 4) means greater possibilities for marine pollution in those scenarios, though the incremental pollution between scenarios is likely to be extremely small relative to total marine oil pollution in the region.			
	Solid wastes from nuclear fuel cycle operations	9,270 m^3 reprocessing wastes; 1.33 Mt conversion wastes; 1.68 Mt depleted U; 108 kt fuel fabrication wastes (UOx/MOx)	9,740 m^3 reprocessing wastes; 1.34 Mt conversion wastes; 1.69 Mt depleted U; 109 kt fuel fabrication wastes (UOx/MOx)	10,400 m^3 reprocessing wastes; 1.38 Mt conversion wastes; 1.75 Mt depleted U; 112 kt fuel fabrication wastes (UOx/MOx)	470 m^3 reprocessing wastes; 1.44 Mt conversion wastes; 1.82 Mt depleted U; 112 kt fuel fabrication wastes (UOx/MOx)
	Nuclear waste/spent fuel (by type) (Note: medium and low-level reprocessing wastes not listed, but proportionate to HLW)	221 PBq U Mill tailings (about 2/3 in-country), 7100 m^3 HLW (most in-country); SF for disposal (t HM) 72 kt UOx, 5.4 kt MOx	163 PBq U Mill tailings (>90% out-of-country), 7500 m^3 HLW (most out-of-country); SF for disposal (t HM) 69 kt UOx, 5.4 kt MOx	168 PBq U Mill tailings (>90% out-of-country), 8000 m^3 HLW (most out-of-country), SF for disposal (t HM) 65 kt UOx, 5.4 kt MOx	175 PBq U Mill tailings (>90% out-of-country), 360 m^3 HLW (most out-of-country), SF for disposal (t HM) 136 kt UOx, 12 t MOx

Dimension of Energy Security	**Attributes**	**Scenario 1 Result**	**Scenario 2 Result**	**Scenario 3 Result**	**Scenario 4 Result**
	Ecosystem and Aesthetic Impacts	More large-infrastructure-related impacts in-country and in-region than other scenarios (mining, enrichment, reprocessing, interim storage).	More large-infrastructure-related impacts in-region than scenarios 3 or 4.	More large-infrastructure-related impacts in-region than scenario 4, but less than in other scenarios, though for some capacity paths international enrichment (as in scenario 4) and reprocessing facilities will need expansion.	Generally less ecosystem and aesthetic impacts in countries of the region, due to limited use of reprocessing and less regional enrichment. Dry-cask storage at existing nuclear sites will have some ongoing aesthetic impacts.
	Exposure to environmental risk	Scenario 1 likely provides more exposure to environmental risks (for example, extreme storms, climate-related events, earthquakes) because more fuel cycle facilities are located in the region. Scenario 4 probably offers the least risk in this regard, and also offers less risk related to nuclear materials transport, by having less material in motion. Scenarios 3 and 4, by providing stockpiles of materials, may provide some protection against environmental risks that are not afforded by the other two scenarios.				

Dimension of Energy Security	**Attributes**	**Scenario 1 Result**	**Scenario 2 Result**	**Scenario 3 Result**	**Scenario 4 Result**
Social and Cultural	Exposure to risk of social or cultural conflict over domestic nuclear systems	Likely higher than other scenarios due to need to develop large in-country enrichment, reprocessing, waste management facilities.	Likely lower than in scenario 1, but higher than scenario 3, due to less nuclear fuel cycle facilities in the region than in the former, and more than in the latter. Conflict over nuclear cooperation with other countries in the region may be an issue, however, due to history of conflict.	Likely lower than scenarios 1 and 2, as most large facilities are located and most spent fuel processing takes place out-of-region.	Likely lower than other scenarios, due to less development of in-country nuclear facilities, but local opposition to indefinite on-site storage possibly problematic in some nations.
	Exposure to risk of social or cultural conflict over nuclear materials transport	Mixed relative to other scenarios due to more in-country transport, offset by less ocean transport of nuclear materials	Except for in those countries hosting regional facilities, likely lower than Scenario 1.	Likely lower than scenario 1 and 2, as most nuclear materials will travel by ship at least most of the way to reactors.	Lower than other scenarios, as spent nuclear fuel and MOx fuel transported is limited.

Dimension of Energy Security	**Attributes**	**Scenario 1 Result**	**Scenario 2 Result**	**Scenario 3 Result**	**Scenario 4 Result**
Military/Security	Exposure to military/ security risks, including proliferation	Likely higher than other scenarios due to individual countries pursuing enrichment and reprocessing, more facilities to secure	Likely somewhat lower than scenario 1, due to more international (and regional) oversight of nuclear materials of concern for proliferation	Likely somewhat lower than scenarios 1 and 2, due to limited in-region reprocessing, though burden of securing Pu would remain with international facilities.	Lower than other scenarios due to very limited future reprocessing, thus lower accessibility of Pu.
	Relative level of spending on energy-related security arrangements	Higher local/national costs for nuclear facility/materials security arrangements than other scenarios, with the possible exception of fuel transport security costs (which are likely of minor importance overall)	Likely somewhat lower national/local security costs, but challenges in coordinating security in regional facilities for enrichment and reprocessing. Somewhat higher of fuel transport security costs (likely minor).	Lower regional costs than in scenarios 2 and 3, though some of those costs transferred to international facilities. Somewhat higher of fuel transport security costs (likely minor).	Likely lower overall security costs than other scenarios, since less Pu, MOx need be secured, spent-fuel security at reactor likely lower-cost than arrangements for new, large facilities, and spent-fuel transport costs minimized.

5.6.3. Summary Energy Security Comparison

Some of the key findings in Table 5-64 are summarized below.

- Energy supply security: Arguably, Scenario 1, in which the major current nuclear energy nations of the region own and run their own enrichment and reprocessing facilities, provides greater energy supply security on a purely national level. On a regional level, depending on the strength of the agreements developed to structure regional cooperation on nuclear fuel cycle issues, Scenarios 2 and 3, and possibly 4, may offer better energy supply security. Scenarios 3 and 4 also offer the added security of shared fuel stockpiles.
- Economic security: Scenarios including reprocessing have significantly higher annual costs, when viewed over the entire fuel cycle, than the scenario without reprocessing. The additional cost is still, however, only a relatively small fraction of the cost of nuclear power as a whole. The use of reprocessing and related required waste-management technologies may, however, expose the countries of the region to additional economic risks if the technologies have costs that are unexpectedly high (as has been the case, for example, with Japan's Rokkasho reprocessing plant). In addition, the required additional investment, probably by governments or backed by governments (tens of billions of dollars, at least) in facilities related to fuel reprocessing may divert investment from other activities, within the energy sector and without, of potentially more benefit to the long-term health of the economies of the region. On the other hand, development of in-country and in-region nuclear facilities will have its own job-creation benefits in the nuclear industry and some related industries.
- Technological security: Scenario 4, which depends on proven dry-cask storage, depends the least on the performance of complex technologies, but implicitly also depends on future generations to manage wastes generated today. Since all of the other scenarios, however, depend on interim storage of spent fuels, plutonium, and high-level wastes from reprocessing, and thus imply dependence on a future means of safe disposal, the scenarios are not so different in this long-term outlook.
- Environmental security: Scenarios 1 through 3 evaluated offer a trade-off between somewhat (on the order of 10 percent) less uranium mining and processing, with its attendant impacts and waste streams, relative to scenario 4, balanced by the additional environmental burden of the need to dispose of a range of solid, liquid, and radioactive reprocessing wastes. Differences between the scenarios with regard to generation of greenhouse gases and more conventional air and water pollutants are likely to be relatively small, and are inconsequential when compared with overall emissions of such pollutants from the economies of the region.
- Social-Cultural security: To the extent that some of the countries of the region have growing civil-society movements with concerns regarding nuclear power in general, reprocessing in particular, and local siting of nuclear fuel-cycle facilities, Scenario 4 arguably offers the highest level of social-cultural security. In some cases current laws—in Japan, for example—would have to be changed to allow the long-term at-reactor storage included in Scenario 4, and changing those laws has its own risks.

- Military security: From a national perspective, safeguarding in-country enrichment and reprocessing facilities in Scenario 1, including stocks of enriched uranium and (especially) plutonium, puts the largest strain on military (or police) resources. Those responsibilities are shifted largely to the regional level in Scenario 2, and to the international level in Scenario 3, with less stress on national resources, but more on the strength of regional and international agreements. The level of military security (guards and safeguard protocols) required of Scenario 4 is arguably considerably less than in the other scenarios.

5.7. Legal/Political Constraints on Regional Cooperation Options

The scenarios developed in Chapter 4 (and evaluated above) have, of necessity, to a certain extent suspended consideration of political and legal constraints in order to focus on alternatives for regional fuel cycle management. It is more than clear, however, that there are substantial legal and political constraints to regional cooperation on nuclear fuel cycles, and that these constraints will either limit the opportunities for cooperation, or need to be overcome in some way, in order to allow regional arrangements to proceed. These constraints include (but are unlikely to be limited to):

- Legal and/or political constraints on regional spent fuel management
- Legal and/or political constraints on regional enrichment
- Legal and/or political constraints on integrated facilities

A specific discussion of each of these issues in each country of the region is beyond the scope of this Report. Below, in order to indicate some of the potential barriers to regional agreements we briefly highlight the legal/political constraints that would likely or possibly be faced in siting and operating regional nuclear fuel cycle facilities.

5.7.1. Legal/political Constraints on Regional Spent Fuel Management

Legal and/or political constraints on regional spent-fuel management may affect siting and operation of, for example, reprocessing centers and centers for interim storage or disposal of spent fuel and/or radioactive wastes from reprocessing operations or other fuel-cycle activities. Legal and/or political constraints on such activities could be posed by the prospective host country of the facility, by the country of origin of spent fuel or other radioactive products, by the country of origin of the original nuclear fuel, or by the country or country through whose territory or territorial waters nuclear materials must be transported.

Potential hosts for regional (and in some cases, international) spent-fuel management facilities include the following, each presented with an indication of some of the issues that could arise in siting and operating spent fuel facilities there:

- **Australia** has considerable lightly-populated territory, and likely includes geologically stable strata suitable for permanent disposal sites. Australia is a major global supplier of uranium, but has no commercial nuclear power sector itself. The bulk of spent fuel and other nuclear materials from the region destined for repositories in Australia would face long sea voyages, offering potential for objections from nations through whose waters ships must pass[81]. Though different national governments have offered different points of view, there is a strong anti-nuclear power movement in Australia, including political opposition and laws legislating against nuclear power at the State level. Opposition to waste repositories are even stronger, with plans for even a small repository for research reactor waste being controversial. Australia did join the US-led Global Nuclear Energy Partnership, but with the proviso that it would not store nuclear waste (but leaving open the option of enriching uranium)[82].

- **China** is a long-time nuclear weapons state, and thus concerns regarding proliferation from siting a spent-fuel storage facility on its territory are probably minimal. China also has lightly populated areas, especially in its Western provinces, that might be suitable for geologic storage, though those areas are relatively far from sea transport links. It is unclear to us what types of positions the Chinese government and civil society groups would take regarding sharing spent-fuel storage with other nations. It is possible that historical relationships between the countries of the region might make other countries—Japan, the ROK, and the DPRK, for example—reluctant to depend on China for spent fuel management services. In addition, the United States might (or might not) be uncomfortable with China playing a central role in the nuclear fuel cycle in the region.
- The **DPRK** is likely to have geological strata suitable to host a permanent disposal site for spent nuclear fuel and related wastes, and its political structure (at least at present) is such that if the leadership decided that hosting a spent fuel management facility was in the country's best interests, there would be little internal debate about doing so. Even if there is a near-term breakthrough, however, in talks with the DPRK regarding giving up its nuclear weapons program (and the weapons itself), it would likely be many years before other nations had sufficient trust in the DPRK government to allow it to be the host for a nuclear materials repository. In addition, in a future where the economies of the ROK and DPRK become closely linked, and/or are moving toward reunification, it seems likely that ROK unwillingness to site a multi-nation spent fuel facility on its territory would also apply to the rest of the Korean Peninsula.
- As heavily populated countries with active civil-society movements, **Japan** and the **ROK** seem unlikely to host international spent-fuel facilities. It also seems likely that, at least in the nearer-term, any moves toward Japan or the ROK hosting such facilities would complication conversations with the DPRK regarding ending its nuclear weapons program.
- **Mongolia** has uranium resources, though little nuclear fuel cycle activities at present. It has considerable lightly-populated territory, is generally politically neutral among the larger economies of the region, and is in need of economic development opportunities. Its status as a non-nuclear weapons state might pose some difficulties for its hosting of a spent-fuel facility (and especially, a reprocessing facility). As with the RFE, it is likely that improved transport facilities would be needed to get spent fuels to facilities located in Mongolia. The

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[81] Though in practice, nuclear spent fuel already has passed through or near the waters of some of those nations in transit from Japan to Europe for reprocessing.

[82] J. Falk (2007), "Nuclear Energy and Australia", presentation at the Asian Energy Security Workshop 2007, October 31 - November 2, 2007, Beijing, China. Available as http://www.nautilus.org/energy/2007/beijingworkshop/papers/AustraliaNuclear.ppt.

internal Mongolian political dynamics associated with potentially hosting a spent fuel facility are currently unknown to us.

- Like China, **Russia** is a nuclear weapons state, thus national proliferation concerns are not considerations in siting a spent fuel repository there. With vast, lightly-populated territory, the **Russian Far East** would seem likely to have areas suitable for geological storage of spent fuels, though new transport facilities would likely need to be built to accommodate shipments to a remote repository. As of about 2006, however, indications were that Russia would be unwilling to serve as a repository for spent fuel from international sources[83], with the exception of ongoing take-back relationships with countries of the former Soviet Union/East Bloc using Russian-technology reactors.
- The **United States**, as the source of some of the nuclear fuel used in East Asia, and as a supplier of nuclear technologies to the region, might, on the face of it, be a possible host for international spent-fuel storage. It also has lightly-populated areas that might be candidates for such facilities, but considerable local and state opposition to nuclear facilities make the siting of an international spent fuel facility in the US unlikely, especially given the difficulty that the US has faced in siting a facility for even its own spent fuel. As a measure of such opposition, after more than two decades and expenditures on the order of 10 billion dollars, funding for the under-construction spent fuel storage facility at Yucca Mountain, Nevada, was cut by the Obama administration, meaning that, absent a change of heart by the current or subsequent administrations, the facility will not be completed[84].

Other potential political/legal issues associated with the use of spent-fuel repositories in other countries could include restrictions on the disposition of fuels issued by the countries of origin (such as restrictions on where US-origin fuels can be placed), restrictions posed by existing reprocessing contracts (though many such contracts, for example, between Japan and EU-based facilities, have expired or are expiring), and specific legal restrictions within individual countries. In Japan, for example, constraints (and in some cases, spurs toward) on using international spent-fuel disposal facilities may follow from laws requiring reactor operators to specify the method of spent fuel disposal, policies of Japanese Atomic Energy Commission's long-term plans favoring reprocessing, definitions of "high-level waste" that exclude spent fuel and thereby limit the ability of the Nuclear Waste Management Organization to handle spent fuels, promises made to local hosts of nuclear reactors not to retain spent fuel on-site, and recent trends toward building interim storage facilities[85].

As noted above, legal and political issues associate with the use of regional and spent-fuel facilities are complex, and a full investigation of these issues for the countries of East Asia is beyond the scope of this Report, but is deserving of and requires further work.

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[83] A. Dmitriev, personal correspondence, 2006.

[84] See, for example, G. Whittell (2010), "Yucca Mountain nuclear waste site dropped despite plans for new plants", TimesOnline, dated February 3, 2010, available as http://www.timesonline.co.uk/tol/news/world/us_and_americas/article7012705.ece.

[85] T. Suzuki (2006), "The Nuclear Power Sector in Japan: Nuclear Materials Management/Fuel Cycles Practices, Plans and Policies", presentation prepared for the 2006 Asian Energy Security Workshop. November 6-7, 2006, Beijing, China, and available as www.nautilus.org/energy/2006/beijingworkshop/papers/Suzuki.ppt.

5.7.2. Legal/political Constraints on Regional Enrichment

Some, but not all, of the legal and political constraints that effect siting and operation of spent fuel facilities also apply to the siting of regional uranium enrichment plants (and related facilities, such as fuel storage/stockpiles or fuel fabrication, though because handling of intensely radioactive fission products is not involved, restrictions are somewhat different. Some of the constraints that apply to the countries of the region are described below.

- **Australia**, as a holder of major uranium reserves, could see an extension to enrichment (and possibly fuel fabrication) as a logical step in offering "value added" to the nuclear community. Some of the Australian political and social opposition to nuclear power (and even, in some States, additional uranium mining) could pose a significant constraint on its hosting enrichment facilities, as could its status as a non-nuclear weapons and power nation.
- **China**, which will be adding most of the nuclear capacity in the region in the coming decades, could be a logical host for a regional enrichment center, though uranium would need to be largely imported to feed such a facility. It seems likely, however, that other states (notably the Koreas and Japan) might find China as a source of regional enrichment capacity unpalatable unless the regional arrangement included stringent safeguards, which China might be reluctant to accept.
- The **DPRK** and the **ROK**, so long as they are two countries, are not good candidates for hosting regional enrichment facilities, as, absent a remarkable thaw in relations, neither is likely to trust the other with an enrichment capability, and/or to adhere to the required safeguards protocols to host such a facility.
- **Japan** already has some enrichment capacity, but it is not clear how Japanese civil society would respond to adding capacity to serve other nations. Japan might well be willing to accept safeguards sufficient to satisfy the IAEA, but would any level of safeguards satisfy both the ROK and DPRK?
- Like Australia, **Mongolia** might also, given its uranium resources, also be a candidate for hosting an enrichment facility, but as a non-nuclear-weapons, non-nuclear-power state, other nations in the region might object to Mongolia hosting such a facility. How the prospect of an enrichment facility might fare with regard to internal Mongolian politics has not yet, to our knowledge, been explored, though the concept of Mongolia participating in multilateral initiatives has been raised in the literature, at least in a general way[86].
- **Russia and the RFE**, with its relatively cheap generation resources to provide electricity for enrichment could serve as a source of market enrichment. Whether there would be political barriers in Russia to hosting a regional enrichment facility (and the level of safeguards/monitoring and verification that would presumably come with it) is unknown.

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[86] See, for example, U. Agvaanluvsan (2009), "The Global Context of Nuclear Industry in Mongolia", Mongolia Today, the Mongolian National News Agency, December 2009, available as http://iis-db.stanford.edu/pubs/22822/AgvaanluvsanMongolia_nuclear_industry.pdf; and R. Sachs and U. Agvaanluvsan, Fueling the Future:Mongolian Uranium and Nuclear Power Plant Growth in China and India, dated September 01, 2009, and available as http://iis-db.stanford.edu/pubs/22637/Uranium_Report___Final.pdf.

- The **United States** has shutting down an older (gaseous-diffusion-based) enrichment facility in Piketon, Ohio, but continues to operate another older facility in Paducah, Kentucky. Three new centrifuge enrichment facilities are under construction in the U.S., though construction of one the facilities (the American Centrifuge Plant in Piketon) was suspended in mid-2009 when its owners failed to receive a loan guarantee from the U.S. Department of Energy. A fourth new U.S. enrichment plant, based on laser isotope separation, is in the final stages of Nuclear Regulatory Commission licensing prior to construction[87]. It is politically uncertain whether sufficient additional capacity to service East Asia and the Pacific, if located in the U.S., would be easy to site, even if it the region's customers were comfortable with sourcing their enrichment needs from the United States, though the current group of new plants (three of which are owned partly or entirely by non-U.S. companies) under construction or in advanced licensing suggests that new facilities might not be all that hard to site.

In addition to the possible country-specific constraints described above, other political or legal constraints, such as existing long-term contracts between international enrichment services vendors and buyers in the region, could also apply.

5.7.3. Legal/political Constraints on Integrated Facilities

Integrated nuclear fuel cycle facilities, which could provide a combination of enrichment, fuel fabrication (UOx and MOx), spent-fuel reprocessing, and/or spent fuel storage, would likely be subject to the same sorts of national and international restraints that have been identified in the context of non-integrated facilities.

6. Study Conclusions, and Next Steps

Nuclear power will certainly continue to play a significant role in the economies of the countries of the East Asia and Pacific region for decades to come, but the extent of that role, and how the various cost, safety, environmental, and proliferation-risk issues surrounding nuclear power are addressed on the national and regional levels is not at all certain. Below we present a brief summary of study findings, and provide a sense of the "next steps" we intend to pursue in the collaborative East Asia Science and Security analyses.

6.1. Summary of Study Findings

The section of the report that follows provides a brief summary of the results of the nuclear energy capacity expansion paths presented in sections 2 and 3 of this report, and of the regional scenarios for nuclear cooperation (or non-cooperation) described and analyzed in sections 4 and 5.

6.1.1. Results of Different Nuclear Paths, by Country

Table 6-1 below (which is the same as Table 3-1, but is copied here for the reader's convenience) summarizes the nuclear capacity included for each the three nuclear capacity

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[87] World Nuclear Association (2010), "US Nuclear Fuel Cycle". Updated March 26, 2010, and available as http://www.world-nuclear.org/info/inf41_US_nuclear_fuel_cycle.html.

expansion paths (Business as Usual, Maximum Nuclear, and Minimum Nuclear) for each country for the years 2010, 2030, and 2050. Key results by country are as follows:

- **Japan**, with relatively little additional space for reactors and a declining population, shows slow growth in reactor capacity from 2010 to 2050 in the BAU case—adding about 33 percent more capacity over 40 years, and only modestly more rapid growth in the MAX case. The MIN case, which amounts to a nuclear phase-out as reactors reach the end of their operating lifetimes, represents a significant departure for Japan, virtually eliminating its nuclear fleet by 2050.
- In the **ROK**, Additional reactor space is also limited, but more and larger reactors are added to existing sites in the BAU case, resulting in a near-doubling of 2010 capacity by 2050, and in the MAX case, where capacity increases by a factor of nearly 2.5 (though new sites would probably be needed in the MAX case). I the MIN case, existing reactors are retired without life extension and not replaced, resulting in a reduction in capacity of more than 50% by 2050.
- For **China**, all three capacity expansion paths show explosive growth in nuclear capacity through 2030. Growth continues in the BAU path after 2030, though at a lower rate as the Chinese economy matures and population begins to decline, In the MAX path, the growth rate of capacity also declines somewhat after 2030, but nearly 100 GW are still added in between 2030 and 2050, nearly twice as much as is added in the BAU case. In the MIN case, capacity additions essentially cease after 2030 (and growth to 2030 is less than in the other paths), with older reactors retired as they reach the ends of their operating lifetimes.
- The **Russian Far East** add some capacity between about 2020 and 2050 in the BAU case to its very small existing reactors in the far north. This capacity is mostly to serve export markets and/or to provide power for producing export commodities such as aluminum. In the MAX case, future capacity is approximately twice that in the BAU case, reflecting a stronger market for RFE power exports. In the MIN case, only one new (larger) reactor is added in the RFE by 2030, and no more thereafter.
- In **Taiwan**, as in Japan and the ROK, limited space for new reactors and a declining population limit the extent to which nuclear capacity can increase. In the BAU case, capacity increases by 2 GW, as a result of adding reactors now under construction, but remains at the resulting 7 GW level through 2050. In the MAX case, larger reactors are added at existing sites when older reactors are decommissioned, pushing capacity to 11 GW by 2050. In the MIN case, older reactors are not replaced, resulting in Taiwan's capacity falling to 3 GW by 2050.
- In the BAU case, the **DPRK** is assumed to reach an agreement with other parties regarding its nuclear weapons program in the next few years, and as a result completes (or, more likely, works with the ROK to complete) by 2030 the reactors at Simpo begun under the KEDO project. In the MAX case, a additional 4 GW of capacity is added in the years around 2030, for a total of 6 GW. In the MIN case, the DPRK does not develop nuclear power.
- For **Indonesia, Vietnam**, and **Australia**, which do not have and are not yet building nuclear power capacity, the BAU case includes first reactors that come on line between 2020 and 2030, with Vietnam's program being much more aggressive than in the other two nations.

The MAX path includes greater use of nuclear power for each nation by both 2030 and 2050. In the MIN path, none of these nations ultimately adopt nuclear power.

Table 6-1: Regional Nuclear Generation Capacity, Summary of BAU, MAX, and MIN Paths

	Total Nuclear Capacity Net of Decommissioned Units (GWe)								
	RAU (Reference) Case			Maximum Nuclear Case			Minimum Nuclear Case		
Nation	2010	2030	2050	2010	2030	2050	2010	2030	2050
Japan	47	62	64	47	68	69	47	20	2
ROK	19	33	35	19	42	47	19	18	9
China	10	120	170	10	161	257	10	93	84
RFE	0	3	6	0	6	11	0	1	1
Taiwan	5	7	7	5	9	11	5	3	3
DPRK	-	2	2	-	6	6	-	-	-
Indonesia	-	2	6	-	4	13	-	-	-
Vietnam	-	10	20	-	15	30	-	-	-
Australia	-	2	6	-	7	20	-	-	-
TOTAL	81	241	316	81	318	464	81	134	97

6.1.2. Summary of Regional Scenario Results

The results of the regional scenario evaluation described in Chapter 5 indicates that Scenario 4, which focuses on at-reactor dry cask storage and coordinated fuel stockpiling, but largely avoids reprocessing and MOx use, results in lower fuel-cycle costs, and offers benefits in terms of social-cultural and military security. These results are consistent with (and, indeed, draw ideas and parameters from) broader studies by other groups, including, for example, the joint work by the Harvard University Project on Managing the Atom and the University of Tokyo Project on Sociotechnics of Nuclear Energy[88].

That said, there are definite trade-offs between scenarios. Scenario 1, by using much more domestic enrichment and reprocessing than the other scenarios, arguably improves energy supply security for individual nations, but results in higher technological risk due to national reliance on one or a small number of enrichment and reprocessing plants, rather than the larger number of plants that constitute the international market. Scenario 1 also results in the build-up of stockpiles of plutonium in each of the nations pursuing reprocessing. Though the magnitude of the plutonium stockpiles, and the rate at which they are used, varies considerably by nuclear path and scenario, the quantities accrued, ranging from about 130 to about 270 tonnes of Pu at a maximum in Scenarios 1 through 3 (in the years around 2040—see Figure 5-14), are sufficient for tens of thousands of nuclear weapons, meaning that the misplacement or diversion of a very small portion of the stockpile becomes a serious proliferation issue, and thus requires significant security measures in each country where plutonium is produced or stored. Scenario 4, without additional reprocessing, maintains a stockpile of about 70 tonnes of Pu from about 2010 on. This still represents a serious proliferation risk, but does not add to existing stockpiles or create stockpile in new places.

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[88] M. Bunn, J. P. Holdren, A. Macfarlane, S. E. Pickett, A. Suzuki, T. Suzuki, and J. Weeks (2001), Interim Storage of Spent Nuclear Fuel: A Safe, Flexible, and Cost-Effective Near-Term Approach to Spent Fuel Management, dates June, 2001, and available as belfercenter.ksg.harvard.edu/files/spentfuel.pdf.

Scenarios 1 through 3, which include reprocessing, result, as noted above, in higher annual costs-about $5 billion per year higher in 2050 relative to Scenario 4, over the entire region (see Figure 6-1). Scenarios 1 through 3 reduce the amount of spent fuel to be managed substantially—by 50 percent or more over the period from 2000 through 2050, relative to Scenario 4—but imply additional production of 7000 to 7600 cubic meters of high-level waste that must be managed instead (versus about 300 cubic meters in Scenario 4). This in addition to medium- and low-level wastes from reprocessing, and wastes from MOx fuel fabrication that must be managed in significant quantities in Scenarios 1 through 3, but not in Scenario 4. Scenarios 1 through 3 offer a modest reduction—less than10 percent in for the BAU nuclear capacity paths case—in the amount of natural uranium required region-wide, and in attendant needs for enriched uranium and enrichment services. This reduction is not very significant from a cost perspective unless uranium costs rise much, much higher in the next four decades. Reductions in the quantities of electricity and fuel used for uranium mining and milling, as well as production of depleted uranium, are generally somewhat lower under Scenarios 1 through 3 than under Scenario 4, though results for Scenario 1 differ from Scenarios 2 and 3 because of the emphasis on sourcing uranium from domestic mines in the region. Figure 6-2 shows aggregated front-end (fuel preparation) and back-end (spent fuel management) costs by Scenario and for each of the three nuclear capacity paths for the region.

Figure 6-1: Summary of Fuel-cycle Costs by Scenario, BAU Capacity Expansion Path

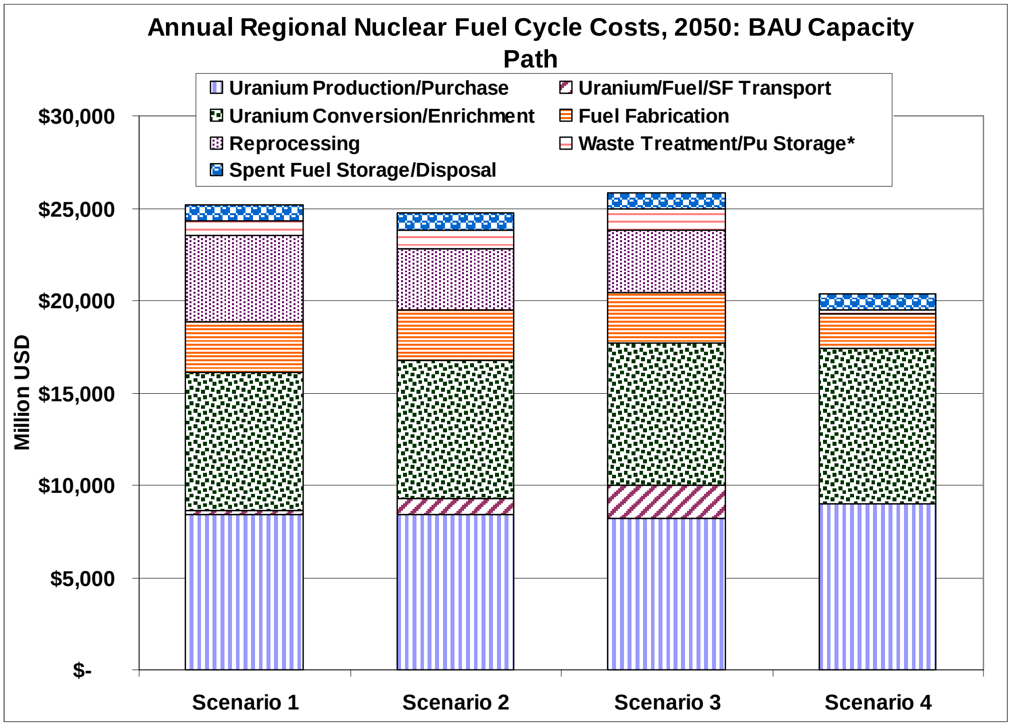
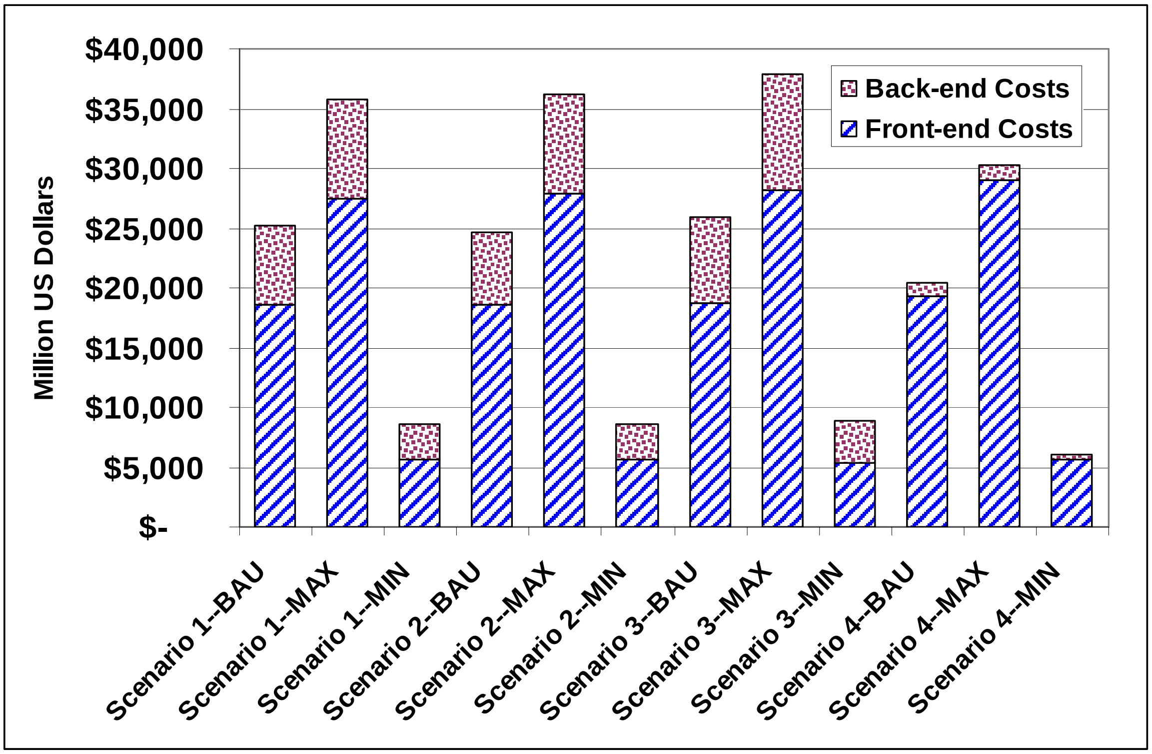


Figure 6-2: Summary of Year 2050 Annual Costs by Scenario and by Nuclear Capacity Expansion Path



Scenarios 2 and 3, though they include reprocessing, place more of the sensitive materials and technologies in the nuclear fuel cycle in regional and international facilities, and as a consequence, are likely to be superior to Scenario 1 in terms of reducing proliferation opportunities, reducing security costs, and increasing the transparency of (and thus international trust in) fuel cycle activities. The costs of Scenarios 2 and 3 shown in this analysis are not significantly different, overall, from those of Scenario 1, but a more detailed evaluation of the relative costs of nuclear facilities (particularly, enrichment and reprocessing facilities) in different countries, when available, might result in some differentiation in the costs of these three scenarios. Scenarios 2 and 3 result in significantly more transport of nuclear materials—particularly spent fuel, enriched fuel, MOx fuel, and possibly high-level wastes around the globe, likely by ship, than Scenario 1, though there would be somewhat more transport of those materials inside the nations of East Asia in Scenario 1.

6.2. Next Steps

The combination of, tools, methods, and human networks created, adapted, and/or applied to prepare the analysis described in this Report can be usefully applied to a number of additional studies. The tools used for the EASS project include the LEAP models for each of the East Asia and Pacific countries included in the project, and the regional nuclear fuel cycle scenarios workbook tool that allows us to look at physical and cost parameters of nuclear cooperation scenarios for each part of the fuel cycle (except, at present, nuclear generation itself), and in each country of the region, for the time period between 2000 and 2050. The methods used in the project include our techniques for comparing the energy security benefits and costs of different scenarios across a broad range of energy security attributes. And most importantly, the network of active Country Teams in each of the EASS nations provides an invaluable set of perspectives, as well as access to data and information on national policy developments, that is, we believe, unique among studies of this kind.

Some of the research efforts described below are currently underway or being initiated by Nautilus Institute and its partners, while others are opportunities that we hope to address (or we hope to see others address) in the future.

6.2.1. Improve Assumptions and Analytical Methodologies

In preparing the analysis described in this report, we have made a host of assumptions (described in Annex B) and estimates. For some factors we have been obliged, for lack of data, to use rough estimates from the literature, even when some variation in parameters across countries almost certainly exist (such as in the costs of nuclear fuel cycle facilities. For other factors we have so far been unable to find literature estimates, and though generally these factors are unlikely to result in significant change in results, we would like to be able to include reasonable estimates of these parameters (as just one example, electricity input into conversion of U_3O_8 to UF_6) for the sake of completeness. In addition our analytical tools allow us to perform sensitivity analyses—such as on future costs of natural uranium, or of enrichment services—that would be useful to run and evaluate, but at present remain undone.

6.2.2. Implications of New Reactor and Other Fuel Cycle Technologies for Regional Spent Fuel Management/Enrichment Proposals in Asia

A number of new types of reactors—including, for example, small, modular reactors, “fast” reactors using and producing plutonium fuels, and reactors based on a Thorium fuel cycle, to name just a few—have been proposed for implementation in the coming decades (typically after 2030, and often later). In addition, variants on the existing LEU/MOx fuel cycle, including a version of reprocessing called “pyroprocessing”, have been proposed by various groups, including, recently, in the ROK. How might the implementation of these new nuclear technologies affect the form or prospects of nuclear fuel cycle cooperation in East Asia? This topic will be addressed specifically by Nautilus and its partners for selected technologies (such as pyroprocessing) and for the ROK and Japan in the context of Nautilus’ Korea-Japan Nuclear Weapons Free Zone Initiative, starting in mid-2010. Analysis of the more general implications of the development and implementation of new reactor types and fuel cycles may be taken up by Nautilus and its collaborating organizations in the future.

6.2.3. Implications of Climate Change Mitigation/Adaptation for Nuclear Power, and for Regional Spent Fuel Management/Enrichment Proposals in Asia

Climate change is a major and growing concern worldwide, with countries and sub-national jurisdictions making plans not just for reducing GHG emissions, but for adapting to impacts of climate change that seem inevitable. To offer just a few examples, a number of states in the United States have, in the absence (until recently) of Federal leadership on climate change, convened “stakeholder” groups to develop climate change mitigation and, in some cases, adaptation plans[89], and China[90], Japan, and the ROK have each formulated and released climate

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[89] For a summary of climate plans in US states, see, for example, Pew Center on Global Climate Change (2010), " Climate Action Plans”, available as http://www.pewclimate.org/what_s_being_done/in_the_states/action_plan_map.cfm.

change mitigation plans over the last few years, some of which also include reference to adaptation activities, and all of which feature nuclear power as a potential greenhouse gas emissions mitigation option.

Nuclear power is enjoying a resurgence of interest worldwide—though as yet, with the exception of possibly of China, relatively little new reactor construction is underway. A part of this interest is related to nuclear power's potential role in meeting energy needs without substantial GHG emissions. Some of the major issues associated with the linkages between nuclear power and climate change include the environmental implications of a "nuclear renaissance" for GHG emissions reduction, the economic, social, and political implications of a broad program of nuclear power development, relative to other GHG mitigation strategies, and the benefits and challenges posed by nuclear power in terms of adaptation to a changing climate.

Work in the coming year of the EASS Project will focus on the topic of "Climate Change and Nuclear Power: Energy Security Implications", addressing topics such as the potential contribution of nuclear energy in East Asia and the Pacific to climate change mitigation, the adaptation of nuclear power systems to changing climates, the interaction of nuclear power support and investments with other approaches to/investments in climate change mitigation, and with investments in climate change adaptation, and the exposure to climate change impacts and risks of different types (including energy security, physical, and social risks) related to power system choices. This work will involve updating and comparing climate change mitigation paths (as developed with LEAP and other quantitative and qualitative tools) with and without substantial expansion in nuclear power use, evaluating—based as much as possible on existing studies—the impact that climate change adaptation measures will have on the energy systems of the countries of the region, and integrating consideration of the interaction of nuclear power systems with climate change mitigation and adaptation.

We expect that the output of this work will include:

- **A Report on the Interactions of Climate Change and Nuclear Power/Nuclear Fuel Cycle:** In the context of the national expert team analyses and elaboration of regional policy measures, an expert report has been commissioned to "scope out" the issues on the potential interactions between nuclear power/nuclear fuel cycles and climate change mitigation and adaptation. This report is assembling a summary of the literature on the topic, lay out generically the key interactions between the issues, and suggest which issues will be most applicable to/important for the East Asia/Pacific region. The report will help to point the way toward additional key areas of research for the national teams and Nautilus to address. A second report (or set of reports) may be commissioned in the coming year to provide a more in-depth review of one or more topics related to the interaction of climate change and nuclear energy, and to provide background for the Country Teams as they prepare their national analyses.
- **Synthesis Report on Nuclear Power/Nuclear Fuel Cycles and Climate Change:** In the coming year, the EASS project will produce a report synthesizing the national reports on the topic, the Report on the Interactions of Climate Change and Nuclear Power/Nuclear Fuel Cycle, as well as prior reports by our collaborating teams and others on other

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[90] National Development and Reform Commission of the PRC (2007), China's National Climate Change Programme, dated June, 2007, and available as http://en.ndrc.gov.cn/newsrelease/P020070604561191006823.pdf.

regional energy security policy measures. The Synthesis report will explore key policy energy security tradeoffs posed by the interaction of nuclear power/nuclear fuel cycles and climate change, produce insights into how such interactions will affect regional nuclear enrichment/spent-fuel cooperation options, and identify additional actionable recommendations for bilateral (US-regional partners) and multilateral (IAEA, Pacific Nuclear Basin, APEC Energy Working Group, and sub-regional dialogues) discussions on critical issues associated with the East Asian energy sector in general, and the interactions of climate change and non-proliferation policy in particular.

6.2.4. Refinement and Further Analysis of Regional Fuel Cycle Cooperation Options

Also in the coming year, we expect that the EASS project will work with our partners in the region to refine the nuclear cooperation scenarios included in this report, and also to refine the analysis of those scenarios. Bringing in more detailed consideration of other elements of cooperation proposals, looking first at existing proposals described in the literature, will help us to prepare results for policymakers that clearly show the costs and benefits of a set of potential nuclear fuel cycle cooperation policies. We expect to focus particularly, as a part of the Korea-Japan Nuclear Weapons Free Zone Initiative mentioned above, on the analysis of the implications of nuclear fuel cycle cooperation proposals for the Koreas and Japan.

7. REGIONAL SAFEGUARDS IMPLICATIONS

Analysis of the implications of regional scenarios for how nuclear materials are "safeguarded"—continuously accounted for, monitored to make sure they are handled appropriately, and kept out of the hands of those who might use them to build weapons of mass destruction with them, for example—is a step that must be taken before any regional cooperation option can approved for implementation. Although a full safeguards analysis of the scenarios described in Chapter 4 is beyond the scope of this Report, we outline below the key issues associated with such an analysis, and describe a proposed analytical approach.

7.1. Safeguards Issues Posed By Regional Nuclear Fuel Cooperation Scenarios

Adoption of regional nuclear fuel cooperation schemes will have a pervasive impact on safeguards from domestic, bilateral/regional, and international perspectives. Comprehensive safeguards encompass manifold technical and legal measures. These measures include an evolving set of procedures to counter threats from sub-national groups and to verify the political agreements of states not to use nuclear material to manufacture nuclear weapons—that is, to confirm, in IAEA parlance, that such material "remains in peaceful activities," and to deter any such weapons use.

One of the "next steps" in this study of regional nuclear scenarios, as noted above, will be to examine the impacts of the four regional nuclear fuel cooperation scenarios—and variants thereof that illuminate specific issues—on six efforts to counter sub-national proliferation (nuclear terrorism) and to strengthen international safeguards:

1. Strengthening States' and Regional Systems of Accounting and Control (SSAC/RSAC). The first line of defense in protecting nuclear materials from theft by sub-national groups is the national legal framework and regulatory mechanisms of the State, including the development and implementation of a system of accounting for, and control of, nuclear materials and activities; and technical measures and best practices employed by nuclear facility operators. An effective SSAC is also an essential element of international safeguards, providing reports to, and interfacing with, the IAEA. A regional system of accounting and control (e.g., ASIATOM) could be a logical outcome of regional nuclear fuel cooperation concepts for the States under consideration in this study.

2. Detecting undeclared nuclear material or activities has been the focus of efforts to strengthen IAEA safeguards following the discovery of undeclared nuclear activities in Iraq and the DPRK in the early 1990's. Here the primary issue is the impact of regional nuclear fuel cooperation schemes on a state's ability to develop and operate clandestine facilities, especially enrichment and plutonium production and reprocessing, and the IAEA's ability to detect such activities, in the regional and decentralized regional nuclear fuel cooperation models;

3. Detecting undeclared production or processing of nuclear material at declared facilities is an IAEA safeguards verification objective designed to, for example, detect excess HEU or LEU production at enrichment facilities or plutonium production and separation at reactors. The impacts of regional nuclear fuel cooperation institutional and technical measures on this verification objective will be examined.

4. Detecting diversion of declared nuclear material will employ on-site inspections and other safeguards tools such as real-time monitoring and the use of bulk facility owner-operator equipment and laboratories. The scale and complexity differences between the two regional nuclear fuel cooperation models for facility reporting may have significant impacts on this aspect of the safeguards system. In addition, facilities for regional fuel supply and spent fuel processing that use new chemical processes may pose serious technical verification challenges to ensure adequate accounting for material extracted. Examples may include: pyro-processed plutonium flows, even if no separated plutonium is involved; and bulk processing schemes that entail the IAEA's use of owner labs and equipment authentication issues. In both regional nuclear fuel cooperation models, there will also be much larger and many more flows of fresh and spent fuel, possibly of separated plutonium, and interim storage of spent fuel and processing wastes in various forms and containers (ponds, dry casks), all of which would have to be accounted for, and integrated into, an overall accounting scheme. In this increasingly demanding and complex task, accountancy may draw also on new systems analysis modeling and simulation tools. Due to their differential scale and complexity, the decentralized vs centralized regional nuclear fuel cooperation schemes may pose more or fewer challenges for material accountancy, and bear careful examination.

5. Implementing customized, country-based safeguards.: The use and integration of data from open-sources, third parties, environmental sampling, and complementary access (where there is an Additional Protocol in force), along with traditional safeguards on declared nuclear materials to verify safeguards agreements, using the so-called State-Level Approach being developed by the IAEA, may be more subjective, ambiguous, and adversarial than criteria-driven inspections employed previously. The implication is that the IAEA (and any regional supplementary or adjunct inspections system created as part of a regional nuclear fuel cooperation scheme), focused on the states mentioned above would face a tradeoff between high cost inspections on the one hand, and a potentially conflicted and politicized institutional arrangement on the other. The extra demand for IAEA capacities to provide safeguards in the two regional nuclear fuel cooperation models needs to be estimated. The net result on the credibility of appraisal of the non-existence of clandestine facilities of such focused and integrated approaches in the two regional models bears careful evaluation, as do the cost savings and efficiency gains for the monitoring agency from substituting technology and information for on-site inspections. Whether the IAEA could follow the customized approach in the two regional nuclear fuel cooperation models without becoming embroiled in regional conflicts driven by unrelated issues must be considered. It is essential that the IAEA safeguards system remain credible, nondiscriminatory, and transparent in perception and fact. Conversely, a regional nuclear fuel cooperation policy measure that centralizes or distributes new levels of latent proliferation capacity and materials may generate higher levels of neighborly surveillance that ease the IAEA's task on the one hand, and thereby increase transparency by regional fuel cycle -hosting states seeking to sustain "good neighbor" reputations on the other. Again, hybrids of IAEA-regional safeguards systems bear thinking about in this context.

6. Employing extrinsic non-proliferation and safeguards-related measures such as credible enforcement and other deterrence conditions, and non-safeguard non-proliferation measures such as dual-use export controls, bilateral safeguards-related fuel and technology export conditionalities, and national, bilateral and regional legal and treaty frameworks may affect the effectiveness of safeguards and need to be examined in relation to the impact of the

two regional nuclear fuel cooperation models on these measures. As noted in item #1 above, the evolving legal requirements imposed by the 2004 United Nations Security Council's (UNSC's) Resolution 1540 for effective control of nuclear materials and facilities may also affect the definition of safeguards required for the two regional nuclear fuel cooperation models, especially as it relates to the proliferation activities of non-state actors.

7.2. Approach to Analyzing Safeguards Impacts of Cooperation Scenarios

The results described in Chapter 5, augmented by additional analysis, can be used to explore the possible safeguards implications of the various nuclear fuel cycles and related cooperation scenarios offered in Chapter 4. The basic framework whereby these implications will be identified and analyzed is as follows.

The first step is to describe a "time zero" (present) baseline of the safeguards situation in each country, and regionally. This provides the foundation for comparison of safeguards outcomes across the pathways and regional cooperation schemes.

The second step is to compare the various regional proliferation propensities of each nuclear weapons state (to arm or disarm nuclear weapons more or less) on one side, and non-nuclear weapons state (with and without nuclear power) on the other under the different national nuclear pathways, and under each regional cooperation scenario. Part of this evaluation is purely a risk-benefit comparison across scenarios. As examples, analysis might be examine how short the time required to proliferate in a country is relative to the probable amount of time that will elapse before detection of proliferation and response by the IAEA and the UNSC, or how proliferation risks might vary as a function of the absolute amount of fissile material in processing or storage in a country, or what the risk is of diversion of materials in transport to/from a national vs. an international repository. Part of these comparisons will be qualitative--for example, the proliferation dampening effects arising from nuclear cooperation between nuclear weapons states or potential proliferant states and their adversaries—and some will be quantitative.

The last step in the analysis of the safeguards implications of different regional scenarios will be to we examine the possible policy options for treating safeguards in each scenario, and to look at the implications for different "players" (nuclear sector actors in the region and beyond) in terms of functional capacity and accountability for implementation of each of the elements of the scenarios, examining players in all sectors (international governmental organizations, civil society organizations, states, and private companies). Part of this step is to co-relate these necessary combinations of policies, players, and roles in regional nuclear cooperation with a macro-analysis of geo-political and geo-economic trends in the region, recognizing the radical uncertainties that may drive outcomes.

These analytical steps form the basis for a proposed outline of the safeguards study, as described below.

- Baseline Regional Safeguards
    - Baseline Nuclear Safeguards in Asia-Pacific Region
    - Baseline Safeguards Deficits and Challenges in Asia-Pacific Region

- New Regional Safeguards
    - Safeguards Deficits and Challenges Posed by Nuclear Pathways in Asia-Pacific Region
    - New Safeguards Technologies and Techniques
    - Safeguards Issues Posed by Regional Enrichment and Spent Fuel Management Schemes
- Policy Implications
    - Comparison of Baseline and Alternative Pathways Safeguards Deficits and Challenges with Safeguards Responses from Deploying New Safeguards and Techniques, without Regional Enrichment and Spent Fuel Management Schemes
    - Comparison of Baseline and Alternative Pathways Safeguards Deficits and Challenges with Safeguards Responses from Deploying New Safeguards and Techniques, with Regional Enrichment and Spent Fuel Management Schemes
    - Conclusion: Policy Implications of Analytic Outcomes for International, Regional, and National Safeguards Policies
    - Conclusion: The Role of US leadership in Multilateral Safeguards Innovation in the Asia-Pacific Region

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9. List of Annexes

ANNEXES: WORKPAPERS/DETAILED RESULTS

ANNEX A: Selected Printouts of Workbooks/Worksheets Used to Extend LEAP Nuclear Generation Capacity Expansion Paths

ANNEX B: Selected Printouts of Results of Estimates of Nuclear Fuel Cycle Flows and Costs for Regional Cooperation Scenarios

ANNEX C: Selected Printouts of Worksheets Used to Estimate Nuclear Fuel Cycle Flows and Costs for Regional Cooperation Scenarios