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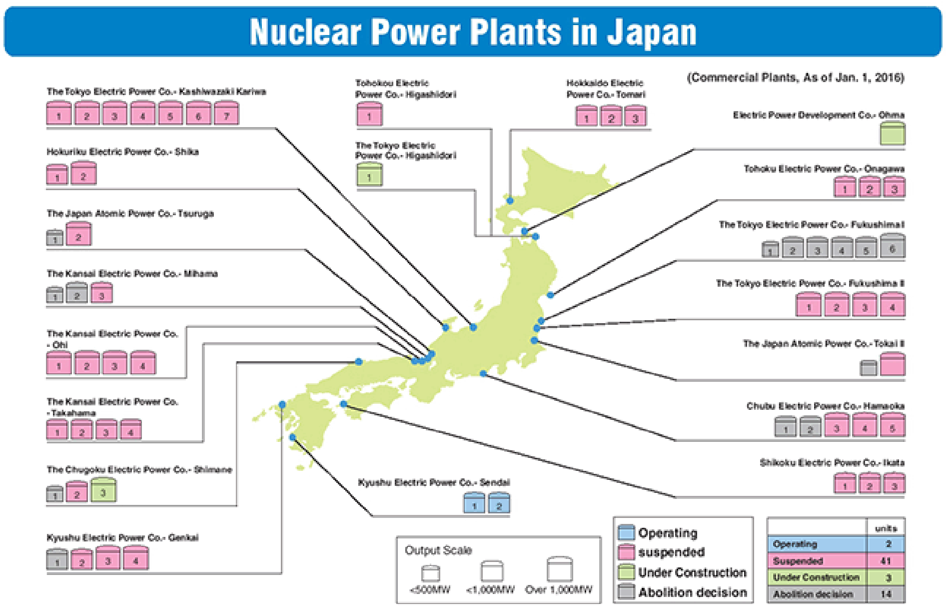
## JAPAN’S POST-FUKUSHIMA CHOICE: FUTURE NUCLEAR FUEL CYCLE PATHS AND THEIR IMPLICATIONS




Banner image: Color-coded map identifies potential nuclear power plants in Japan and their status as of early 2016, from here


**David F. von Hippel and Peter Hayes**

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**Nautilus Institute for Security and Sustainability**



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# Japan's Post-Fukushima Choice: Future Nuclear Fuel Cycle Paths and Their Implications

**David F. von Hippel and Peter Hayes**

**Revised July 2016 (with additional minor revisions April 2018)**

***THE NAUTILUS INSTITUTE FOR SECURITY AND SUSTAINABILITY***

**Prepared as a Part of the Nautilus Institute Project**

## Vulnerability to Terrorism in Nuclear Spent Fuel Management

**Funded by the John D. and Catherine T. MacArthur Foundation**

# SUMMARY

Spent fuel in Japan and elsewhere is vulnerable to attack by non-state actors. Following the March 11, 2011 catastrophe at the Fukushima Daiichi nuclear power plant, all of Japan's reactors were shut down for extended safety reviews. Since 2011policy analysts have discussed not only the impact of the Fukushima catastrophe on Japan's power supplies and future level of nuclear power, but also on the disposition of spent fuel, including fissile material either separated from or stored in various ways as spent fuel. This Report addresses the vulnerability of this spent fuel by evaluating three "paths" for the future of the Japanese nuclear energy sector and management of spent nuclear fuel. These are:

- **Path 1: Return to Pursuit of Closed Nuclear Fuel Cycle**, which includes the restart of most existing light-water reactors in the next five years, extension of reactor lifetimes, the addition of 10 new reactors, and the resumption of domestic reprocessing of spent fuel use of mixed-oxide fuel (MOx);
- **Path 2: Slower Return to Pursuit of Closed Nuclear Fuel Cycle**, in which the return to a closed nuclear fuel cycle path proceeds at a slower pace than in Path 1, but is otherwise similar to Path 1; and
- **Path 3: Limited Reactor Restart with Once-through Fuel Cycle**, in which only 10 reactors are restarted, MOx is used in about half of restarted reactors, limited life extension is applied, all existing dense-packed spent fuel pools are converted to non-dense-packed operation, and reprocessing is pursued.

These paths have different, and sometimes offsetting, types and levels of vulnerabilities to terrorist attack on nuclear facilities or diversion of nuclear materials.

Cumulative 2015 through 2050 spent fuel arisings in Path 1 are about 40 percent higher than in Path 2, and three times those in Path 3.

Paths 1 and 3 essentially use up (via MOx fuel fabrication and irradiation) Japan's current stockpile of plutonium (Pu) by 2050, whereas on the order of 40 tonnes of Pu remain by 2050 in Path 2, and thus remain vulnerable to diversion or attack.

Conversely, Paths 1 and 2 temporarily increase Japan's aggregate stockpile of Pu (via reprocessing) by 10 to 20 tonnes and require total Pu throughput (and thus handling) for MOx fabrication that is five and three times higher, respectively, than in Path 3 over 2015-2050, thus creating higher vulnerability to attack or diversion.

Path 3 reduces the vulnerability of spent fuel pools to attack by shifting to non-dense-packed configurations and through more rapid decommissioning of reactors, but also requires more spent fuel handling and transfers to dry cask storage earlier than in the other paths.

Path 1 and, to a lesser extent, Path 2, include more reactors with fuels cores that have higher thermal and radiation loads than in Path 3, and thus pose more of a risk of attack on reactors themselves.

To understand the risks arising from malevolent non-state actors, Nautilus also evaluated three scenarios of the potential radiological impacts of an accident or attack at the Hamaoka nuclear

power plant.  These scenarios indicated potential exposures resulting in near-zero to hundreds of thousands of early cancer deaths, with potential health-related damages from low levels to trillions of dollars, depending on which nuclear plant components are involved in the accident or attack, and on which direction prevailing winds are blowing.  This enormous range represents the true uncertainty and unpredictability of such extreme events, the probability of which cannot be determined except to say that it is finite and should therefore be managed, not ignored. The evaluation also includes each path's 2015 through 2050 estimated cumulative nuclear energy sector costs, overall cost in terms of electricity generation, greenhouse gas emissions, and other qualitative and quantitative "energy security" (broadly defined) attributes.

Nuclear fuel cycle costs, measured per unit of electricity output, were substantially lower in Path 3, which does not include reprocessing.

The minor differences between the paths in terms of nuclear energy sector or overall electricity generation costs, or even greenhouse gas emissions, are not, however, significant in determining the best policy direction to reduce the vulnerability of Japan's nuclear sector to accident or terrorist attack.

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# 1 Introduction

As a part of Nautilus Institute's MacArthur Foundation-funded "Vulnerability to Terrorism in Nuclear Spent Fuel Management" Project, Nautilus has prepared and evaluated three different "paths" for the future of the Japanese nuclear energy sector and the way that spent nuclear fuel is managed in Japan. The three basic paths that we have considered, which have been modelled for the period from 2015 through 2050, are described below and in section 2 of this Report. These are:

- **Path 1: Return to Pursuit of Closed Nuclear Fuel Cycle**, in which most existing light-water reactors (LWRs) are restarted in the next five years, reactor lifetimes are extended, 10 planned new reactors are constructed/completed, and domestic reprocessing of spent fuel resumes, along with use of mixed-oxide fuel (MOx), with the goal of fast reactor deployment after 2050.
- **Path 2: Slower Return to Pursuit of Closed Nuclear Fuel Cycle**, in which the return to a closed nuclear fuel cycle path proceeds at a slower pace than in Path 1, with the restart of 10 existing reactors in next five years, and 15 more by 2030. As in Path 1, reactor lifetimes extended to 60 years. Five new reactors are built, MOx use restarts slowly, and the restart of domestic reprocessing is delayed to early 2019 and phased in more slowly than in Path 1.
- **Path 3: Limited Reactor Restart with Once-through Fuel Cycle**, in which 10 reactors are restarted over five years, focusing on the most power-hungry areas of Japan, MOx is used in about 50% of restarted reactors, and only modest (five-year—accounting for the period most plants have been idle) of life extension is applied to Japan's existing reactor fleet. Additionally, all existing dense-packed spent fuel pools are converted back to non-dense-packed operation within five years, reprocessing is not restarted due to limited overall MOx use.

In the remainder of this introduction, we briefly review the background of this assessment of nuclear fuel cycle paths, provide a summary of the methods used in the assessment, and describe the contents of the remaining sections of this Report.

## 1.1 Background

In the tragic aftermath of the March 2011 Great East Japan (Sendai) Earthquake and tsunami and the resulting Fukushima nuclear plant disaster, as all of Japan's fleet of nuclear reactors were shut down for a period that, at the time, appeared indefinite, for safety checks, it seemed that the citizens of Japan, and particularly the northern part of the island of Honshu, would be destined to endure power shortages, perhaps for years. Although there were some brief periods of rotating blackouts and brownouts in some areas served by the utilities most affected by the earthquake and the devastation that followed, including the accident at the Tokyo Electric Power Company's (TEPCO's) Fukushima Daiichi nuclear power station, power shortages were not as severe as expected. Widespread power shortages have been averted in part by the ramping up of fossil-fueled generation to compensate for the off-line nuclear plants, but also, significantly, to a combination of a huge effort on the part of the people of Japan to save electricity, and to rapidly expanding additions of electricity generation from renewable sources. These changes were in part been driven by need and a change in attitudes nationally, post-Fukushima, but also by government policies such as feed-in tariffs (FIT),[1] as well as by the traditionally high cost of electricity in Japan, which combined with other considerations (changes in attitudes, FIT, and falling costs for renewable generation technologies) have helped to make renewable generation more attractive.

Following the destruction that crippled the six-unit Fukushima Daiichi nuclear power plant, all of Japan's reactors were shut down for extended safety reviews. The period of reactor shut-down, in addition to the impacts on electricity supplies alluded to above, has included a period of national (and, for that matter, international) reflection and debate on the safety of nuclear reactors, and Japan's future plans for nuclear power. A committee was convened in Japan to explore different futures for the electricity and nuclear power sectors, and to recommend a course of action to the government. The committee explored options ranging from nearly full restart of Japan's reactor fleet, with a renewed commitment to recycling of nuclear spent fuel and, ultimately, use of recycled plutonium in fast reactors, to essentially no further use of nuclear power. Although a limited restart scenario was discussed and seemed to be favored, at the time, by the Noda administration, the incoming administration of Japanese President Shinzo Abe, in 2012, focused largely on a return to Japan's previous nuclear energy policy.

To date, however, only a handful of the 50 reactor units have been restarted at all since Fukushima, and although the first restart occurred in mid-2012, by late 2013 all of Japan's reactors were once again offline. No commercial reactors operated in Japan in 2014. Since August of 2015, the two Sendai units have been placed back in service. These remain, as of this writing (early 2016), the only commercial nuclear plants in operation in Japan, though utilities have applied to start more than 20 additional reactors. Although the Abe administration supports the restart of reactors that have passed safety tests, there remains considerable public anxiety about and opposition to reactor restarts.

Part of this anxiety and opposition is related to the management of spent nuclear fuel. Japan's policy has historically been to work toward reprocessing of all spent fuel to separate fissile plutonium (Pu) for formulation into mixed oxide (MOx) fuel for use in the existing fleet of Japan's light water reactors (LWRs), along with fuel made using enriched uranium (UOx fuel). Ultimately, the goal of Japan's nuclear sector has been to develop a "closed" nuclear fuel cycle in fast neutron reactors that are designed "breed" as much plutonium as they use. Fast reactors have been tested in Japan and a number of other countries, most notably France, with results that have thus far been considered less than satisfactory, with a number of incidents and accidents marking fast reactor deployment.[2] Widespread commercial deployment of fast reactor

[1] See, for example, Kae Takase (2015), *Japan Energy Update,* prepared for the Nautilus Institute "Vulnerability to Terrorism in Nuclear Spent Fuel Management" project, dated November 9, 2015, and Tadahiro Kasuta, (2015), both forthcoming at http://nautilus.org/publications/napsnet/reports/.

[2] See, for example, Mycle Schneider (2009), "Fast Breeder Reactors in France", *Science and Global Security*, 17:36–53, 2009, available as https://www.princeton.edu/sgs/publications/sgs/archive/17-1-Schneider-FBR-France.pdf.

technology, if it occurs, is thus likely decades away.[3] Reprocessing of spent fuel, however, maintains the option for fast reactor deployment. Japan's reprocessing program has focused on bringing the reprocessing plant at Rokkasho into commercial operation. Rokkasho's operation has been delayed by a series of technical and other issues, although it did undergo testing with spent nuclear fuel during the period 2006 through 2008. In part due to plans to reprocess fuel at Rokkasho, and in part (and relatedly) due to agreements with communities that host nuclear power plants to remove nuclear spent fuel that had been cooled in onsite spent fuel pools for reprocessing, most nuclear spent fuel in Japan continues to be stored in at-reactor spent fuel pools, though some has been removed and placed in spent fuel pool at Rokkasho, and prior to 2000, considerable spent fuel was sent to Europe (France and the United Kingdom) for reprocessing. Dry cask storage, a technique in which spent reactor fuel that has been cooled for five or more years in spent fuel pools is transferred to massive steel and (often) concrete casks designed for 50 to 100 years of service, has been used to a limited extent and mostly only recently in Japan—for example, for fuel from the damaged Fukushima reactors and at the to-be-commissioned Mutsu Intermediate Storage Facility.[4]

Spent fuel pools in Japan, as in many other nations, are configured as "dense racked" or "dense-packed". This means that the racking system used to support the fuel assemblies placed in the pools maintain the assemblies close to each other—nearly as close as in a reactor core. To prevent neutrons released by cooling fuel assemblies from starting a nuclear chain reaction, as would occur in a reactor core, dense-packed spent fuel pools are fitted with neutron-absorbing dividers. These dividers, in addition to absorbing neutrons to prevent criticality in the stored spent fuel, impede the flow of heat away from fuel assemblies, heat that would be lost more easily through conduction and convection is an open racking system, in which assemblies are placed much further apart, is used. A serious concern regarding dense-racked spent fuel pools is that in the event of an accident, such as that at Fukushima, or a targeted terrorist attack, the loss of cooling water, either through the interruption of water pumped through the pool or from a rupture in the pool itself (or both) could ultimately, following a loss of pool water, lead to a rise in temperature sufficient to cause the zircaloy cladding of the fuel elements (which make up fuel assemblies) to ignite.[5] The resulting "pool fire" has the potential to spread a vast amount of radioactive material—much more than would result from a breach in the core of a reactor, because the inventory of radioactivity in a spent fuel pool is much higher than in a reactor core—over a wide area. In the Fukushima accident, the possibility of a spent fuel pool fire in the pool

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[3] In November 2015, the Nuclear Regulatory Agency in Japan rules that a new entity is required to operate the Monju breeder reactor safely. "Fast breeder reactor brings Japan's policy to crossroads," November 5, 2015, at: http://asia.nikkei.com/Politics-Economy/Policy-Politics/Fast-breeder-reactor-brings-Japan-s-policy-to-crossroads?page=1

[4] The first phase of the Mutsu facility, accommodating 3000 tonnes of spent fuel, was due to be commissioned in 2016, with the second phase (2000 tonnes) schedule for 2028 (World Nuclear Organization (2015), "Japan—Nuclear Fuel Cycle", available as http://www.world-nuclear.org/info/Country-Profiles/Countries-G-N/Japan--Nuclear-Fuel-Cycle/. See also Tatsuya Ishikawa (2013), "Current Status of Japan's Storage facility for Spent fuels", prepared for a conference held 2-4 July 2013, and available as https://www.iaea.org/OurWork/ST/NE/NEFW/Technical-Areas/NFC/documents/spent-fuel/TM-45455/Agenda-22-JAPAN-Current_status_of_Japans_ISFS.pdf.

[5] For a discussion of this issue see, for example, Gordon Thompson (2013), *Handbook to Support Assessment of Radiological Risk Arising From Management of Spent Nuclear Fuel*, Nautilus Institute Special Report dated May 14, 2013, available as http://nautilus.org/napsnet/napsnet-special-reports/handbook-to-support-assessment-of-radiological-risk-arising-from-management-of-spent-nuclear-fuel/.

for reactor number 4 was of serious concern, as active cooling was interrupted for about 10 days, and emergency cooling (for example, spraying water into the spent fuel pool with concrete pumping trucks) was required.[6]

Japan therefore finds itself at a juncture where Japanese policymakers, with input from the nuclear technical community, academics, non-governmental groups, and many others, are working to decide the future of the Japanese nuclear power industry, and more broadly, the Japanese power sector in general. In the nuclear power industry, decisions facing Japan include not only whether (or how many) existing reactors to restart, and on what timeframe, but also whether to continue to use dense-packed spent fuel pools or shift to another storage method for cooled spent fuel, whether to restart its spent fuel reprocessing program, and, relatedly, whether to continue to aim toward an electricity sector future in which fast reactors play a key role. Not unrelatedly, Japanese policymakers, technical experts, and civil society are also engaged in a debate about whether continuing accelerated deployment of energy efficiency and renewable energy are a feasible and cost-effective means of trending Japan towards a low-greenhouse gas emissions, clean energy future, with or without nuclear power.

Although fully addressing the issues above is clearly beyond the scope of one report, in the remainder of this document we compare the attributes of three "restart" paths for Japan's nuclear industry and the broader electricity sector, in terms of physical flows of nuclear materials, costs, and greenhouse gas emissions, and more qualitatively, risks related to accidents and terrorist attack, as well as other parameters of "energy security" broadly construed.

## 1.2 Assessment Methods

For each of the paths summarized above, and presented in more detail in section 2 of this Report, quantitative and qualitative analysis was done for the period 2015 through 2050 to:

- Track the flow of uranium, plutonium, spent UOx fuel, spent MOx fuel, high-level wastes, and low-level wastes through the system over time, for each process (from uranium mining through waste management) included in the nuclear energy system.
- Estimate the implied use of electricity and water in key nuclear sector processes over time.
- Identify the points at which fissile materials are handled or transported in each path, how and where the handling or transport occurs, and evaluate (qualitatively) the potential exposure to risk of diversion of fissile materials by terrorist activity at each point in the fuel cycle, and at key increments.
- Identify, qualitatively but with reference to a quantitative example (for reactors at the Hamaoka plant, presented in a previous publication by the authors[7]), the relative impacts

[6] See, for example, OECD Nuclear Energy Agency, "Timeline for the Fukushima Daiichi nuclear power plant accident", available as https://www.oecd-nea.org/news/2011/NEWS-04.html.
[7] See David F. von Hippel and Peter Hayes (2017), *Radiological Estimate for Accident at or Attack on Japan's Hamaoka Nuclear Power Plant*, NAPSNet Special Reports, November 23, 2017, Available as https://nautilus.org/napsnet/napsnet-special-reports/radiological-estimate-for-accident-at-or-attack-on-japans-hamaoka-nuclear-power-plant/

on potential radiological releases from nuclear facilities caused by accident or terrorist attack.

- Estimate the production of electricity from nuclear and other types of power plants in each year.
- Estimate the costs of fuel-cycle processes, including an estimate of the contribution of those costs to electricity in Japan.
- Estimate the relative costs of power (that is, costs of fossil and/or renewable power that nuclear power will displace or be displaced by in the paths) from the paths.
- Estimate the greenhouse gas emission from the electricity sector in each path over time.
- Evaluate (mostly quantitatively) the contributions of each path to energy security (defined broadly, as we have in past studies) in Japan.

More detailed descriptions of the methods, data, and assumptions used to prepare the above assessments are presented in sections 2through 5 of this Report.

## 1.3 Contents of this Report

The remaining sections of this Report are organized as follows:

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- **Section 2** presents a more detailed discussion of the three nuclear restart cases (paths) explored in this Report, including the key assumptions included in each path.
- **Section 3** describes the forecasts of overall electricity demand underlying the estimate of the results of each restart path, and of the three future (2015 through 2050) electricity supply configurations associated with each path. Results of each overall restart/electricity supply path with respect to electricity generation capacity and output by for the nuclear sector and by type of power plant overall, the overall costs of electricity generation, and the greenhouse gas emissions associated with the electricity sector, are also provided.
- **Section 4** focuses on the results of the analysis of the nuclear sector in each path, providing estimates of physical flows of nuclear materials both on the front (uranium mining/fuel enrichment/fuel preparation) end and on the back (spent fuel management) end. Also provided are estimates of the costs of nuclear sector activities in several categories for each path.
- **Section 5** offers a comparison of the three paths using an overall energy security (broadly construed) assessment framework first developed in collaboration with Japanese colleagues in the late 1990s. This comparison is vital because it compares both the quantifiable attributes of each path—that is, the “countable”—and many of the non-quantifiable or difficult-to-quantify attributes that may, in the end, prove more important to Japan’s nuclear energy (and electricity sector) decisions—that is, the “things that count”. Section 5 also provides a summary of the relative qualitative vulnerability of Japan’s nuclear energy sector to terrorism directed at nuclear facilities under each path.

- **Section 6** provides key conclusions from the analysis presented, and identifies potential next steps in research and conversation on nuclear restart and related issues in Japan.

# 2 Illustrative Restart/Spent Fuel Paths—Assumptions and Inputs

## 2.1 Common Assumptions Used for All Paths

Three different "paths" for the future of the Japanese nuclear energy sector and spent nuclear fuel management were modeled for the period 2015 – 2050. These are:

- **Path 1: Return to Pursuit of Closed Nuclear Fuel Cycle**, in which most existing light-water reactors (LWRs) are restarted in next five years, reactor lifetimes are extended, 10 planned new reactors are constructed/completed, and domestic reprocessing of spent fuel resumes, along with use of mixed-oxide fuel (MOx), with the goal of fast reactor deployment after 2050.
- **Path 2: Slower Return to Pursuit of Closed Nuclear Fuel Cycle**, in which the return to a closed nuclear fuel cycle path proceeds at a slower pace than in Path 1, with the restart of 10 existing reactors in next five years, and 15 more by 2030. As in Path 1, reactor lifetimes extended to 60 years. Five new reactors are built, MOx use restarts slowly, and the restart of domestic reprocessing is delayed to early 2019 and phased in more slowly than in Path 1.
- **Path 3: Limited Reactor Restart with Once-through Fuel Cycle**, in which 10 reactors are restarted over five years, focusing on the most power-hungry areas of Japan, MOx is used in about 50% of restarted reactors, and only modest (five-year—accounting for the period most plants have been idle) of life extension is applied to Japan's existing reactor fleet. Additionally, all existing dense-packed spent fuel pools are converted back to non-dense-packed operation within five years, reprocessing is not restarted due to limited overall MOx use.

Please note that these restart paths were prepared in 2015 and 2016. As this document is published (in early 2018), the restart of reactors in Japan has been, if anything, somewhat slower thus far than projected in the early years of the paths shown.

Each path summarized above, and presented in more detail below, includes the decommissioning, as currently planned, of the units Genkai #1, Tsuruga #1, and Shimane #1. These are assumed not to restart under any of the three paths. All three paths also include deployment of the Mutsu away-from-reactor dry cask spent fuel storage facility, the opening of which, as of late 2015, was reported to be planned for two stages: 3000 tHM of capacity in 2016 (updated to 2018 as of late 2017), and 2000 tHM of capacity in 2028, though one or both stages may be (further) delayed.[8] We assume, for modeling purposes, that each phase of Mutsu

[8] Note that for these three paths, the operation of the smaller dry cask storage facility at Hamaoka (400 tHM) that is under development and due to be commissioned in 2018 is not explicitly modeled. We have been told by a Japanese colleague that the opening of the first stage of the Mutsu project may be delayed, perhaps to 2018, due to the delay in restarting the Rokkasho reprocessing facility. Private communication, May, 2016.

capacity additions is filled up over a period of 10 years in each path.[9] In each path, MOx fuel is fabricated in Japan, that is, prepared MOx fuel is not imported.

In all three paths, it is assumed that research and development (R&D) continues on long-term storage/disposal options for at least some spent low-enriched uranium (LEU) fuel, as well as all MOx spent fuel and high-level wastes (HLW) from reprocessing. MOx spent fuels are assumed not to be reprocessed under any scenario, as the different cooling profile and composition of MOx spent fuel, relative to LEU spent fuel, substantially complicates reprocessing. This R&D may result in the establishment of a domestic mined repository, collaboration with other nations on a shared Deep Borehole Disposal (DBD) facility (which would, for seismic reasons, be very unlikely to be in Japan[10]), or both, but none of these long-term storage/disposal facilities are assumed to be ready to receive spent fuel or HLW until after 2050.

An additional assumption implicit in the modeling of each restart path is that all reactors to be restarted can be and are restarted smoothly. In reality, not all reactor restarts will be (or have been) smooth, as nuclear reactors are complex machines, and some degradation or corrosion can happen after reactors (or other similarly complex devices) sit idle for several years, even if maintenance during the shutdown period fully followed established protocols.[11]

## 2.2 Path 1: Return to Pursuit of Closed Nuclear Fuel Cycle

***In this path, the nuclear industry starts most of its existing fleet of light water reactors in the next five years, extends reactor lifetimes to sixty years, and constructs new reactors that have been planned, mostly on existing sites. Overall, 30 of Japan's existing reactors (beyond the two Sendai units restarted in 2015) are assumed to restart within 10 years, excluding those at Fukushima Daiichi, where all units remain offline and decommissioning of the damaged reactors and undamaged reactors (in all, units 1 through 6) continues, those older units recently decommissioned (reportedly including Mihama reactors #1 and #2, as well as the Tsuruga #1 and other reactors noted above[12]), plus decommissioning of additional older reactors. Decommissioned reactors are never restarted.***

Table 2-2 show the roster of plants assumed to be restarted, by year, after 2015, under Path 1.

[9] World Nuclear Organization (2017), "Japan's Nuclear Fuel Cycle", dated November, 2017, and available as http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-fuel-cycle.aspx.

[10] See, for example Tomochika Tokunaga (2014), *Update on the Consideration of the Possibility of Deep Borehole Disposal in Japan*, dated July 11, 2014, and available as http://nautilus.org/napsnet/napsnet-policy-forum/update-on-the-consideration-of-the-possibility-of-deep-borehole-disposal-in-japan/, which suggests that the seismic and volcanic nature of Japan's geology, coupled with its large population in a relatively small area, makes it an unlikely host for a deep borehole disposal facility. Japan could, however, share R&D efforts on deep borehole disposal in other nations, and ultimately participate in developing and using an international deep borehole facility, perhaps somewhere in the Northeast Asia region.

[11] See, for example, "Rash of problems prompts fears that Japan's reactor restarts have been too hasty", *The Japan Times*, March 1, 2016, available as http://www.japantimes.co.jp/news/2016/03/01/national/science-health/japan-hit-hasty-bid-restart-reactors-problems-safety-fears-surge/#.V3wyHzXruPV.

[12] See, for example, RT.com (2015), "Japan scraps 3 nuclear reactors, with 2 more to follow", dated 17 Mar, 2015, and available as http://www.rt.com/news/241381-japan-nuclear-reactor-decommission/.

***Table 2-1: Nuclear Power Plants Restarted in Japan under Path 1***

| Plant/Unit | Year of Assumed Restart |
|---|---|
| Takahama 3 | 2016 |
| Takahama 4 | 2016 |
| Ikata 3 | 2016 |
| Ohi 3 | 2017 |
| Ohi 4 | 2017 |
| Genkai 3 | 2017 |
| Genkai 4 | 2018 |
| Tomari 3 | 2018 |
| Onagawa 2 | 2018 |
| Kashiwazaki-kariwa 6 | 2019 |
| Kashiwazaki-kariwa 7 | 2019 |
| Hamaoka 4 | 2019 |
| Shimane 2 | 2020 |
| Tomari 1 | 2020 |
| Tomari 2 | 2020 |
| Mihama 3 | 2021 |
| Takahama 1 | 2021 |
| Takahama 2 | 2021 |
| Higashidori 1 | 2022 |
| Tokai 2 | 2022 |
| Hamaoka 3 | 2022 |
| Shika 2 | 2023 |
| Onagawa 3 | 2023 |
| Hamaoka 5 | 2023 |
| Kashiwazaki-kariwa 4 | 2024 |
| Shika 1 | 2024 |
| Kashiwazaki-kariwa 3 | 2024 |
| Kashiwazaki-kariwa 2 | 2025 |
| Tsurga 2 | 2025 |
| Kashiwazaki-kariwa 5 | 2025 |

All ten of the reactors listed by the World Nuclear Association as "planned" or "under construction" are assumed to be completed by 2030. [13] In a return to previous policies pursuing the goal of a closed nuclear fuel cycle, as the reactors are restarted, Japan also restarts its program of the use of mixed oxide fuel (MOx) in existing units, starting with the nine existing reactors that plan to use MOx fuel (see below), and ramping up so that half of the Japanese reactor fleet is using MOx fuel (at 30 percent of each reload, on average) by 2030.[14] Included among the reactors completed under Path 1 are the Ohma and Shimane 3 units, in 2020 and 2021, respectively. The Ohma plant is designed to be able to use a 100 percent MOx core, and as such could contribute significantly to "burning" of Pu. We do not explicitly track the percent usage of MOx fuel in each reactor, so if Ohma is ultimately used with full MOx cores, its contribution to overall MOx use would be part of the 30 percent MOx overall average for the fleet.[15]

The fabrication of MOx fuel could occur at Japan's Tokai (reported capacity, 10 metric tonnes, or "t", of fuel/year) and Rokkasho (130 t/year) facilities, and possibly by contract at France's Melox plant (195 t/year). The Tokai reprocessing facility associated with the Tokai MOx fuel production facility is to be permanently shut down, however, so it seems unlikely that future MOx fuel production will occur at Tokai. Plutonium in storage at reprocessing plants in Europe is brought back to Japan in the form of MOx fuel fabricated in Europe as needed to keep up with demand for MOx.[16] Japan's reprocessing program is restarted, with Rokkasho going back on line in late 2017 as currently planned, reaching an average annual capacity factor of 85 percent of its full listed operating capacity (800 tHM per year) in two years (by 2020).[17] As no additional reprocessing of Japanese spent fuel in Europe (or elsewhere) is carried out under this Path, no additional spent fuel is transported to Europe.

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[13] For a list and map of reactors in Japan, see, for example, World Nuclear Association (2018), "Nuclear Power in Japan", updated March 2018, and available as http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-power.aspx. We assume that the Monju prototype fast reactor, if it ultimately operates again, does not contribute significantly to meeting electricity demand.

[14] See, for example, Japan Times (2015), "The MOX fuel conundrum", dated July 26, 2013, and available as http://www.japantimes.co.jp/opinion/2013/07/26/editorials/the-mox-fuel-conundrum/#.Vck_1fnruPV.

[15] Because spent MOx fuel has different thermal and radiological characteristics than spent UOx fuel, the use of full cores of MOx fuel at Ohma will require different spent fuel pool operating procedures (and/or different risks of accident or attack) relative to reactors using partial MOx cores or fueled with UOx only.

[16] Recent references on MOx use in Japan and reprocessing/transport arrangements with European service providers include two 2015 web pages from the World Nuclear Organization (http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Fuel-Recycling/Mixed-Oxide-Fuel-MOX/ and http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Transport/Japanese-Waste-and-MOX-Shipments-From-Europe/), and an undated article by Areva ("The shipment of MOX fuel from France to Japan", available as http://www.areva.com/EN/operations-1391/the-shipment-of-mox-fuel-from-france-to-japan.html). Note that at this point the production capacity of the Sellafield MOx plant has been downrated, and a decision to close the plant was made by UK authorities in 2011 (see World Nuclear Organization (2016), "Mixed Oxide (MOX) Fuel", dated April 11, 2016, and available as http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/mixed-oxide-fuel-mox.aspx). The closure of the Sellafield MOx plant may make arrangements for fabricating the 20 tonnes of Pu owned by Japan and stored in the UK into MOx fuel, which is effectively assumed under Paths 1 and 2, more difficult.

[17] World Nuclear Organization (2017), in "Japan's Nuclear Fuel Cycle", updated November 2017, includes the following passage: "[h]owever, in November 2014 JNFL announced that due to the slow NRA safety checks, the plant would not start operation until September 2018." and not reach full capacity until sometime after 2020. Available as http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-fuel-cycle.aspx. We use a slightly later start and ramp-up date, and assume an average annual capacity factor that is less than 100 percent, factoring in the possibility of occasional operational problems or maintenance needs that limit capacity.

Dry cask storage is included in this path only in the form of the Mutsu intermediate storage facility, of which the first 3000 tHM of capacity is assumed to come on line in 2016, with a further 2000 tHM of capacity available starting ”after 10-15 years”. [18] Both phases are assumed to be filled to capacity within 10 years of opening. As reactors are decommissioned, spent fuels pools are slowly emptied, with pools decommissioned an assumed eight years after reactor shutdown. In this path, however, with the exception of the spent fuel going to dry cask storage in the Mutsu facility, all spent fuel either remains in at-reactor spent fuel pools, in the Rokkasho spent fuel pool, or is reprocessed at Rokkasho.

Research continues into the design of fast reactors to “burn” actinides to reduce the volume of wastes to be disposed of, and to breed plutonium, though commercial fast reactors are not assumed to be deployed before 2050 and are not modeled explicitly in this path. Similarly, research continues into nuclear waste long-term storage options, but no final repository facility is opened before 2050, and no long-term storage facility other than those noted above is assumed to open before 2050, although it is possible that such a facility could be built in that time frame. High level wastes from reprocessing are treated and vitrified, and the resulting vitrified HLW are assumed to be stored at Rokkasho and/or at another interim site, but not in a final disposal site before 2050.

A key overarching policy assumption in this Path is that a program of outreach to local government by national government agencies and utilities results in local government agreements to reactor restart and to placement and operation of the necessary additional fuel cycle management infrastructure with timing as assumed in the Path. In addition, it is assumed that a new legal system governing of nuclear power plant operation and reprocessing is agreed to and put into place to allow the Path to unfold as above as electric utility deregulation continues in April of 2016.

As a result of additional investments in nuclear power and in restarting existing nuclear plants, growth rates of renewable power deployment decline (though growth continues) from their recent rapid pace, in part due to competition for financial resources, and in part due to utility emphasis on nuclear over renewable energy.

## 2.3 Path 2: Slower Return to Pursuit of Closed Nuclear Fuel Cycle

***This path generally follows Path 1, above, but returns to a closed nuclear fuel cycle at a slower pace under the assumption that it will take more time to get the necessary permissions for reactor restart and construction/operation of other facilities in place than in Path 1.[19] Here, the nuclear industry starts 10 of its existing fleet of light water reactors in the next five years (beyond the two Sendai units restarted in 2015), with 15 more started by 2030. Reactor lifetimes are extended to sixty years, but only five of the new reactors that have been planned for construction on existing sites are built (by 2035). Decommissioning of Fukushima Daiichi units 1-6 continues, as does decommissioning of other older reactor units (reportedly***

[18] World Nuclear Association (2017), “Japan-Nuclear Fuel Cycle”, updated November 2017, and available as http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-fuel-cycle.aspx.

[19] There is evidence that difficulty in receiving permissions for restart may be likely in many cases. See, for example, Reuters (2015), “Outlook bleak for nuclear power despite first reactor restart”, *The Japan Times*, September 1, 2015, available as http://www.japantimes.co.jp/news/2015/09/01/national/outlook-bleak-nuclear-power-despite-first-reactor-restart/#.VecfYJfruPV.

***including Mihama reactors #1 and #2 as well as the Tsuruga #1 and other reactors noted above[20]), plus decommissioning of additional older reactors as in Path 1. As in Path 1, decommissioned reactors are never restarted.***

Table 2-2 shows the roster of plants assumed to be restarted by year of restart.

[20] See, for example, RT.com (2015), "Japan scraps 3 nuclear reactors, with 2 more to follow", dated 17 Mar, 2015, and available as http://www.rt.com/news/241381-japan-nuclear-reactor-decommission/.

***Table 2-2: Nuclear Power Plants Restarted in Japan under Path 2***

| Plant/Unit | Year of Assumed Restart |
|---|---|
| Takahama 3 | 2016 |
| Takahama 4 | 2016 |
| Ikata 3 | 2017 |
| Ohi 3 | 2017 |
| Ohi 4 | 2018 |
| Genkai 3 | 2018 |
| Genkai 4 | 2019 |
| Tomari 3 | 2019 |
| Onagawa 2 | 2020 |
| Kashiwazaki-kariwa 6 | 2020 |
| Kashiwazaki-kariwa 7 | 2021 |
| Hamaoka 4 | 2021 |
| Shimane 2 | 2022 |
| Tomari 1 | 2023 |
| Tomari 2 | 2023 |
| Mihama 3 | 2024 |
| Takahama 1 | 2025 |
| Takahama 2 | 2025 |
| Higashidori 1 | 2026 |
| Tokai 2 | 2027 |
| Hamaoka 3 | 2027 |
| Shika 2 | 2028 |
| Onagawa 3 | 2029 |
| Hamaoka 5 | 2029 |
| Kashiwazaki-kariwa 4 | 2030 |

In a return to previous policies pursuing the goal of a closed nuclear fuel cycle, as the reactors are restarted, Japan also slowly restarts its program of the use of mixed oxide fuel (MOx) in existing units, starting with the nine existing reactors that plan to use MOx fuel (see below), and ramping up so that 40 percent of the Japanese reactor fleet is using MOx fuel (at 30 percent of each reload, on average) by 2035.  The fabrication of MOx fuel takes place at Japan's Tokai and

Rokkasho facilities, but not by contract at France's Melox plant. Plutonium in storage at reprocessing plants in is not brought back to Japan. Japan's reprocessing program is restarted as in Path 1, but the restart of Rokkasho is assumed to be further delayed, to early 2019, and five years are required to bring it up to an assumed average of 55 percent of its full listed operating capacity (800 tHM per year). No further reprocessing of Japanese spent fuel occurs outside of Japan.

As in Path 1, dry cask storage is included only in the form of the Mutsu intermediate storage facility, with the first 3000 tHM of cooled spent fuel capacity assumed to come on line in 2016, a further 2000 tHM of capacity available starting in 2028, and both phases assumed to be filled to capacity within 10 years of opening. Also as in Path 1, as reactors are decommissioned, spent fuels pools are slowly emptied, with pools decommissioned an assumed eight years after reactor shutdown. Except for dry cask storage at Mutsu facility, all spent fuel either remains in at-reactor spent fuel pools, in the Rokkasho spent fuel pool, or is reprocessed at Rokkasho.

Research continues into the design of fast reactors to "burn" actinides and to breed plutonium; commercial fast reactors, as in Path 1, are not deployed before 2050, and are not modeled explicitly in this path. Research also continues into nuclear waste long-term storage options, but no medium or long-term storage/disposal facility is opened before 2050. As in Path 1, a program of outreach to local government by national government agencies and utilities takes place to secure local government agreements to reactor restarts and for development and operation of additional fuel cycle management infrastructure, and new rules for legal jurisdiction over the nuclear sector are put in place, but the process of policy development takes place more slowly than in Path 1. Renewable electricity sources are deployed at the same rate as in Path 1, since the underlying policy framework for the two paths is similar.

## 2.4 Path 3: Limited Reactor Restart with Once-through Fuel Cycle

In this path, in addition to the two Sendai reactors restarted in 2015, 10 reactors are restarted over a period of five years, focusing on those in areas of Japan that are most power-hungry, and restarting reactors that are relatively new. The list of reactors assumed to be restarted under this Path are Hamaoka Units #4* and #5 (BWR/ABWR), Kashiwazaki-Kariwa Units #6 and #7 (both ABWR), Takahama Units #3* and #4* (both PWR), Shimane Unit #2* (BWR), Tomari Unit #3* (PWR), Genkai Unit #4 (PWR), and Onagawa Unit #3 (BWR).[21] This list includes five reactors (identified with asterisks *) that, according to a statement by Japan Nuclear Fuel Limited (JNFL), "…plan to use mixed-oxide… fuel if they are allowed to restart operation…".[22] Path 3 thus assumes that about 50 percent of the reactors restarted use MOx fuel. Table 2-3 shows the plants assumed to be restarted under Path 3, with their year of restart.

[21] World Nuclear Association (2018), ibid.

[22] NucNet (2015), "Nuclear Fuel Reprocessing Essential For Long-Term Plans, Says JNFL", dated 27 April, 2015, and available as http://www.nucnet.org/all-the-news/2015/04/27/nuclear-fuel-reprocessing-essential-for-long-term-plans-says-jnfl.

*Table 2-3: Nuclear Power Plants Restarted in Japan under Path 2*

| Plant/Unit | Year of Assumed Restart |
|---|---|
| Takahama 3 | 2016 |
| Takahama 4 | 2016 |
| Genkai 4 | 2017 |
| Tomari 3 | 2017 |
| Kashiwazaki-kariwa 6 | 2018 |
| Kashiwazaki-kariwa 7 | 2018 |
| Shimane 2 | 2019 |
| Onagawa 3 | 2019 |
| Hamaoka 3 | 2020 |
| Hamaoka 4 | 2020 |

Life extension is not applied to Japan's existing reactor fleet, and no new reactors are built. It is, however, assumed that the standard reactor operating lives are calculated such that the post-Fukushima outage period is not counted—that is, if, for example, a reactor was offline from 2011 through 2016, it would be decommissioned 45, not 40, years after it began initial operation,[23] A program of outreach to reactor hosts results in the acceptance of at-reactor dry cask storage, additional off-site dry cask storage facilities are developed, and all existing dense-packed spent fuel pools are converted back to non-dense-packed operation within five years by moving part of the inventory of dense-packed pools to other pools in the same reactor complexes or to on-site dry casks. For the purposes of modeling the number and costs of casks required by such a policy, we assume that in the five years starting in 2017, a quantity of spent fuel is moved to dry cask storage, including the 3000 tHM away-from-reactor Mutsu dry-cask storage facility that is reportedly due to begin operation in 2016 (and its second phase in 2028),[24] such that the total remaining spent fuel in at-reactor pools and at the Rokkasho reprocessing plant is equal to 90 percent of half of the listed (assumed to be dense-packed) storage capacity of those pools. The 90 percent figure is used to make sure that the pools have space for a core off-load if needed, while maintaining a non-dense-packed configuration. Note that there are a number of different

[23] This is entirely an assumption on our part—input from a Japanese colleague suggests that, at least to date, the current life extension licensing review in Japan is considering crediting time for which a plant is idle in considering its operating life. That is, under current practice either a plant built 40 years ago would be decommissioned when it is 40 years old, or it would be granted a life extension to 50 or 60 years (the latter more likely, as it is more attractive to reactor operators)—no credit would be given for time when a plant is not operating due to safety reviews. If, under Path 3, decommissioning of all plants takes place after 40 calendar years of reactor life, then nuclear capacity and electricity output, and new spent fuel arisings (and related costs), would fall more rapidly in this path than is shown below.

[24] The Mutsu dry storage facility was built in 2010-2013, and as of late 2017 was scheduled to be put in service in late 2018, as reported in the World Nuclear Association (2017) document "Japan's Nuclear Fuel Cycle", dated November, 2017, and available as http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-fuel-cycle.aspx.

options for reducing the density of dense-packed spent fuel pools. Open-racked systems, in which the spacing between fuel assemblies is over 50 cm (for PWRs), have about 20 percent of the fuel density of dense-packed fuels, where the spacing between fuel assemblies is 23 cm (for PWRs). The degree of "de-densification" modeled here is therefore intermediate between the current dense-racking approach and a pure open-racking arrangement, and is consistent with, for example, removing every other row of assemblies and providing holes in remaining neutron-absorbing partitions between assemblies to allow water (and heat) to flow.[25] In addition, it is assumed that within eight years of the decommissioning of reactors, starting with the Fukushima Daiichi units, the equivalent of the volume of spent fuel in those reactor pools is also transferred to dry casks, and that when decommissioned, spent fuel pools at the decommissioned reactors are occupied at about 85 percent of capacity. "Full capacity" here follows the definition of "effective storage capacity" used by Suzuki and Katsuta, that is, total pool capacity less the capacity required for the total of one full core plus one year of annual discharge—that is Effective storage capacity = storage capacity - (1 full core plus annual discharge).[26]

The net results of this "Limited Restart with Once-through Fuel Cycle path, and of the assumptions above used to model it, with respect to spent fuel inventories, are shown in Table 2-4. By 2050, all of the spent fuel generated through 2050 has either been placed in dry cask storage or reprocessed abroad or domestically (but all prior to 2010), and the remaining spent fuel is stored in spent fuel pools at reactors that are operating as of 2050 or have not yet been fully decommissioned. The remaining active or under-decommissioning spent fuel pools are essentially full as of 2050. It should be acknowledged that in practice spent fuel will be moved between pools in reactor complexes and possibly between reactor complexes, some pools will be reconfigured for non-dense-packed storage in different ways than others and with different impacts in terms of net storage capacity, and additional complexities of spent fuel management mean that the results shown here are certainly approximations, and a more detailed accounting may produce somewhat different results. This analysis has intended to provide an approximate estimate of the timing and amounts of spent fuel that will need to be transferred to dry cask storage in order to rapidly reduce the density of spent fuel storage in pools in Japan, and to ultimately transition all virtually all spent fuel not yet reprocessed to dry cask storage. As such, this analysis serves as an input to the estimate of the cost of dry cask storage in Path 3.

[25] See, for example, Robert Alvarez, Jan Beyea, Klaus Janberg, Jungmin Kang, Ed Lyman, Allison Macfarlane, Gordon Thompson, and Frank N. von Hippel (2003), "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States", *Science and Global Security*, 11:1–51, dated April 21, 2003, and available as https://www.princeton.edu/sgs/publications/articles/fvhippel_spentfuel/rAlvarez_reducing_hazards.pdf.

[26] Tadahiro Katsuta and Tatsujiro Suzuki (2007), "Japan's Spent Fuel and Plutonium Management Challenges", prepared for the Carnegie Non-proliferation Conference, 2007, and available as http://carnegieendowment.org/files/SuzukiReprocessPanelCarnegie26June07.pdf.

*Table 2-4: Summary Spent Fuel Disposition/Storage Results of Path 3 through the Year 2050*

| Quantity | Tonnes Heavy Metal | Notes |
|---|---|---|
| Total Spent Fuel Generated | 25,390 | |
| Spent Fuel Reprocessed | 8,650 | Domestic and abroad, all prior to 2010 |
| Spent Fuel to Dry Cask Storage during de-densification | 1,463 | Carried out 2017 through 2021 |
| Spent Fuel to Dry Cask Storage during Decommissioning | 13,710 | Carried out 2017 through 2050 (Fukushima Daichi-4 by 2015) |
| Implied Net Spent Fuel Inventory at Reactors (and Rokkasho) in Pools in 2050 | 1,567 | |
| Estimated Spent Fuel Pool Capacity of Remaining Active Reactors as of 2050 | 267 | Shika-2 and Tomarii-3; Non-dense-packed configuration |
| Estimated Spent Fuel Pool Capacity of Remaining Reactors Not Yet Decommissioned | 292 | Higashidori-1 (Tohoku) and Hamaoka 5 |
| Estimated Spent Fuel Pool Capacity of Reactors Partially Decommissioned | 173 | Kashiwazakikariwa 7, Genkai 4, Onagawa 3; |
| Estimated Spent Fuel Pool Capacity Remaining at Rokkasho | 1350 | Non-dense-packed configuration |
| Implied Fraction of Remaining Spent Fuel Capacity Occupied as of 2050 | 75% | Fraction of remaining non-dense-packed capacity |

Reprocessing in Path 3 is not restarted because the limited stock of reactors that would consume MOx fuel would make it difficult to consume the Pu output of reprocessing facilities in Japan, as well as due to other considerations, and MOx fuel fabrication would be limited to that required to slowly use up Japan's onshore stock of plutonium[27]. Plutonium from past offshore reprocessing of Japanese spent fuel that has not yet been shipped to Japan as of early 2015 is assumed to continue to be stored in Europe. MOx fuel is assumed to be used as 30 percent of each reload in the five reactors that plan to use it and are restarted in this Path (that is, an average of 30 percent of each core is composed of MOx fuel elements). A fast reactor fuel cycle is not pursued.

[27] Spent fuel reprocessing is also uneconomic at any low-enriched uranium fuel (LEU) costs within several (and up to 10 or more, depending on the study)-fold of current or any historical values. The International Panel on Fissile Materials (2015), in *Plutonium Separation in Nuclear Power Programs: Status, Problems, and Prospects of Civilian Reprocessing Around the World* (available as http://fissilematerials.org/library/rr14.pdf), quotes (in Chapter 11) a study by the Japan Atomic Energy Commission as indicating that the costs of MOx fuel was over 10 times that of LEU fuel. The economics of reprocessing however, are not explicitly included as a criterion in formulating the Paths described here; rather, cost estimates are an output of the analysis described in this Report.

Because reactor lives are not (appreciably) extended under this Path, and no new reactors are built, the net result is effectively a near phase-out of nuclear power in Japan by 2050. If a plutonium inventory remains in Japan at that time, either as separated Pu or in MOx fuel, this Path assumes that the remaining inventory must be disposed of. Options for doing so include A) recombining separated Pu (or Pu/U) with liquid HLW, if any remains at Tokai or Rokkasho, and vitrifying the resulting mix for long-term storage at Rokkasho, in a mined repository, or via deep borehole disposal; B) preparing the Pu (or Pu/U) into MOx fuel that is placed in dry casks along with cooled spent LEU and MOx fuel from the operating reactor fleet and/or decommissioned reactors; and/or C) blending the Pu (or Pu/U) with depleted U and other materials, and vitrifying the resulting mixture for disposal in a mined repository or deep borehole facility.

The assumption is that Path 3 has resulted from overt policy choices to limit the number of restarts, not permit life extension, cease new reactor construction, and not attempt to restart the Rokkasho reprocessing plant. These policy choices would likely be driven by the pressure of public opinion. Additional policy decisions that are likely needed under this Path include a revision of laws related to spent fuel storage at reactor and/or other sites, agreements on repaying debts for construction of Rokkasho, and probably other policies as well.

In this Path, essentially, Japan slowly phases out nuclear power through changes in policy. Part of this Path, however, may come about without an overt policy decision if, ultimately, key processes at Rokkasho prove not functional or unreliable, and reprocessing abroad either is not sought or is unavailable due to plant closures in Europe.

With less investment going into new nuclear power plants and reprocessing facilities, and with related decreases in aggregate operating costs for nuclear power, it is assumed that more investment funding is available for renewable—largely solar photovoltaic (PV) and wind power—and that renewable generation is deployed to fill a portion of the gap between the levels of nuclear generation in Paths 1 and 3. In addition, it is assumed that the policy shift away from nuclear power, perhaps augmented by the ongoing transition to a liberalized electricity market, results in less reluctance on the part of utilities (and other electricity producers) to incorporate renewable energy into Japan's electricity mix. Additional gap-filling is provided by more aggressive deployment of energy efficiency in all sectors, and by the use of fossil fuels for generation (with a trend toward use of combined-cycle gas-fired plants continuing).

## 2.5 Nuclear Capacity and Generation in the Three Paths

Figure 2-1and Figure 2-2 show, respectively, the trends in nuclear power generation capacity and nuclear generation in Japan through 2050 under the three restart paths described above. Under Path 1 ("Return to Pursuit of Closed Nuclear Fuel Cycle"), nuclear capacity falls slowly through about 2019, as several older reactors are decommissioned, then rises to a peak of about 56 GWe (gigawatts of electric capacity) by the late 2020s, remaining at that level until decommissioning of older units begins in 2034. By 2050, nuclear generation capacity falls to just over 33 GWe. Power Generation in Path 1 rises rapidly after 2015 to over 300 terawatt-hours of electricity generation (TWhe) by 2029, remaining at that level until 2034, when nuclear generation starts to decrease slowly as capacity falls. In Path 2 ("Slower Return to Pursuit of Closed Nuclear Fuel Cycle"), generation capacity rises more slowly to a post-Fukushima peak of nearly 48 GWe in 2031, falling starting in 2034 as older reactors are decommissioned to less than 26 GWe by 2050.

Nuclear generation in Path 2 rises to about 215 TWhe by 2031, falling after 2034 to about 162 TWhe by 2050. In Path 3 ("Limited Reactor Restart with Once-through Fuel Cycle"), nuclear capacity falls fairly steadily through 2042 as reactors are decommissioned without significant life extension, then plateaus for a few years before falling again in the final years of the 2040s. By 2050, only two units, Shika-2 and Tomari-3, totaling about 2.3 GWe, remain operable, though only Tomari-3 is operating (because Shika-2 was not restarted). Nuclear generation in Path 3 rises to about 80 TWhe in 2020 as reactors are restarted, remaining at that level through 2029, when decommissioning of the restarted reactors begins. Nuclear generation gradually falls through the 2030s, reaching 11.4 TWhe in 2042, then falling to 6.0 TWhe in 2047, remaining at that level through 2050.

***Figure 2-1: Nuclear Generation Capacity (GWe) Under Three Restart Paths for Japan***

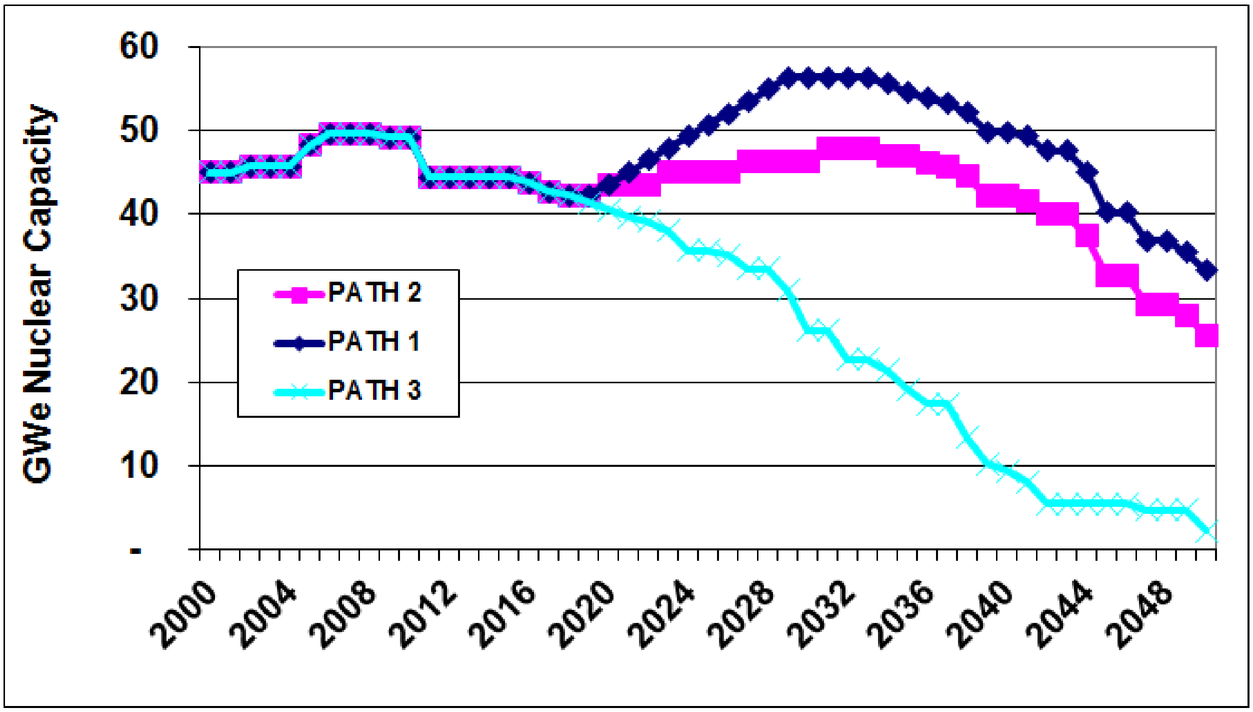
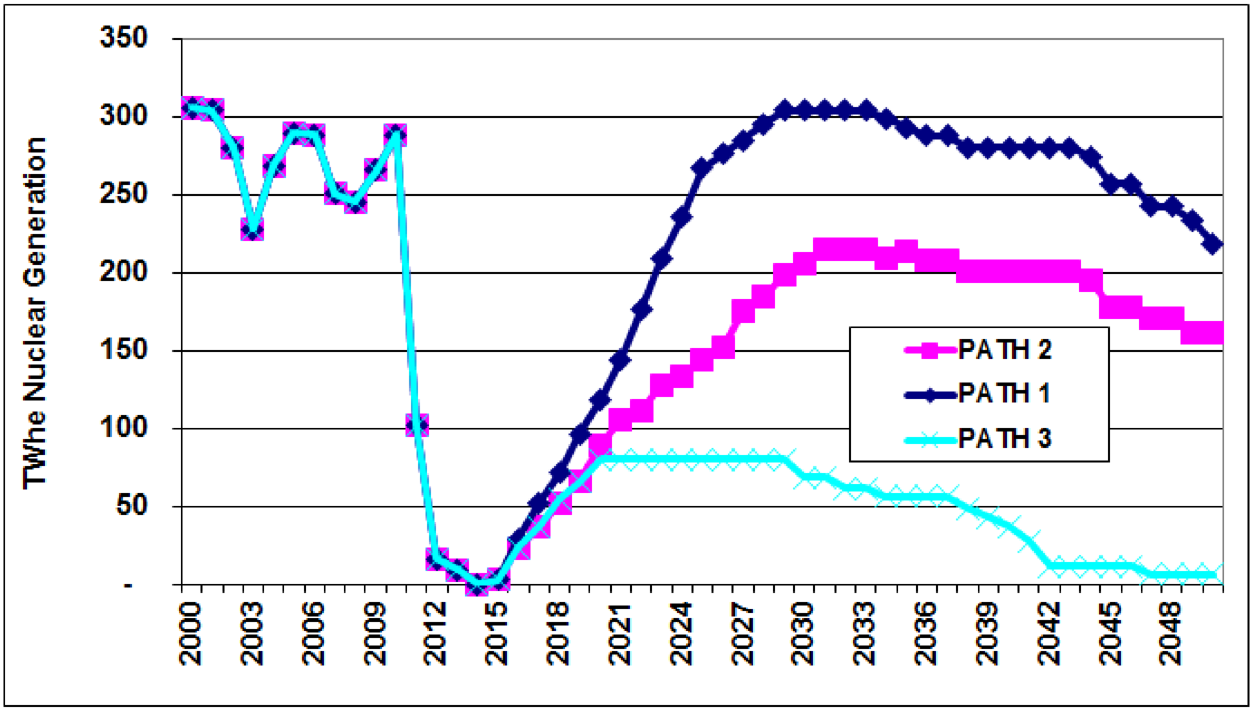


*Figure 2-2: Nuclear Generation (TWhe) Under Three Restart Paths for Japan*




Additional results for each of the three paths with respect to flows and stocks of nuclear materials, as well as costs, are provided in Section 4 of this report.

# 3 Forecast of Electricity Demand and Projections of Electricity Supply in Japan

Detailed estimates of energy use by sector and fuel in Japan have been prepared using the Long-range Energy Alternatives Planning (LEAP) software system[28] by Japanese colleagues working with Nautilus. The most recent of these projections, however, was prepared in 2013,[29] and does not extend to 2050. As a result, in order to use a forecast consistent with the time period of the nuclear sector analysis, we prepared an approximate long-term forecast for electricity demand (and thus required generation) that serves as the basis for determination of the fraction and amount of electricity generation provided by nuclear power and by other generation sources under each Path, as well as, by extension, for the estimation of the implied difference in greenhouse gas emissions between the Paths. This estimate of forecast electricity use in Japan is broadly similar to previous forecasts by our Japanese colleagues for the periods in which the two overlap, showing a slow decline in overall electricity use, even in the absence of aggressive energy efficiency programs, as population falls and the Japanese economy continues to grow only slowly.

## 3.1 Demand Driving Assumptions

The overall assumptions used to drive this electricity demand forecast are as follows:

- We start with the most recent available historical electricity consumption data by sector (residential, commercial/institutional, industrial, and transport), and consider recent trends in electricity demand adjusted somewhat to take into account the (assumedly) mostly temporary impact on electricity demand of the global recession in 2009, as well as of the 2011 Tohoku earthquake and tsunami.
- For the household sector, we use and extend existing estimates of future trends in the number of households in Japan—which is declining, but not as fast as population, as the number of people per household (HH) is also declining—and assume essentially constant per- household annual electricity consumption (in kilowatt-hours per household-yr, or kWh per HH-yr) until 2035, with per-household consumption declining slightly (at 0.2%/yr) after 2035 to take into account the reduced number of people per household, underlying and ongoing improvements in energy efficiency, and other factors. Note that in combination with the decline in population in Japan (expected to be over 25 percent by 2050, relative to 2010), these assumptions still imply a substantial increase in per-capita electricity consumption in the next three-and-a-half decades.

[28] The LEAP energy/environment planning tool is a product of the Stockholm Environment Institute—United States. See http://www.energycommunity.org/default.asp?action=47 for further information on LEAP.

[29] Kae Takase (2013), *The Japanese Energy Sector and Nuclear Spent Fuel Scenarios*, dated December, 2013, and available as http://nautilus.org/napsnet/napsnet-special-reports/the-japanese-energy-sector-and-nuclear-spent-fuel-scenarios/.

- Assume (as per Takase, 2013[30]) that commercial/institutional floorspace rises until 2020, and falls very slowly (at about 0.1% per year) after about 2020, and that electricity use per unit floorspace will likewise remain constant through 2035, declining at 0.1% per year thereafter due to the combined impacts of underlying improvements in energy efficiency, fewer people using the buildings due to falling population, and other factors. Note that these assumptions still imply increasing commercial/institutional floorspace per capita, due to the ongoing decline in population being steeper than the decline in overall floorspace.
- Assume essentially constant industrial electricity use per unit GDP through 2035, with an average 0.5% per year increase in industrial GDP through 2035. After 2035, we assume that the increase in industrial GDP falls to 0.3% annually and is offset by a reduction in electricity use per unit of GDP, such that the increase in industrial electricity use is zero from 2035 through 2050.
- Assume an increase in per-person transport electricity use by 2.0% per year, offsetting the decline in population but reflecting increased use of electrified public passenger transport and electric private transport and freight vehicles.
- Assume that electricity transmission and distribution (T&D) losses remain at recent levels (just over 5 percent of electricity consumption) through 2025, then decline slowly through 2050 due to the combination of investments in T&D efficiency and slightly lower loading. Lower loading could ultimately be due to a combination of factors, including reduced overall electricity consumption, improvements in transmission management, and/or increases in distributed generation that puts more generation closer to loads during times of peak power demand.

Table 3-1 shows the evolution of key parameters in the baseline electricity demand forecast for Japan as projected through 2050, based on the assumptions described above.

[30] Kae Takase (2013), *Renewable Energy Burst in Japan*, dated February 9, 2014, and available as javascript:downGo('2014%2D3%5FWorkingPaper%5FRenewable%5FEnergy%5FBurst%5Fin%5FJapan0%2Epdf',' 194').

*Table 3-1: Key Parameters of Electricity Forecast for Japan, 2010 - 2050*

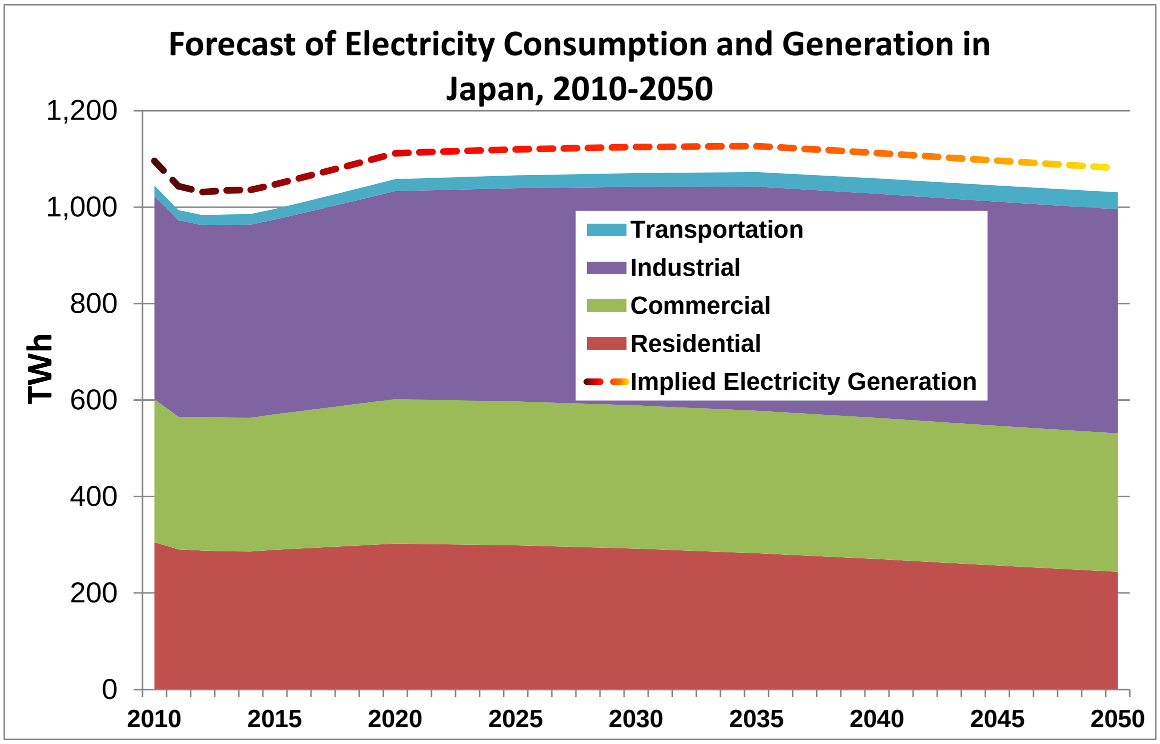
| Parameter | 2010 | 2015 | 2020 | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|---|
| National Population (thousand) | 128,057 | 126,376 | 124,100 | 120,301 | 116,618 | 107,276 | 97,076 |
| Households (thousand) | 51,842 | 52,904 | 53,053 | 52,439 | 51,231 | 47,934 | 44,119 |
| Persons per household | 2.47 | 2.39 | 2.34 | 2.29 | 2.28 | 2.24 | 2.20 |
| Index of Commercial Floorspace | 100.0% | 103.0% | 105.5% | 105.0% | 104.5% | 103.5% | 102.5% |
| Index of Electricity use per Unit Commercial Floorspace | | 100.0% | 100.0% | 100.0% | 100.0% | 99.5% | 98.5% |
| Index of Electricity use per Household | | 100.0% | 100.0% | 100.0% | 100.0% | 99.0% | 97.0% |
| Index of Industrial GDP | | 100.0% | 102.5% | 105.1% | 107.8% | 112.2% | 115.6% |
| Index of Electricity Use per Unit Industrial GDP | | 100.0% | 100.0% | 100.0% | 100.0% | 98.5% | 95.6% |
| Index of Transport Electricity Use per Capita | | 100.0% | 110.4% | 121.9% | 134.6% | 164.1% | 200.0% |
| T&D Losses as a Fraction of Consumption (Sales) | 4.92% | 5.08% | 5.08% | 5.08% | 5.06% | 4.98% | 4.88% |

## 3.2 Demand Forecast Results

Figure 3-1, below summarizes the forecast electricity consumption and overall generation in Japan through 2050 as used to prepare and evaluate the reactor restart/spent fuel management paths above. The "baseline" forecast features the decline in consumption following the 2011 earthquake and tsunami, followed by a recovery in demand through about 2020. Thereafter, residential and commercial/institutional sector demand begins to decline slowly, while industrial demand continues a slow increase, and transportation electricity demand also increases, albeit from a low base. As a result, overall electricity demand grows slowly from 2020 until 2035, when total demand begins to decline. The dotted line in Figure 3-1 denotes the generation requirement required after transmission and distribution (T&D) losses are factored in. Generation requirements follow the same pattern as end-use electricity demand but fall slightly faster than demand after 2035 due to assumed improvements (reductions) in T&D losses.

Note that this electricity forecast is meant to be illustrative. It is quite possible, given the projected 23 percent decline in Japan's population between 2015 and 2050, that electricity demand in the residential and commercial/institutional sectors will fall faster than projected, and/or that growth in absolute (as opposed to per-capita) industrial GDP will be lower than assumed. As such, it seems to the authors more likely that the forecast presented here turns out to be higher than electricity demand will ultimately prove to be in Japan, rather than lower.

*Figure 3-1: Summary of Electricity Forecast for Japan*




Note that "overall generation" here is assumed to be before any additional energy efficiency savings, which are most prominent in Path 3 (10 percent by 2050), but included at a lower level in Paths 1 and 2 (5 percent by 2050) due to an assumed lower emphasis on energy efficiency in the event that most of the nuclear reactor fleet is restarted. This does not mean that there are no post-2014 energy efficiency improvements in the base forecast, but rather that those efficiency savings are assumed to be part of the "baseline", unlike the active, policy-driven efforts included explicitly in each of the paths, and most prominently in Path 3, in which more aggressive, well-funded efforts to improve efficiency are assumed. By way of comparison, a number of US states have been achieving electricity sector incremental electricity energy efficiency savings as a result of energy efficiency policies upwards of 1 percent of retail sales annually—some have achieved this level of savings for a number of years.[31] As such, even though Japan starts with an economy that is more energy-efficient overall than that in the US, we feel that the efficiency savings included in these paths—averaging just 0.14 percent (Paths 1 and 2) and 0.28 percent (Path 3) annually over 2014 through 2050, should be readily achievable given sustained and effective policy support for energy efficiency programs and regulations.

[31] See, for example, Annie Gilleo, Seth Nowak, Meegan Kelly, Shruti Vaidyanathan, Mary Shoemaker, Anna Chittum, and Tyler Bailey, American Council for an Energy-efficient Economy (ACEEE, 2015), *The 2015 State Energy Efficiency Scorecard*, dated October 2015, Report U1509, available as http://aceee.org/sites/default/files/publications/researchreports/u1509.pdf.

## 3.3 Electricity Supply Assumptions by Path

The general approach used to evaluate the relative electricity supply output, costs, and emissions by type of generator was as follows.

- First, the electricity demand forecast presented above was used to determine the overall need for electricity generation in Japan.
- Second, the nuclear generation implied by each of the three reactor restart paths was calculated, using an assumed average capacity factor for the restarted reactor of 75 percent for the period from 2015 through 2050 (which is generally consistent with historical Japanese experience, on average), resulting in three different sets of net requirements for non-nuclear generation.
- Third, for each path an estimate was made of the amount to which renewable generation and energy efficiency would contribute to overall generation in each year. For Paths 1 and 2, the trend in renewable generation capacity was based on the "Low" scenario for future renewable capacity as compiled by Takase from Ministry of Environment and Energy and Environment Council documents.[32] The capacity trends for Paths 1 and 2 are provided in Table 3-2, below. For Path 3, the "High" scenario capacity trends from the same document were assumed, as shown in Table 3-3. Capacity factors of 15, 35, and 54 percent were assumed to be applicable for all forecast years for solar PV, wind, and hydroelectric and other renewable generation (geothermal, tidal, waste-to energy, and other biomass plants, for example), respectively. These capacity factors are generally consistent with values used in previous electricity sector modeling by Takase.[33] Application of the capacity factors to trends in installed capacity yielded estimated electricity output by year and by power source.

***Table 3-2: Capacity Assumptions for Renewable Generation in Japan, Restart Paths 1 and 2***

| | **Using** | LOW | Scenario from MOE | | |
|---|---|---|---|---|---|
| | Cumulative GW installed | | | | |
| | 2010 | 2014 | 2020 | 2035 | 2050 |
| Solar Photovoltaics | 0.017 | 3.40 | 27.90 | 61.51 | 201.80 |
| Wind | 1.31 | 2.40 | 7.50 | 23.20 | 30.00 |
| Hydro/Other | 24.59 | 25.40 | 26.70 | 32.20 | 40.20 |

[32] Kae Takase (2013), *Renewable Energy Burst in Japan*, dated February 9, 2014, and available as http://nautilus.org/napsnet/napsnet-special-reports/energy_burst_japan/ . Renewable energy capacity data are included in "Table 7: Outlook by The Ministry of Environment (2013) and the Energy and Environment Council (2012) , in GW, for Renewable Generation Capacity in Japan"

[33] Kae Takase (2013), ibid.

*Table 3-3: Capacity Assumptions for Renewable Generation in Japan, Restart Path 3*

| | **Using** | HIGH | Scenario from MOE | | |
|---|---|---|---|---|---|
| | Cumulative GW installed | | | | |
| | 2010 | 2014 | 2020 | 2035 | 2050 |
| Solar Photovoltaics | 0.017 | 3.40 | 34.40 | 112.88 | 254.40 |
| Wind | 1.31 | 2.40 | 11.50 | 39.37 | 70.00 |
| Hydro/Other | 24.59 | 25.40 | 30.40 | 42.39 | 59.30 |

- Fourth, energy efficiency savings as a fraction of forecast generation were calculated for each year, based on 5 percent savings beyond the baseline forecast achieved in Paths 1 and 2, and 10 percent saving beyond baseline in Path 3, as described above. These savings were added together with renewable generation and subtracted from the non-nuclear generation needs as calculated above to estimate the required non-nuclear, non-renewable, after-efficiency requirements for power generation—that is, the annual amount of generation in each year and each path to be provided by fossil-fueled generation.
- Fifth, fossil-fueled power generation by type of plant was estimated based on the net power requirements from fossil generation calculated as above, multiplied by the assumed fraction of generation from each type of fossil-fueled plant. Future fractions of generation by these plants were assumed to be similar to those included in the LEAP model for Japan prepared earlier by Kae Takase.[34] As shown in Table 3-4, under all of the restart paths, gas combined cycle power plants become the dominant form of fossil generation, with gas steam-cycle and coal steam-cycle plants used progressively less over time, and the use of oil-fired steam-cycle plants mostly phased out.

*Table 3-4: Assumptions for Fossil-fueled Generation Fractions in Japan, All Restart Paths*

| | Fraction of Fossil Generation as | | | | |
|---|---|---|---|---|---|
| | 2010 | 2014 | 2020 | 2035 | 2050 |
| --Gas Combined Cycle | 15.0% | 20.0% | 30.0% | 50.0% | 70.0% |
| --Gas Steam Cycle | 34.2% | 29.4% | 30.0% | 25.0% | 13.0% |
| --Oil Steam Cycle | 11.5% | 16.1% | 10.0% | 5.0% | 2.0% |
| --Coal Steam Cycle | 39.3% | 34.5% | 30.0% | 20.0% | 15.0% |

- Sixth, the fuel requirements of fossil-fueled generation were calculated based on an assumed set of average net efficiencies for each type of generation, as shown in Table 3-5. These are intended to be rough average values for the power plant fleets of each type in each year shown, and are derived from a combination of sources, including the Japan LEAP model referenced above, and a compilation of power plant cost and performance data assembled by a working group convened by Japan's Agency for Natural

[34] Kae Takase (2013), *The Japanese Energy Sector and Nuclear Spent Fuel Scenarios*, dated December, 2013, and available as http://nautilus.org/napsnet/napsnet-special-reports/the-japanese-energy-sector-and-nuclear-spent-fuel-scenarios/.

Resources and Energy of the Ministry of Economy, Trade, and Industry (METI).[35] Efficiencies of both gas combined-cycle and coal-fired power plants are assumed to increase somewhat over time as technologies improve.

***Table 3-5: Assumptions for Fossil-fueled Generation Fractions in Japan, All Restart Paths***

| | Average Net Efficiency | | | | |
|---|---|---|---|---|---|
| | 2010 | 2014 | 2020 | 2035 | 2050 |
| --Gas Combined Cycle | 50% | 51% | 52% | 53% | 55% |
| --Gas Steam Cycle | 38% | 38% | 38% | 39% | 39% |
| --Oil Steam Cycle | 37% | 37% | 37% | 37% | 37% |
| --Coal Steam Cycle | 39% | 40% | 41% | 43% | 44% |

- Seventh, emission factors were applied to calculate greenhouse gas emissions based on fuel consumption. Emission factors for coal, oil, and gas consumption in electricity generation were derived from inputs to the 2014 *National Greenhouse Gas Inventory Report of JAPAN* as shown in Table 3-6.[36]

***Table 3-6: Assumptions for Fossil-fueled Generation Fractions in Japan, All Restart Paths***

| Fuel | As Described in *GHG Inventory Report* | kg C/TJ Gross Heating Value | kg $CO_2$/TJ Gross Heating Value | kg $CH_4$/TJ Gross Heating Value | kg $N_2O$/TJ Gross Heating Value | Implied kg $CO_2$e/TJ Gross Heating Value |
|---|---|---|---|---|---|---|
| Coal | Imported Coal for Power Generation (Boiler) | 2.47E+04 | 90,567 | 0.13 | 0.85 | 90,833 |
| Oil | Fuel Oil C | 1.95E+04 | 71,500 | 0.1 | 0.22 | 71,570 |
| LNG | Liquefied Natural Gas | 1.35E+04 | 49,500 | 0.23 | 0.17 | 49,558 |
| GWP (Table 1) | | | 1 | 21 | 310 | |
| Source Table | (in *National Greenhouse Gas Inventory Report, 2014*) | Table 3-2 | | Table 3-11 | Table 3-12 | |

- Eighth, the costs of the gas, coal, and oil fuels needed to power fossil-fueled generation was estimated by applying the estimated fuel consumption requirements calculated as above by projections of fuel costs in Japan. Fossil fuel costs were estimated based on published 2014 average costs for these fuels in Japan, escalated based on real growth rates for fuel prices derived from the central "New Policies Scenario" of the International

[35] Advisory Committee on Energy and Natural Resources Power generation cost verification working group (first meeting), References 1-2. Data from Table I, whose title translates roughly as: "Power supply parameters by type of generation". Document undated, but part of a set of document dated February 18, 2015. Document in Japanese available as
http://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/mitoshi/cost_wg/001/pdf/001_11.pdf.

[36] Ministry of the Environment, Japan Greenhouse Gas Inventory Office of Japan (GIO), Center for Global Environmental Research (CGER), and National Institute for Environmental Studies, Japan (NIES) (2014), *National Greenhouse Gas Inventory Report of JAPAN*. Dated April, 2014, and available as http://www-gio.nies.go.jp/aboutghg/nir/2014/NIR-JPN-2014-v3.0.pdf.

Energy Agency's *World Energy Outlook 2015* (IEA WEO).[37] The IEA WEO New Policies Scenario implies an average real price increase from 2014 through 2040 of about 1.1 percent annually for crude oil (we assume that prices for oil products will increase at similar rates) and 1.3 percent for coal, with the cost of natural gas in Japan decreasing by about 0.5 percent annually, as shown in Table 3-7. IEA WEO New Policies Scenario fuel price growth rates for 2030 through 2040 were applied from 2040 through 2050 as well. Table 3-8 shows the resulting projected fossil fuel prices for Japan through 2050 as used for this analysis.

***Table 3-7: Implied Growth Rates for Fossil Fuel Prices from IEA World Energy Outlook, 2014-2040***

| **Implied Annual Growth Rates in Real Prices** | | New Policies Scenario | | | |
|---|---|---|---|---|---|
| **International Energy Agency Price Projections for:** | | 2014-2020 | 2020-2030 | 2030-2040 | 2014-2040 |
| IEA crude oil imports | | -3.2% | 3.5% | 1.3% | 1.07% |
| Natural gas | United States | 1.1% | 2.8% | 1.9% | 2.07% |
| | Europe imports | -2.9% | 3.7% | 1.0% | 1.11% |
| | Japan imports | -6.2% | 1.7% | 0.8% | -0.53% |
| OECD steam coal imports | | 3.2% | 0.8% | 0.6% | 1.26% |

***Table 3-8: Projected Fossil Fuel Prices for Electricity Generation in Japan Based on IEA World Energy Outlook Fuel Price Growth Rates, 2010-2050***

| | Real Fuel Cost (Y/GJ) | | | | |
|---|---|---|---|---|---|
| Fuel | 2010 | 2014 | 2020 | 2035 | 2050 |
| --Coal | 366 | 324 | 412 | 470 | 577 |
| --Oil | 1,300 | 1,700 | 1,402 | 2,437 | 3,818 |
| --Gas | 1,100 | 1,600 | 1,086 | 1,420 | 1,903 |

- Ninth, in order to estimate the non-fuel costs of electricity generation, we estimated the annualized capital, fixed, and variable operating and maintenance (O&M) costs for each of the types of generation included in the analysis. Most of the base year and future costs of generation used were derived from values published by a recent working group on power generation costs convened by METI.[38] The capital costs for technologies shown in Table 3-9 were converted to annualized capital costs assuming a real interest/discount

[37] Fuel price projections derived from Table 1.6 of International Energy Agency (IEA, 2015) *World Energy Outlook 2015*, Chapter 1: Introduction and scope, available as http://www.worldenergyoutlook.org/media/weowebsite/2015/WEO2015_Chapter01.pdf.

[38] Japan's Agency for Natural Resources and Energy of the Ministry of Economy, Trade, and Industry (METI, 2015), *Advisory Committee on Energy and Natural Resources Power generation cost verification working group (first meeting), References 1-2*. Cost data described here are taken from Table I of this source, the title of which translates roughly as: "Power supply parameters by type of generation". Document undated, but part of a set of documents dated February 18, 2015. Document in Japanese available as http://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/mitoshi/cost_wg/001/pdf/001_11.pdf.

rate of 5 percent/yr and the technology lifetimes shown in Table 3-9.[39] Annualized capital costs, and the annual O&M costs shown in Table 3-10, were converted to costs per kWh using the average capacity factor assumptions in Table 3-11. Variable O&M cost assumptions are shown in Table 3-12. Values highlighted in yellow are based on values compiled by the METI working group. We assumed that most costs for fossil-fueled, nuclear, and hydroelectric/geothermal do not change or change relatively little over time, with the exception being an increase in costs for coal-fired power plants between 2020 and 2035. For renewable technologies, again based on the values from the working group convened by METI, we assumed that wind power costs would increase somewhat after 2020 as more offshore wind turbines are constructed, as offshore wind turbines are more expensive than onshore. Solar photovoltaic system capital costs are projected to decline by a factor of three. Source material providing estimates of the average costs of energy efficiency measures in Japan were not readily identified, at least in English, but the costs of energy efficiency improvements in Japan are known to be higher than in the United States, in part due to the higher current average energy efficiency of many technologies in Japan. As a consequence, and based in part on results for particular technologies, we used an average estimated levelized cost of 10 Yen/kWh saved by energy efficiency measures, which is on the order of three times as high as experienced in many places in the United States, and thus a conservative estimate for this analysis. It is very possible that energy efficiency costs in Japan could be lower than the level we have assumed.

***Table 3-9: Capital Cost Assumptions for Generation Technologies in Japan, 2010-2050***

| | Capital (Y/kW) | | | | | Lifetime |
|---|---|---|---|---|---|---|
| Generation Type | 2010 | 2014 | 2020 | 2035 | 2050 | Years |
| --Gas Combined Cycle | 122,532 | 122,532 | 122,532 | 122,532 | 122,532 | 35 |
| --Gas Steam Cycle | 150,000 | 150,000 | 150,000 | 150,000 | 150,000 | 35 |
| --Oil Steam Cycle | 194,009 | 194,009 | 194,009 | 194,009 | 194,009 | 35 |
| --Coal Steam Cycle | 234,854 | 234,854 | 234,854 | 292,652 | 292,652 | 35 |
| Nuclear--Existing | 379,116 | 379,116 | 379,116 | 379,116 | 379,116 | 40 |
| Nuclear--New | 379,116 | 379,116 | 379,116 | 379,116 | 379,116 | 40 |
| Solar Photovoltaics | 666,705 | 566,996 | 417,433 | 320,089 | 222,745 | 22 |
| Wind | 280,830 | 280,830 | 280,830 | 324,442 | 324,442 | 25 |
| Hydro/Other | 868,021 | 868,021 | 868,021 | 870,064 | 862,915 | 50 |

[39] Currently, and in recent years, interest rates in Japan have been significantly lower than 5 percent annually (see, for example, Trading Economics (2016), "Japan's Long-Term Prime Rate", available as http://www.tradingeconomics.com/japan/bank-lending-rate. Although a five percent annual interest rate over the long term is not unreasonable for most industrialized nations, it is, of course, unknown whether Japanese rates will rise from their current levels of on the order of one percent to the five percent/year range, which Japan last saw in the 1990s. Using a 1.5 percent annual interest rate rather than 5 percent over 2015 through 2050 reduces the overall cumulative undiscounted costs of each restart path (see Figure 3-10) by on the order of 10 percent, but results in very little change in the relative costs of the three paths.

***Table 3-10: Fixed O&M Cost Assumptions for Generation Technologies in Japan, 2010-2050***

| | Fixed O&M (Y/kW-yr) | | | | |
|---|---|---|---|---|---|
| | 2010 | 2014 | 2020 | 2035 | 2050 |
| --Gas Combined Cycle | 4,631 | 4,631 | 4,631 | 4,631 | 4,631 |
| --Gas Steam Cycle | 8,000 | 8,000 | 8,000 | 8,000 | 8,000 |
| --Oil Steam Cycle | 6,766 | 6,766 | 6,766 | 6,766 | 6,766 |
| --Coal Steam Cycle | 8,599 | 8,599 | 8,599 | 8,599 | 8,599 |
| Nuclear--Existing | 19,492 | 19,492 | 19,492 | 19,492 | 19,492 |
| Nuclear--New | 19,492 | 19,492 | 19,492 | 19,492 | 19,492 |
| Solar Photovoltaics | 12,740 | 12,740 | 12,740 | 12,740 | 12,740 |
| Wind | 6,358 | 6,358 | 6,358 | 8,860 | 8,860 |
| Hydro/Other | 9,634 | 9,634 | 9,634 | 19,032 | 24,871 |

***Table 3-11: Capacity Factor Assumptions for Generation Technologies in Japan, 2010-2050***

| | Average Capacity Factor | | | | |
|---|---|---|---|---|---|
| | 2010 | 2014 | 2020 | 2035 | 2050 |
| --Gas Combined Cycle | 50% | 50% | 55% | 65% | 70% |
| --Gas Steam Cycle | 35% | 35% | 35% | 35% | 35% |
| --Oil Steam Cycle | 15% | 15% | 15% | 15% | 15% |
| --Coal Steam Cycle | 75% | 75% | 75% | 75% | 75% |
| Nuclear--Existing | 75% | 75% | 75% | 75% | 75% |
| Nuclear--New | 75% | 75% | 75% | 75% | 75% |
| Solar Photovoltaics | 12% | 12% | 12% | 12% | 12% |
| Wind | 25% | 25% | 25% | 27.5% | 30% |
| Hydro/Other | 45% | 45% | 45% | 47.5% | 50% |

***Table 3-12: Variable O&M Cost Assumptions for Generation Technologies in Japan, 2010-2050***

| | Variable Non-fuel O&M (Y/kWh) | | | | |
|---|---|---|---|---|---|
| | 2010 | 2014 | 2020 | 2035 | 2050 |
| --Gas Combined Cycle | 0.28 | 0.28 | 0.28 | 0.28 | 0.28 |
| --Gas Steam Cycle** | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| --Oil Steam Cycle | 1.86 | 1.86 | 1.86 | 1.86 | 1.86 |
| --Coal Steam Cycle | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 |
| Nuclear--Existing** | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| Nuclear--New** | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| Solar Photovoltaics | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Wind | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Hydro/Other** | 0.70 | 0.70 | 0.70 | 0.70 | 0.70 |
| Electric Energy Efficiency Improvements* | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |

*Intended to represent full annualized net cost of electric energy efficiency improvements.

** Hydro is rough estimate form http://www.eia.gov/forecasts/aeo/pdf/electricity_generation.pdf. Nuclear is representative estimate as found in various sources, including http://www.nrel.gov/docs/fy11osti/48595.pdf. Gas-steam is a rough estimate between oil-steam and gas combined-cycle values.

- Tenth, we estimated the front-end and back-end nuclear fuel cycle costs—that is, nuclear costs not related to generation—for each restart path. These estimates were prepared using a Nautilus workbook tool developed to compare physical flows of materials and costs in scenarios for nuclear fuel cycle cooperation in the countries of East Asia and the Pacific, although in this instance focusing on Japan.[40]

## 3.4 Electricity Supply Results by Path—Capacity and Generation

In the first of the Restart Paths, Path 1, Return to Pursuit of Closed Nuclear Fuel Cycle, much of Japan's reactor fleet, as described in the path assumptions in section 2, above, come back on line in the next decade, and a number of new reactors are completed. As a result, as shown in Figure 3-2, fossil generation, and particularly coal-fired generation that had increased dramatically in the post-Fukushima era, decreases over time, as the share of nuclear power rises to over 32 percent of generation in the mid-2020s, declining to just over 20 percent by 2050 as solar PV and other renewable generation increases and as older reactors are decommissioned. Gas-fired power constitutes just over a quarter of Japan's generation by 2050 under Path 1, with coal-fired power declining to less than 5 percent of the total.

[40] A description of an earlier version of the methodology used to estimate front- and back-end nuclear costs is provided in David von Hippel, Tatsujiro Suzuki, Tadahiro Katsuta, Jungmin Kang, Alexander Dmitriev, Jim Falk, and Peter Hayes (2010), *Regional Nuclear Fuel Cycle Cooperation in East Asia: Energy Security Costs and Benefits*. Nautilus Institute East Asia Science and Security Project Report dated June, 2010, and available as http://nautilus.org/wp-content/uploads/2012/01/EASS_Report_6-2010_rev.pdf.

*Figure 3-2: Fraction of Generation by Source, Path 1*

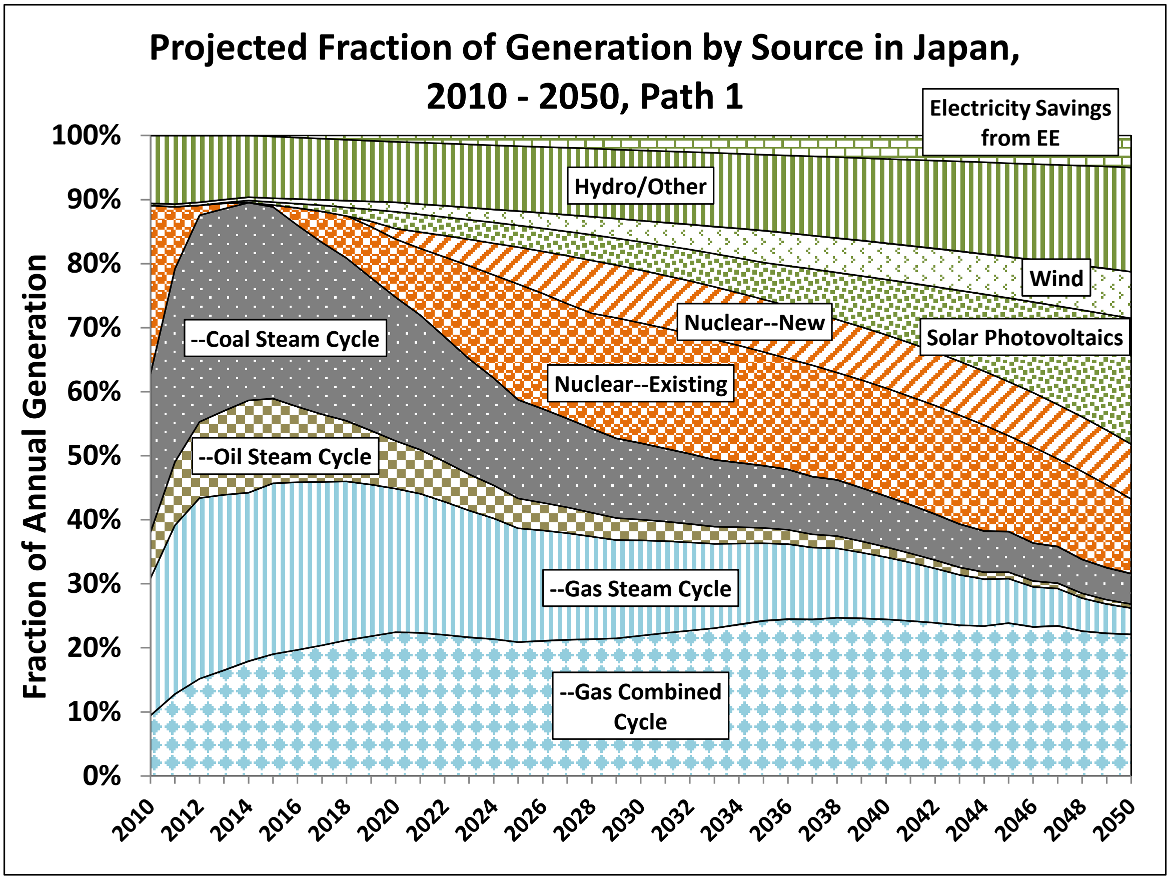
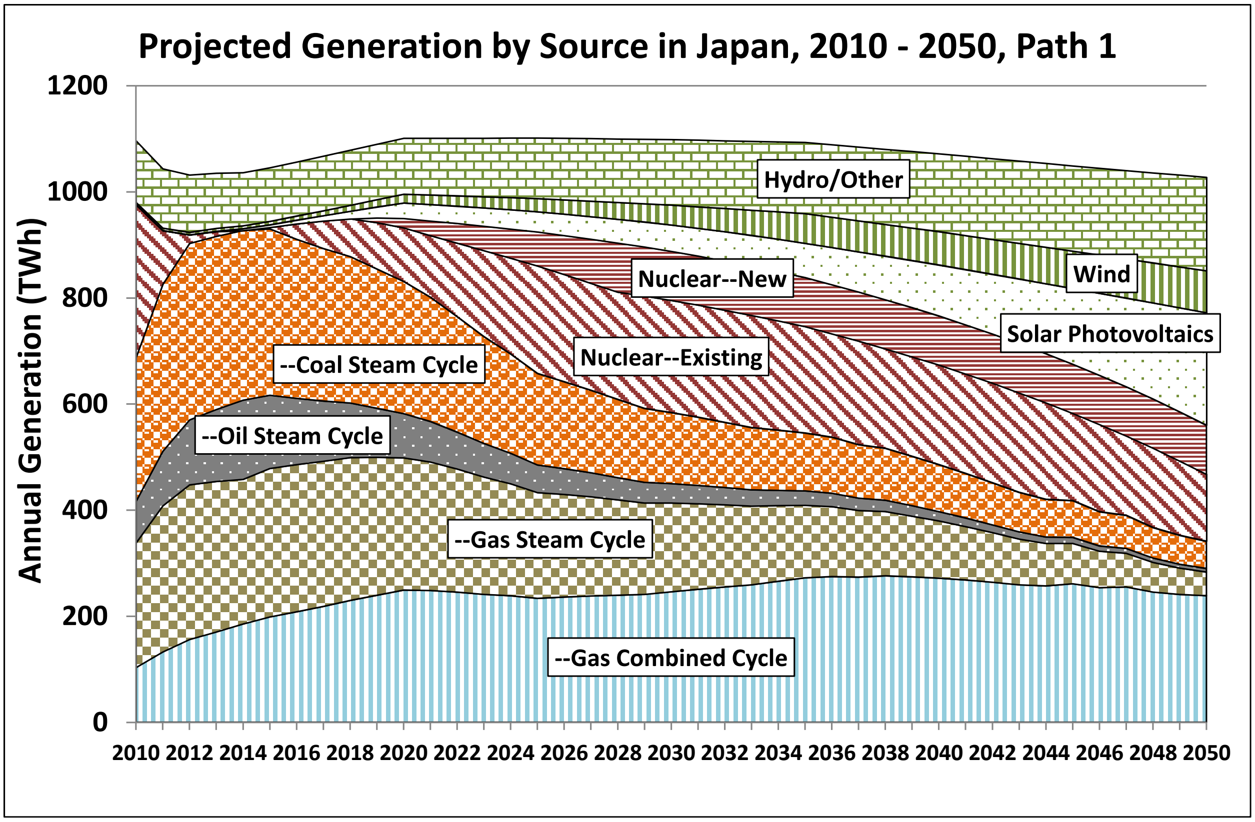



Figure 3-3 shows projected generation by source in terawatt-hours. Overall generation peaks in 2025, at just over 1,100 TWh, then falls slowly through 2050 to under 1,030 TWh due to the combination of the gradually declining demand forecast and the policy-driven energy efficiency improvements included in the Path.

*Figure 3-3: Generation by Source, Path 1*




As shown in Figure 3-4, the fractions of generation accounted for in Path 2 are similar to those in Path 1. Here, nuclear generation peaks at just over 30 percent of total electricity output in 2021, but declines more significantly than in Path 1, to 15 percent of overall output by 2050. Gas-fired power constitutes over 30 percent of generation by 2050, with coal-fired power providing 5.5 percent, and most of the rest of generation supplied by renewable power sources. Figure 3-5 shows generation in TWh by source for Path 2.

*Figure 3-4: Fraction of Generation by Source, Path 2*

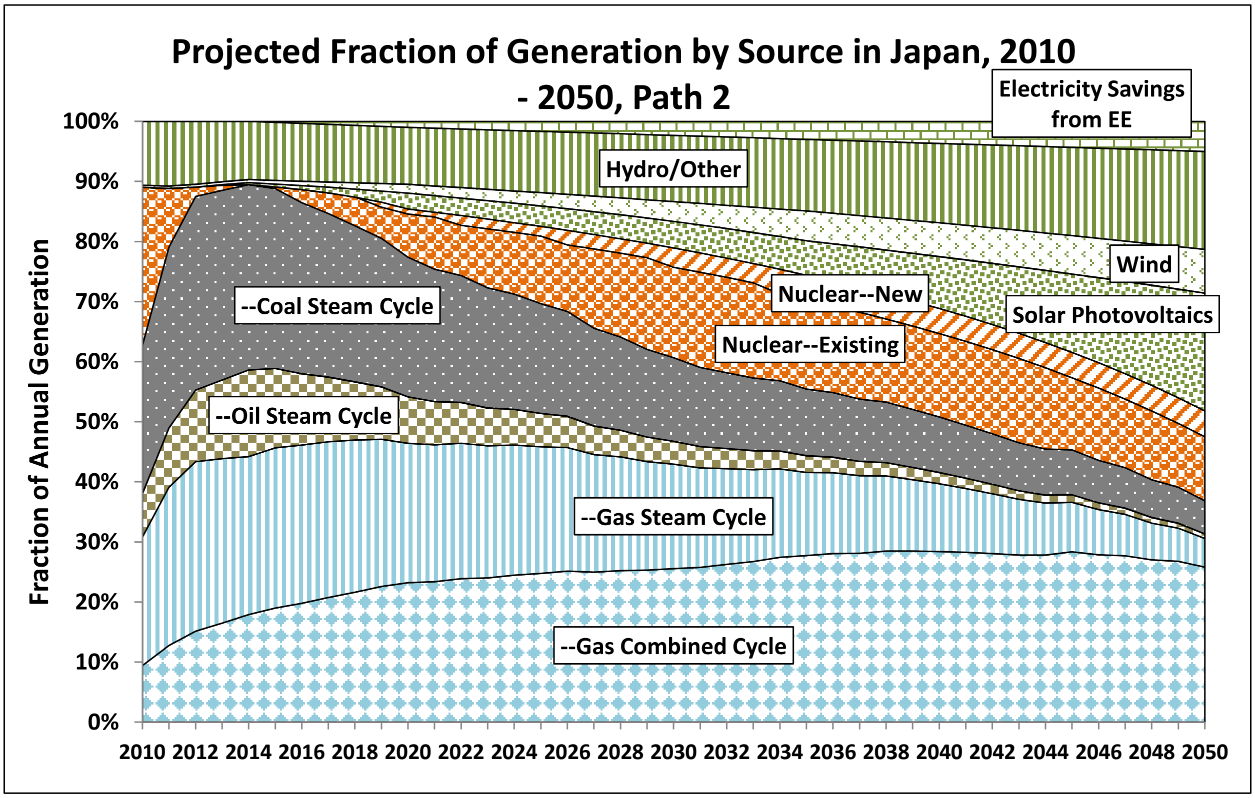
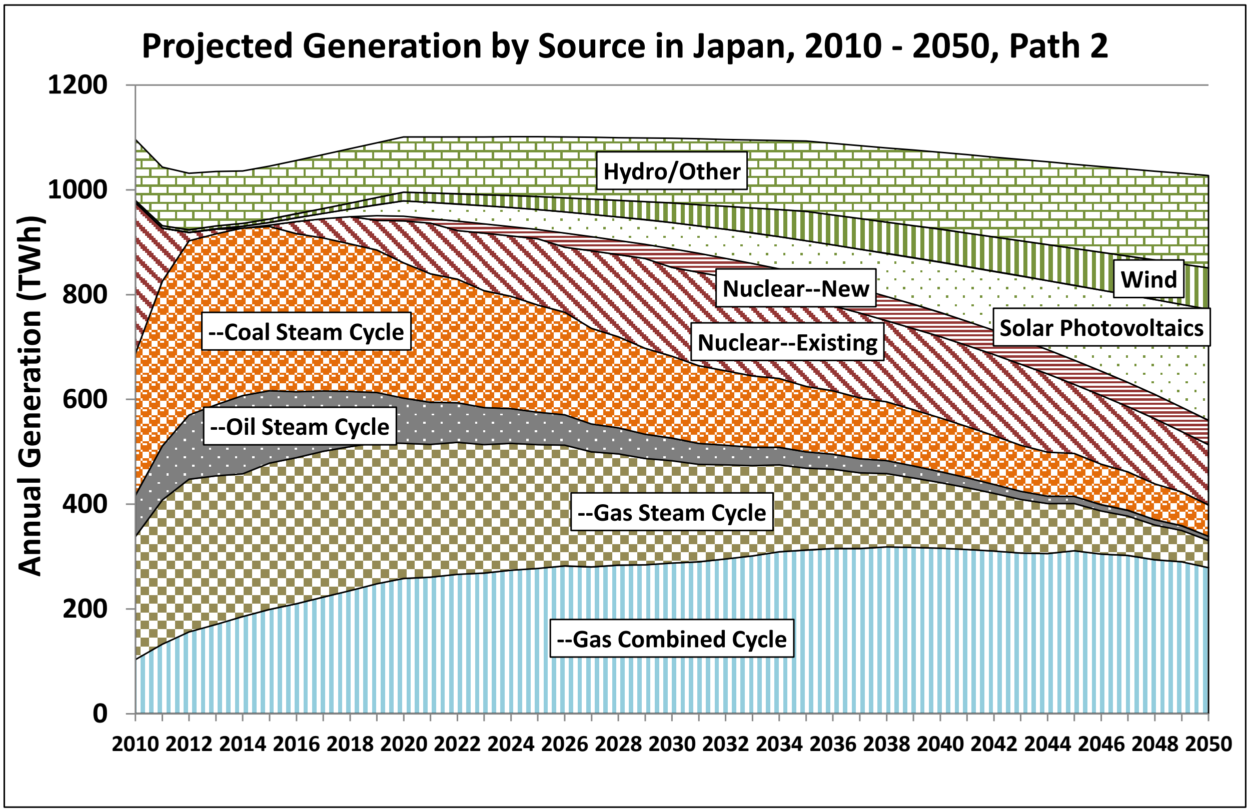
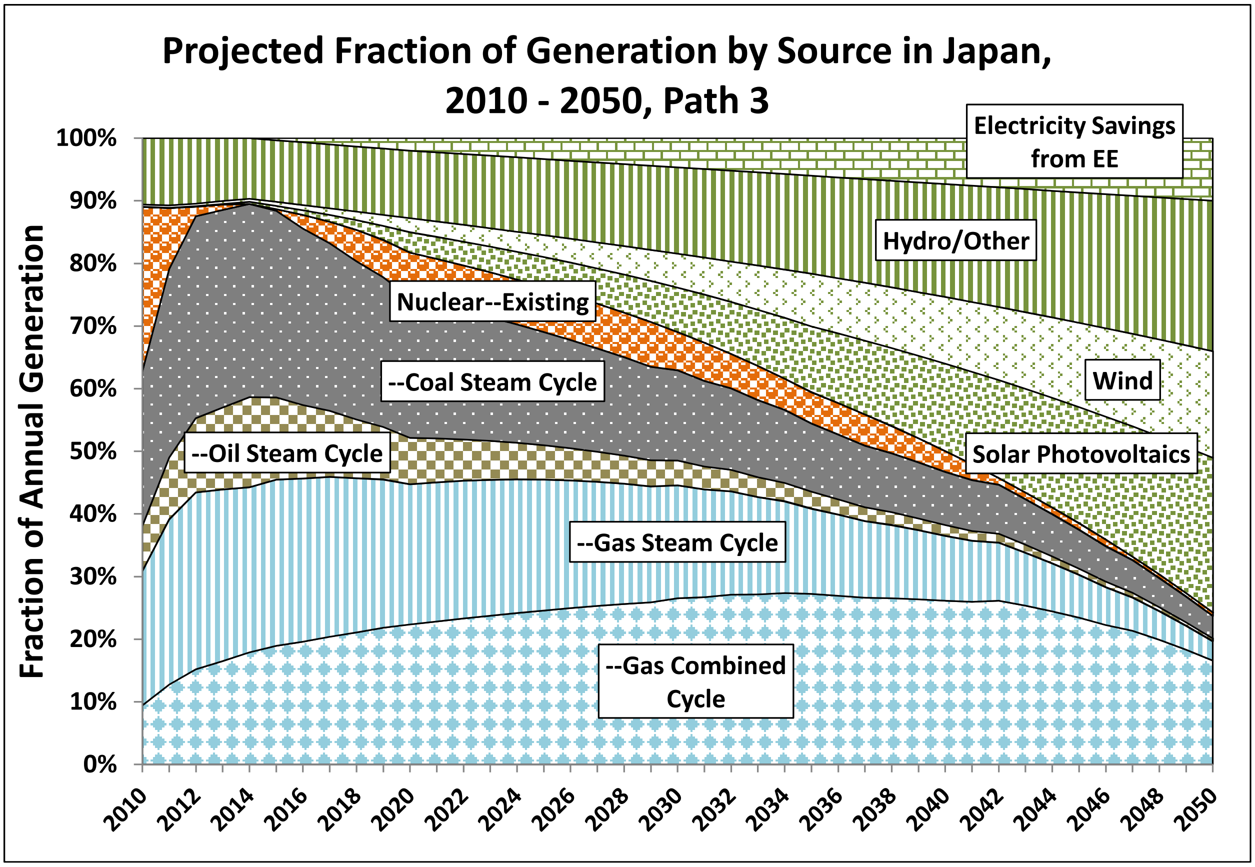


*Figure 3-5: Generation by Source, Path 2*



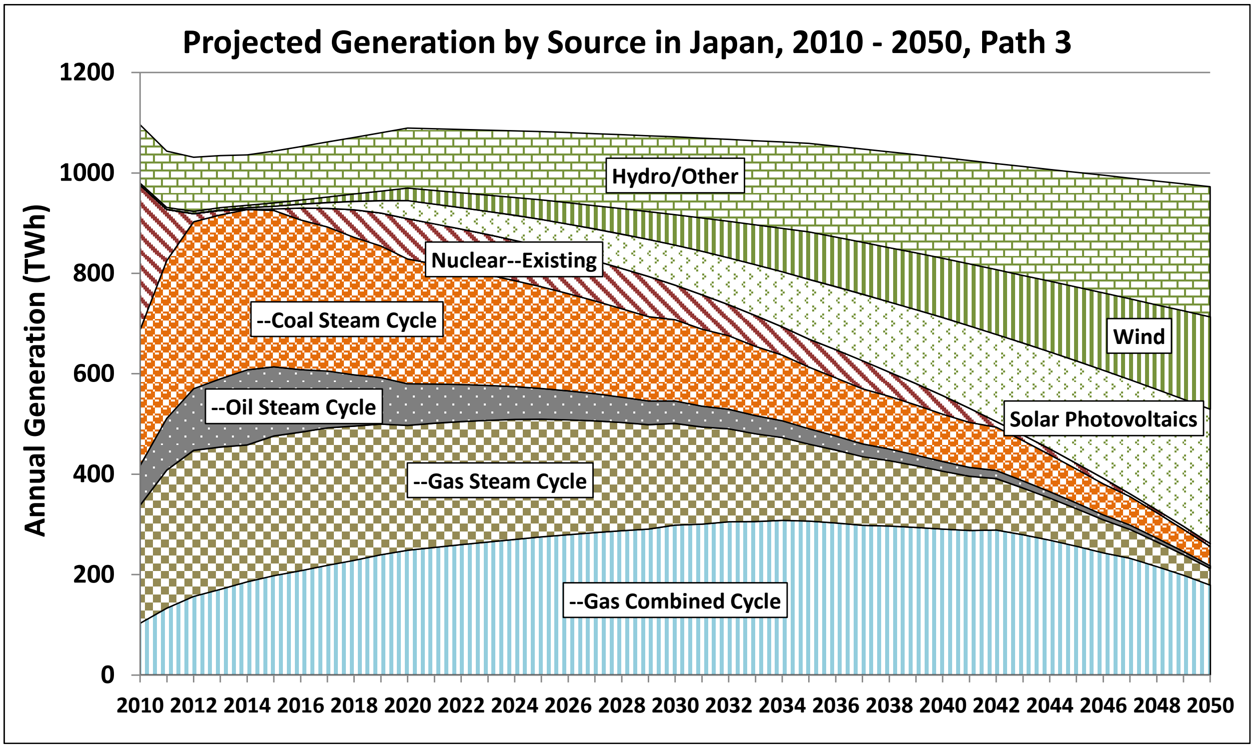

As shown in Figure 3-6, Path 3 differs significantly from Paths 1 and 2 in that restarted nuclear generation supplies a maximum of 7.2 percent of total generation (in 2020 through 2026), but due to the virtual phase-out of nuclear power supplies only 0.6 percent of generation by 2050. Gas-fired power plants supply slightly under 20 percent of generation by 2050, and coal-fired power provides less than 4 percent. The majority of generation is generated from renewable resources by 2050 in Path 3, with wind and solar PV systems combining to provide over 40 percent of generation by that year.

*Figure 3-6: Fraction of Generation by Source, Path 3*




Total generation in TWh in Path 3 is shown in Figure 3-7. Total generation in Path 3 by 2050 is less than in Paths 1 and 2—973 TWh versus 1,031 TWh in Paths 1 and 2—because a more aggressive set of policy-driven energy efficiency programs is assumed to be implemented in order to reduce the capital requirements and costs for aggressive implementation of renewable generation.

*Figure 3-7: Generation by Source, Path 3*




## 3.5 Electricity Supply Results by Path— Emissions and Costs

In all three paths, greenhouse gas emissions from the electricity sector decline significantly between the peak year of 2014 and 2050, though by different amounts. In all cases, declines are due to the restart of nuclear power and to the implementation of energy efficiency and renewable generation, but these factors have different proportional influence in the three paths. Figure 3-8 compares the annual emissions of electricity sector GHGs by fossil fuel type for selected years. In Path 1, emissions decline by two thirds from their 2010 (pre-Fukushima accident) peak of about 560 million tonnes of carbon dioxide equivalent (Mt $CO_2e$), to just over 140 Mt $CO_2e$ by 2050. Declines in Path 2 are similar, but not quite as substantial, with emissions declining by more than 60 percent to 164 Mt $CO_2e$ by 2050 from 2010 levels. Path 3 shows the strongest declines in GHG emissions of the three paths, with emissions in 2050 falling by three-quarters from 2010 levels, and by over 80 percent from peak 2014 levels, to about 105 Mt $CO_2e$. The larger declines in Path 3 relative to the other two paths, despite the much more limited nuclear restart assumed, are due to the more aggressive implementation of renewable energy and energy efficiency in Path 3. Figure 3-9 show GHG emissions by type of fossil-fueled generation for all years for Path 2. The overall shapes of these curves are similar for all three paths, though the 2050 end-points, as noted, differ somewhat.

*Figure 3-8: Greenhouse Gas Emissions by Year and Path*

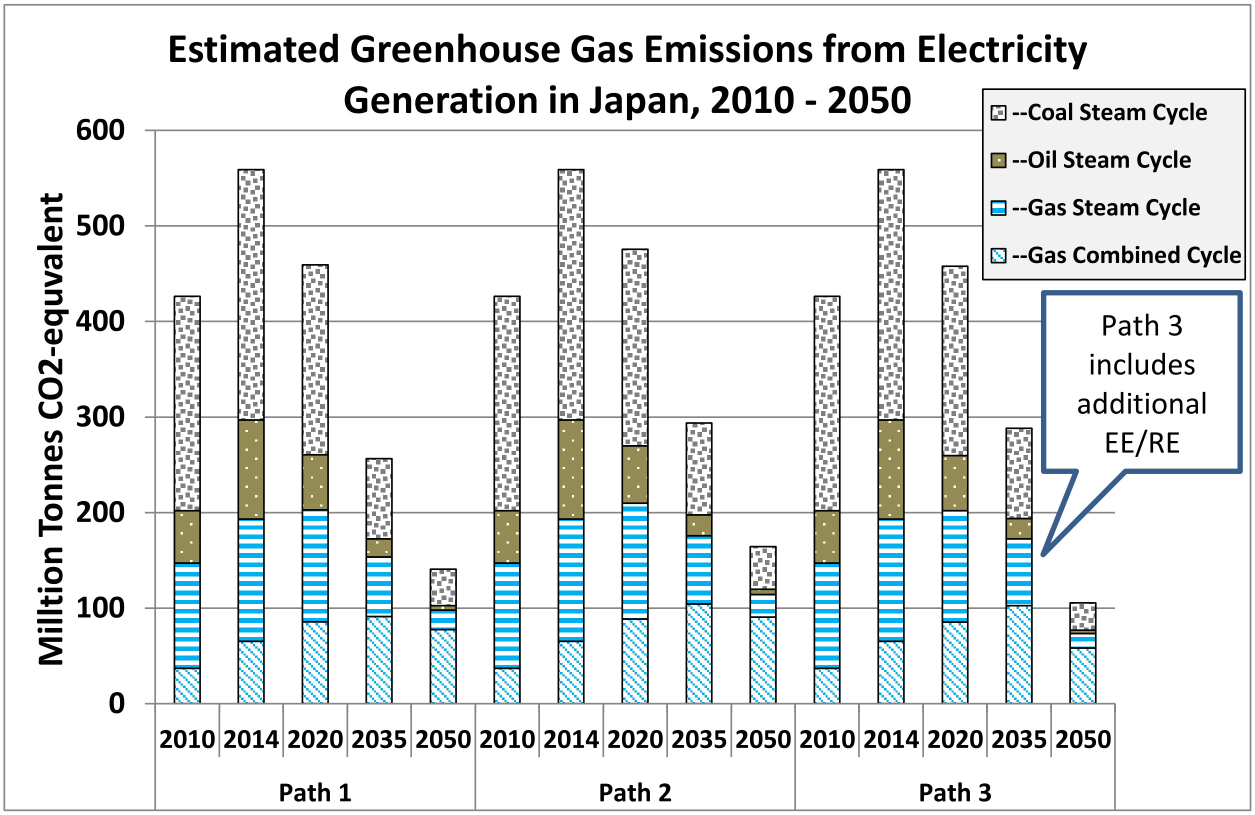


*Figure 3-9: Greenhouse Gas Emissions by Source, Path 2*

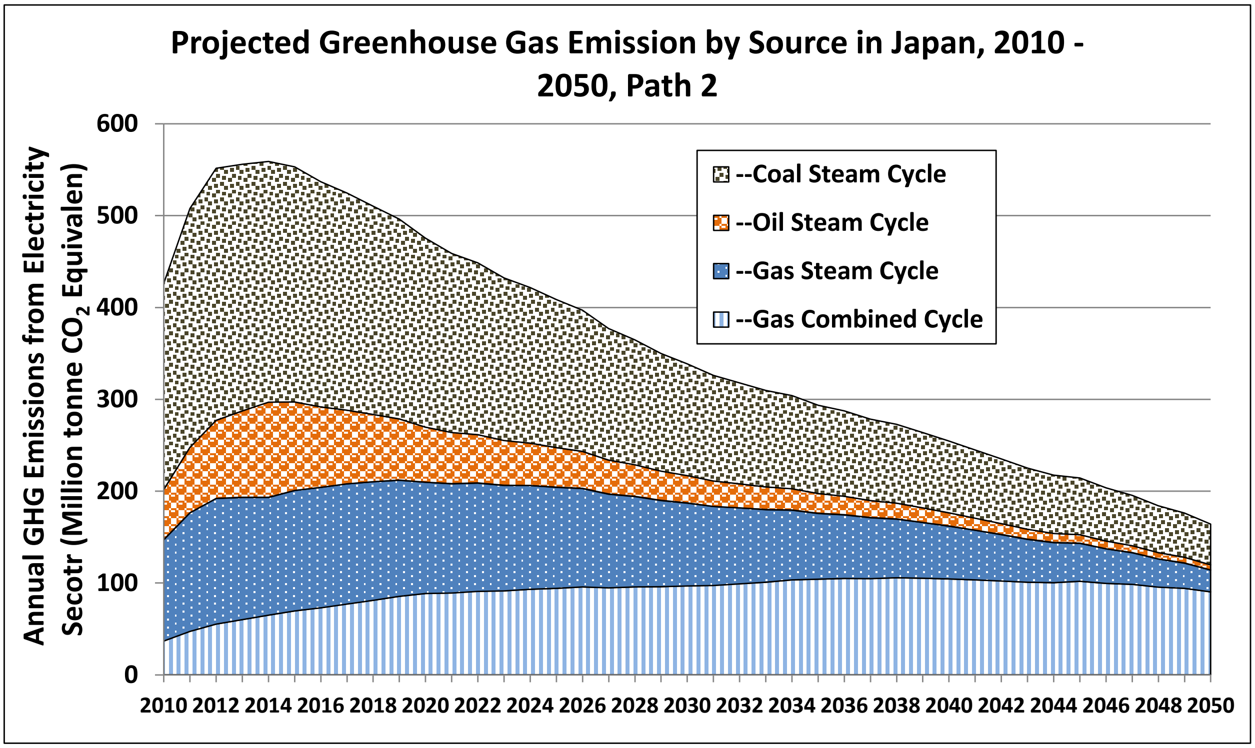



Figure 3-10 compares the total cumulative undiscounted costs of electricity generation in Japan under the three restart paths, calculated based on the paths assumptions presented earlier in this Chapter, and incorporating assumptions, with some updates, on nuclear fuel cycle costs and performance as described in our earlier regional work on costs and physical flows in the nuclear fuel cycle, as referenced above. These costs include annualized capital and operating costs for all of the types of power plants, fuel costs for fossil-fueled plants, plus nuclear fuel-cycle costs, including both front end (uranium provision, enrichment, fuel preparation, and transport) and back-end (spent fuel management and related costs) costs. In each case, nuclear fuel cycle costs are based on the data and assumptions described in section 3.3 of this Report. Annualized capital costs are expressed on a per kWh basis, meaning that costs are included only if and when power plants (of all types) were actually run. This assumption affects the overall level of costs for all technologies, but especially for nuclear power, since in the different restart paths some plants sit idle, and some are decommissioned,[41] while others generate power. A detailed study of

[41] Based on data in Japanese source documents used to estimate generation costs for all technologies, decommissioning costs are included in annualized per kWh capital costs. In a more detailed study, decommissioning costs for power plants retired before the end of their useful life might effectively be higher than included here, because those costs are incurred earlier, and are not fully amortized over a plant's nominal lifetime. If, for example, a fund is set up to collect funds for decommissioning over 40 years of reactor operation, but the plant is decommissioned after 25 years, presumably the decommissioning funds collected would be inadequate for the actual decommissioning activities, and additional funds will be required. Not knowing how decommissioning costs are likely to be handled in Japan, we have used the same annualizing technique for all capital (including decommissioning) costs for all types of power plants. Our guess is that a more explicit accounting of

how "sunk costs"—capital costs already incurred for reactors that nominally have remaining life but will not be restarted—are to be managed in Japan, and the effects of sunk costs management on the relative overall average costs generation in the three restart cases, is beyond the scope of this Report.[42]

The results in Figure 3-10 indicate that the overall undiscounted 2015 through 2050 costs of the three paths as modeled are within a few percent of each other, at somewhat over 500 trillion Yen (2015 Yen). Path 2 is slightly more expensive, overall, than the other two paths, but given the large uncertainties associated with any cost or other projections of this type, the small percentage difference is insignificant, meaning (as elaborated further in sections 5 and 6 of this Report, that policy decisions regarding which path to pursue should not be driven by the considerations of overall costs to the Japanese economy, at least as we have modeled those costs here. In all three paths, the major costs are the costs of fossil-fueled generation, at 58 percent (Path 1) to 64 percent (Path 2) of total undiscounted costs. Discounting costs (at 5.0 percent annually) yields net-present-value (NPV) overall costs that are less than half of undiscounted costs, at about 245 trillion Yen, again with the total costs of the three paths varying by only a few percent (see Table 3-13). Fossil generation costs are even more dominant when costs are discounted, ranging from 66 percent (Path 1) to 71 percent (Path 2) of the total. Fossil costs are more dominant in the discounted totals because more fossil costs occur earlier in the 2015-2050 period, falling as renewable power plants and energy efficiency meet larger shares of the demand for electricity services over time.

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decommissioning costs are unlikely to change the overall power sector costs shown in the Figure 3-10 by more than a few percent, given the dominance of fossil generation costs in overall costs, but would likely change costs in Path 3 more than in the other paths **unless**, as has happened in the past in other places, nuclear decommissioning costs escalate over time, in which case, earlier decommissioning might in fact be favorable.

[42] Evaluating the impact of sunk costs on these restart paths requires an understanding of the possible treatments of sunk costs that policymakers may make available to owners of nuclear plants, ranging, for example, from disallowing further recovery of capital costs for non-operating plants (meaning that the companies and investors lose the remaining value of the plant) to full repayment of sunk costs by the public, either by electricity ratepayers (through electricity bills), by the Japanese government (ultimately funded by taxpayers), or a combination of the two.

*Figure 3-10: Cumulative Electricity Generation Costs by Path*

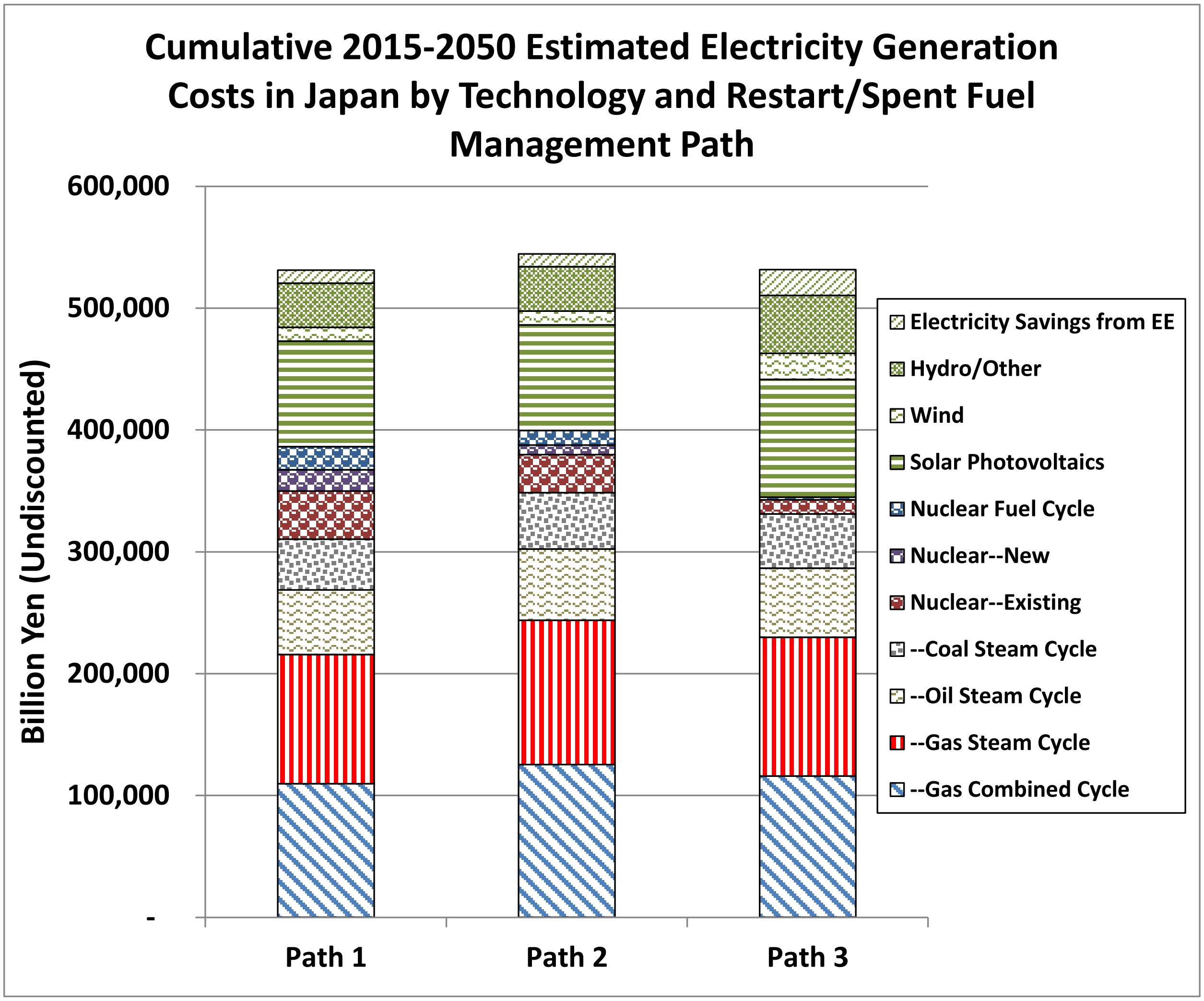


*Table 3-13: Cumulative Generation Costs by Restart Path and Cost Category, Undiscounted and Discounted (2015 Yen)*

**Cumulative Generation Costs by Path**

| | Cumulative 2015-2050 Costs in Billion Undiscounted Yen | | | Fraction of Cumulative 2015-2050 Costs in Billion Undiscounted Yen | | |
|---|---|---|---|---|---|---|
| Type of Generation | Path 1 | Path 2 | Path 3 | Path 1 | Path 2 | Path 3 |
| --Gas Combined Cycle | 109,596 | 125,339 | 115,951 | 20.7% | 23.0% | 21.8% |
| --Gas Steam Cycle | 105,913 | 118,395 | 113,821 | 20.0% | 21.8% | 21.4% |
| --Oil Steam Cycle | 53,087 | 58,414 | 56,633 | 10.0% | 10.7% | 10.7% |
| --Coal Steam Cycle | 41,577 | 46,319 | 44,490 | 7.8% | 8.5% | 8.4% |
| Nuclear--Existing | 39,646 | 31,234 | 11,664 | 7.5% | 5.7% | 2.2% |
| Nuclear--New | 17,408 | 7,793 | - | 3.3% | 1.4% | 0.0% |
| Nuclear Fuel Cycle | 17,778 | 11,795 | 2,173 | 3.4% | 2.2% | 0.4% |
| Solar Photovoltaics | 86,574 | 86,574 | 96,675 | 16.3% | 15.9% | 18.2% |
| Wind | 11,382 | 11,382 | 21,329 | 2.1% | 2.1% | 4.0% |
| Hydro/Other | 36,342 | 36,342 | 47,680 | 6.9% | 6.7% | 9.0% |
| Electricity Savings from EE | 10,577 | 10,577 | 21,154 | 2.0% | 1.9% | 4.0% |
| **TOTAL OF ALL COSTS** | 529,880 | 544,163 | 531,570 | 100.0% | 100.0% | 100.0% |
| Fraction of Path 2 | 97.4% | 100.0% | 97.7% | | | |
| Fraction of Which Fossil Generation | | | | 58.5% | 64.0% | 62.2% |

| | Cumulative 2015-2050 Costs in Billion Net Present Value Yen | | | Fraction of Cumulative 2015-2050 Costs in Billion Net Present Value Yen | | |
|---|---|---|---|---|---|---|
| Type of Generation | Path 1 | Path 2 | Path 3 | Path 1 | Path 2 | Path 3 |
| --Gas Combined Cycle | 47,460 | 53,026 | 50,786 | 19.6% | 21.4% | 20.9% |
| --Gas Steam Cycle | 58,208 | 63,527 | 62,071 | 24.0% | 25.6% | 25.5% |
| --Oil Steam Cycle | 32,520 | 34,954 | 34,267 | 13.4% | 14.1% | 14.1% |
| --Coal Steam Cycle | 23,385 | 25,439 | 24,841 | 9.6% | 10.3% | 10.2% |
| Nuclear--Existing | 16,246 | 12,467 | 6,083 | 6.7% | 5.0% | 2.5% |
| Nuclear--New | 6,257 | 2,670 | - | 2.6% | 1.1% | 0.0% |
| Nuclear Fuel Cycle | 7,403 | 4,698 | 1,160 | 3.1% | 1.9% | 0.5% |
| Solar Photovoltaics | 29,098 | 29,098 | 32,158 | 12.0% | 11.7% | 13.2% |
| Wind | 3,922 | 3,922 | 6,913 | 1.6% | 1.6% | 2.8% |
| Hydro/Other | 14,434 | 14,434 | 18,033 | 6.0% | 5.8% | 7.4% |
| Electricity Savings from EE | 3,623 | 3,623 | 7,247 | 1.5% | 1.5% | 3.0% |
| **TOTAL OF ALL COSTS** | 242,557 | 247,857 | 243,560 | 100.0% | 100.0% | 100.0% |
| Fraction of Path 2 | 97.9% | 100.0% | 98.3% | | | |
| Fraction of Which Fossil Generation | | | | 66.6% | 71.4% | 70.6% |

# 4 Nuclear Materials Flows and Nuclear Sector Costs by Path

Each of the three restart paths described in section 2 of this Report have different implications for the magnitude and timing of the flows of nuclear materials on both the front end and back end of the fuel cycle, and also for the costs of nuclear fuel cycle activities. Below we present key results of our analysis with respect to the requirements for uranium imports and enrichment and uranium oxide (UOx) fuel fabrication, for reprocessing, plutonium handling, and MOx fuel preparation, and for spent fuel transport and management. Also presented are our estimates for nuclear fuel cycle costs, by type, for each restart path. An analysis of the sensitivity of selected results to changes in key parameters, including uranium prices and enrichment costs, is also presented.

## 4.1 Uranium Supply, Enrichment, and Fuel Fabrication Requirements

The three different restart paths imply three different levels of requirements of uranium, enrichment, and associated inputs and costs. Selected annual and cumulative (2015-2050) results for mining and milling parameters are provided in Table 4-1. On the order of 190 thousand metric tonnes of uranium are required over the period 2015 through 2050 in Path 1, with about 130 thousand tonnes required in Path 2, and under 40 thousand tonnes needed in Path 3. Other mining and milling inputs and costs scale with U requirements, with Path 3 being about 30 percent, on a cumulative basis of Path 2 values (that is, 70 percent lower), and Path 1 being about 45 percent higher than in Path 2. Paths 1 and 2 imply the mining of a cumulative 3.3 to 4.7 million tonnes of uranium ore over 2015 through 2050, which sounds substantial, but should be considered in its energy context, since the amount of coal used over the same period in Japan in the three paths ranges from about 1.7 to 1.9 **billion** tonnes.

***Table 4-1: Requirements, Inputs, and Wastes Associated with Mining and Milling of Uranium in Each Restart Path, 2010 through 2050***

| **Parameter** | YEAR | Path 1 | Path 2 | Path 3 |
|---|---|---|---|---|
| Annual Total Metric Tons Natural Uranium (as U) Imported plus Domestic Production | 2010 | 7,120 | 7,120 | 7,120 |
| | 2030 | 6,425 | 4,500 | 1,453 |
| | 2050 | 4,620 | 3,533 | 127 |
| | Cumulative, 2015-2050 | 188,180 | 131,014 | 37,780 |
| Annual Total Thousand Metric Tons Uranium Ore (from In-country and outside mines) to Supply All Domestic Uranium Needs | 2010 | 177 | 177 | 177 |
| | 2030 | 160 | 112 | 36 |
| | 2050 | 115 | 88 | 3 |
| | Cumulative, 2015-2050 | 4,681 | 3,259 | 940 |
| Annual Total Electricity Used (Mining and Milling) for Domestic and Imported Production (GWh) | 2010 | 64 | 64 | 64 |
| | 2030 | 58 | 41 | 13 |
| | 2050 | 42 | 32 | 1 |
| | Cumulative, 2015-2050 | 1,700 | 1,183 | 341 |
| Annual Total Total Fossil Fuel (likely mostly diesel) Used (Mining and Milling) for Domestic and Imported Uranium Production (TJ) | 2010 | 176 | 176 | 176 |
| | 2030 | 159 | 111 | 36 |
| | 2050 | 114 | 87 | 3 |
| | Cumulative, 2015-2050 | 4,643 | 3,233 | 932 |
| Annual Total Water Use for Milling (including in-situ leaching) for Production of Domestic and Imported Uranium (million cubic meters) | 2010 | 7.1 | 7.1 | 7.1 |
| | 2030 | 6.4 | 4.5 | 1.5 |
| | 2050 | 4.6 | 3.5 | 0.1 |
| | Cumulative, 2015-2050 | 188 | 131 | 38 |
| Annual Radioactivity in Mill Tailings from Uranium Produced Domestically and Imported for Use in Reactors in the Region (TBq) | 2010 | 576 | 576 | 576 |
| | 2030 | 583 | 396 | 133 |
| | 2050 | 382 | 282 | 10 |
| | Cumulative, 2015-2050 | 16,381 | 11,097 | 3,302 |

The enriched uranium requirements, associated requirements for inputs to enrichment (uranium hexafluoride, or $UF_6$, fuel, and electricity), and wastes (solid, liquid, and depleted U) from enrichment under each restart path are shown in Table 4-2. As with uranium mining and milling, the flows of enrichment-related inputs, energy, and wastes associated with Path 3 over the period 20150 through 2050 are less than one third of those in Path 2, and on the order of one-fifth of those in Path 1.

*Table 4-2: Requirements, Inputs, and Waste Flows Associated with Enrichment of Uranium in Each Restart Path, 2010 through 2050*

| Parameter | YEAR | Path 1 | Path 2 | Path 3 |
|---|---|---|---|---|
| Annual Total Metric Tons Natural Uranium (as UF6, but expressed as U) Enriched Inside and Outside the Country for Use in Domestic Reactors | 2010 | 7,085 | 7,085 | 7,085 |
| | 2030 | 6,393 | 4,478 | 1,445 |
| | 2050 | 4,597 | 3,516 | 126 |
| | Cumulative, 2015-2050 | 267,955 | 211,075 | 118,307 |
| Implied Million Tonne-km U3O8 Transport to In-country and Out-of-country Enrichment for Use in Domestic Reactors | 2010 | 69 | 69 | 69 |
| | 2030 | 51 | 36 | 12 |
| | 2050 | 37 | 28 | 1 |
| | Cumulative, 2015-2050 | 1,505 | 1,048 | 302 |
| Annual Total Fossil Fuel Used in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (TJ) | 2010 | 17 | 17 | 17 |
| | 2030 | 15 | 11 | 3 |
| | 2050 | 11 | 8 | 0 |
| | Cumulative, 2015-2050 | 451 | 314 | 90 |
| Annual Total Electricity Used in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (GWhe) | 2010 | 7.1 | 7.1 | 7.1 |
| | 2030 | 6.4 | 4.5 | 1.5 |
| | 2050 | 4.6 | 3.5 | 0.1 |
| | Cumulative, 2015-2050 | 188 | 30,775 | 35,327 |
| Annual Solid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (metric tons) | 2010 | 4,984 | 4,984 | 4,984 |
| | 2030 | 4,497 | 3,150 | 1,017 |
| | 2050 | 3,234 | 2,473 | 89 |
| | Cumulative, 2015-2050 | 131,726 | 91,710 | 26,446 |
| Annual Liguid Waste Produced in Converting U3O8 to UF6 for Uranium Enriched In-country or Out-of-country (cubic meters) | 2010 | 46,282 | 46,282 | 46,282 |
| | 2030 | 41,762 | 29,252 | 9,442 |
| | 2050 | 30,033 | 22,966 | 823 |
| | Cumulative, 2015-2050 | 1,223,172 | 851,593 | 258,097 |
| Annual Total Enriched Fuel Requirements for Uranium Enriched In-country or Out-of-country for Domestic Use (metric tons enriched fuel as U) | 2010 | 781 | 781 | 781 |
| | 2030 | 704 | 493 | 159 |
| | 2050 | 507 | 387 | 14 |
| | Cumulative, 2015-2050 | 20,634 | 14,366 | 4,143 |
| Annual Total Enrichment Requirements for Uranium Enriched In-country or Out-of-country for Domestic Use (Million kg SWU) | 2010 | 5.5 | 5.5 | 5.5 |
| | 2030 | 5.0 | 3.5 | 1.1 |
| | 2050 | 3.6 | 2.7 | 0.1 |
| | Cumulative, 2015-2050 | 145.4 | 101.2 | 29.2 |
| Annual Total Electricity Used for Uranium Enrichment In-country or Out-of-country for Fuel Used in Domestic Reactors (GWh) | 2010 | 3,086 | 3,086 | 3,086 |
| | 2030 | 248 | 174 | 56 |
| | 2050 | 179 | 137 | 5 |
| | Cumulative, 2015-2050 | 7,271 | 5,062 | 1,460 |
| Annual Total Depleted Uranium Produced from Uranium Enrichment In-country or Out-of-country for Fuel Used in Domestic Reactors (metric tons U) | 2010 | 6,304 | 6,304 | 6,304 |
| | 2030 | 5,688 | 3,984 | 1,286 |
| | 2050 | 4,091 | 3,128 | 112 |
| | Cumulative, 2015-2050 | 166,605 | 115,993 | 33,449 |

The estimated requirements for fresh UOx fuel in Japan for each of the three restart paths are shown in Figure 4-1. The maximum annual fuel requirements in each path are about 800 tHM in Path 1, 600 tHM in Path 2, and 200 tHM in Path 3. The maximum requirements occur earlier in Path 3, because no new reactors are deployed, and in Path 1, because restart and completion of new reactors is more rapid, than in Path 2. The jagged peaks that show in the annual UOx requirements curve for Path 2 correspond to the need to prepare fresh full cores for new reactors. In practice, it is probable that fuel preparation would anticipate restarts so as to moderate year-to-year differences in fuel production.

***Figure 4-1: UOx Requirements by Path***

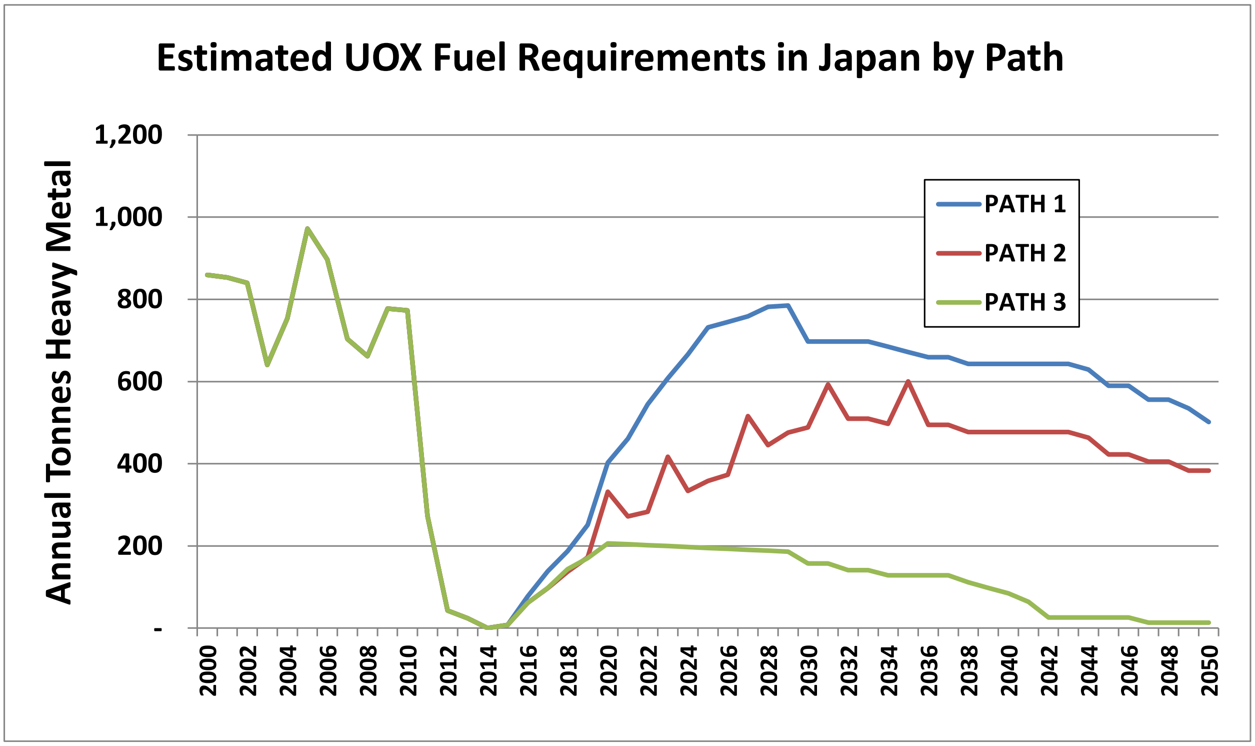



Table 4-3 list the estimated annual requirements for UOx fuel in the three paths in selected years and over the period 2015 through 2050, along with the solid and liquid wastes produced in fuel fabrication and the energy (fuel and electricity) needs for fuel fabrication.[43] All of these parameters are considerably higher, both in total and, especially, by year 2050, in Paths 1 and 2 than in Path 3, because of the more limited use and more rapid phase-out of nuclear power in Path 3.

[43] Per unit wastes production from and energy inputs during UOx fuel preparation were derived from the WISE Uranium Project's (2009), "Nuclear Fuel Material Balance Calculator", available as http://www.wise-uranium.org/nfcm.html. This calculator lists default estimates for the amount of solid and liquid waste per unit uranium metal handled in fuel fabrication plants.

***Table 4-3: Requirements, Inputs, and Waste Flows Associated with Fabrication of Uranium Oxide (UOx) Fuel in Each Restart Path, 2010 through 2050***

| Parameter | YEAR | Path 1 | Path 2 | Path 3 |
|---|---|---|---|---|
| Implied Total Requirements for UOx Fuel (excluding MOx) from All Sources (Metric tonnes heavy metal in fabricated fuel) | 2010 | 773 | 773 | 773 |
| | 2030 | 697 | 489 | 158 |
| | 2050 | 502 | 384 | 14 |
| | Cumulative, 2015-2050 | 20,428 | 14,222 | 4,101 |
| Annual Solid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated, All Sources (metric tons) | 2010 | 386 | 386 | 386 |
| | 2030 | 349 | 244 | 79 |
| | 2050 | 251 | 192 | 7 |
| | Cumulative, 2015-2050 | 10,214 | 7,111 | 2,051 |
| Annual Liquid Waste Produced in Fabricating UOx Fuel for Fuel Enriched and Fabricated, All Sources (cubic meters) | 2010 | 6,956 | 6,956 | 6,956 |
| | 2030 | 6,277 | 4,397 | 1,419 |
| | 2050 | 4,514 | 3,452 | 124 |
| | Cumulative, 2015-2050 | 183,850 | 128,000 | 36,911 |
| Annual Fossil Fuel Use in Fabricating UOx Fuel, All Sources (TJ) | 2010 | 2,094 | 2,094 | 2,094 |
| | 2030 | 1,889 | 1,323 | 427 |
| | 2050 | 1,359 | 1,039 | 37 |
| | Cumulative, 2015-2050 | 55,339 | 38,528 | 11,110 |
| Annual Electricity Used in Fabricating UOx Fuel for Fuel Enriched and Fabricated, All Sources (GWh) | 2010 | 233 | 233 | 233 |
| | 2030 | 210 | 147 | 47 |
| | 2050 | 151 | 115 | 4 |
| | Cumulative, 2015-2050 | 6,147 | 4,279 | 1,234 |

## 4.2 MOx Fuel Requirements and Use

Mixed-oxide fuel is assumed to be used in all three restart paths, but in different quantities. Table 4-4 provides the requirements for MOx fuel in the three paths in 2010, 2030, and 2050, as well as over the period 2015-2050, and also provides estimates of the use of plutonium for MOx fuel, of the wastes produced during MOx fuel preparation,[44] and the energy requirements for MOx fuel preparation.

[44] Lacking specific information on the per unit wastes production from and energy inputs during MOx fuel preparation, estimates for UOx fuel preparation were used, and derived from the WISE Uranium Project's (2009), "Nuclear Fuel Material Balance Calculator", available as http://www.wise-uranium.org/nfcm.html. This calculator lists default estimates for the amount of solid and liquid waste per unit uranium metal handled in fuel fabrication plants.

*Table 4-4: Requirements, Inputs, and Waste Flows Associated with Fabrication of Mixed Oxide (MOx) Fuel in Each Restart Path, 2010 through 2050*

| Parameter | YEAR | Path 1 | Path 2 | Path 3 |
|---|---|---|---|---|
| Implied Requirements for MOx Fuel Blended and Fabricated from All Sources for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel) | 2010 | 4.7 | 4.7 | 4.7 |
| | 2030 | 123.1 | 66.6 | 27.8 |
| | 2050 | 88.5 | 52.3 | 2.4 |
| | Cumulative, 2015-2050 | 3,079 | 1,698 | 506 |
| 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 | 0.4 | 0.4 | 0.4 |
| | 2030 | 11.7 | 6.3 | 2.6 |
| | 2050 | 8.4 | 5.0 | 0.2 |
| | Cumulative, 2015-2050 | 292 | 161 | 48 |
| Annual Solid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated, All Sources (metric tons) | 2010 | 2.3 | 2.3 | 2.3 |
| | 2030 | 61.5 | 33.3 | 13.9 |
| | 2050 | 44.3 | 26.2 | 1.2 |
| | Cumulative, 2015-2050 | 1,539 | 849 | 253 |
| Annual Liquid Waste Produced in Fabricating MOx Fuel for Fuel Blended and Fabricated, All Sources (cubic meters) | 2010 | 42 | 42 | 42 |
| | 2030 | 1,108 | 600 | 250 |
| | 2050 | 797 | 471 | 22 |
| | Cumulative, 2015-2050 | 27,707 | 15,278 | 4,556 |
| Annual Fossil Fuel Use in Fabricating MOx Fuel, All Sources (TJ) | 2010 | 13 | 13 | 13 |
| | 2030 | 333 | 180 | 75 |
| | 2050 | 240 | 142 | 7 |
| | Cumulative, 2015-2050 | 8,340 | 4,599 | 1,371 |
| Annual Electricity Used in Fabricating MOx Fuel from All Sources (GWh) | 2010 | 1.4 | 1.4 | 1.4 |
| | 2030 | 37.0 | 20.0 | 8.4 |
| | 2050 | 26.6 | 15.7 | 0.7 |
| | Cumulative, 2015-2050 | 926 | 511 | 152 |

MOx fuel requirements by path over the modeling period are shown in Figure 4-2. Once again, the “spikes” in the curve for Path 2 correspond to the production of MOx fuels for new reactor cores as the new units come on line. Annual MOx fuel requirements peak at about 120 tHM for Path 1, 100 tHM for Path 2, and 30 tHM for Path 3.

*Figure 4-2: MOx Requirements by Path*

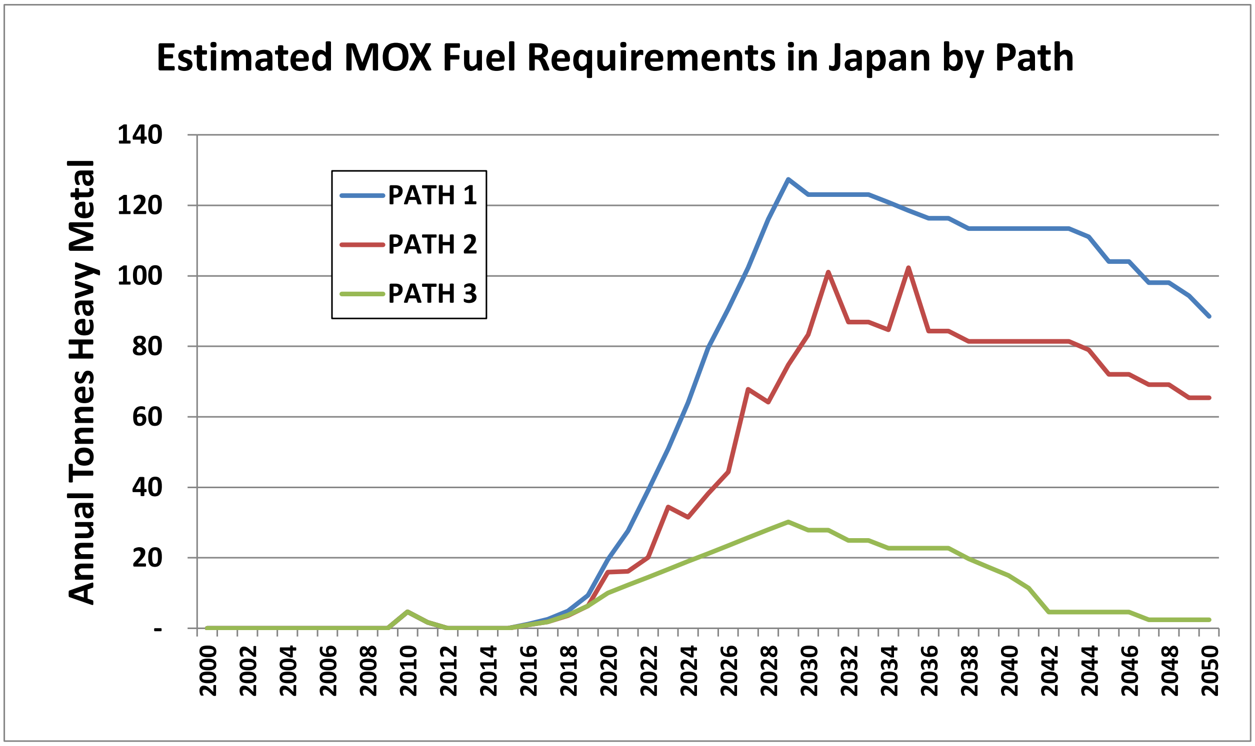



Figure 4-3 shows the cumulative use of plutonium to produce MOx fuel for commercial reactors in Japan over the period 2000 through 2050.[45] In Path 3, total Pu use is about 50 tonnes, which is approximately the amount of Pu Japan has in storage at present (2015—some in Japan, most in Europe) from spent fuel reprocessed domestically and in France and the United Kingdom (UK).

[45] This figure does not include the approximately 5 tonnes of Pu used in the Fugen, Toyo, Monju, and DCA (Deuterium Critical Assembly) test reactors in Japan before 2004. See, for example, Tadahiro Katsuta and Tatsujiro Suzuki (2007), "Japan's Spent Fuel and Plutonium Management Challenges", prepared for the Carnegie Non-proliferation Conference, 2007, and available as http://carnegieendowment.org/files/SuzukiReprocessPanelCarnegie26June07.pdf.

*Figure 4-3: Plutonium Use in MOx Fuel*

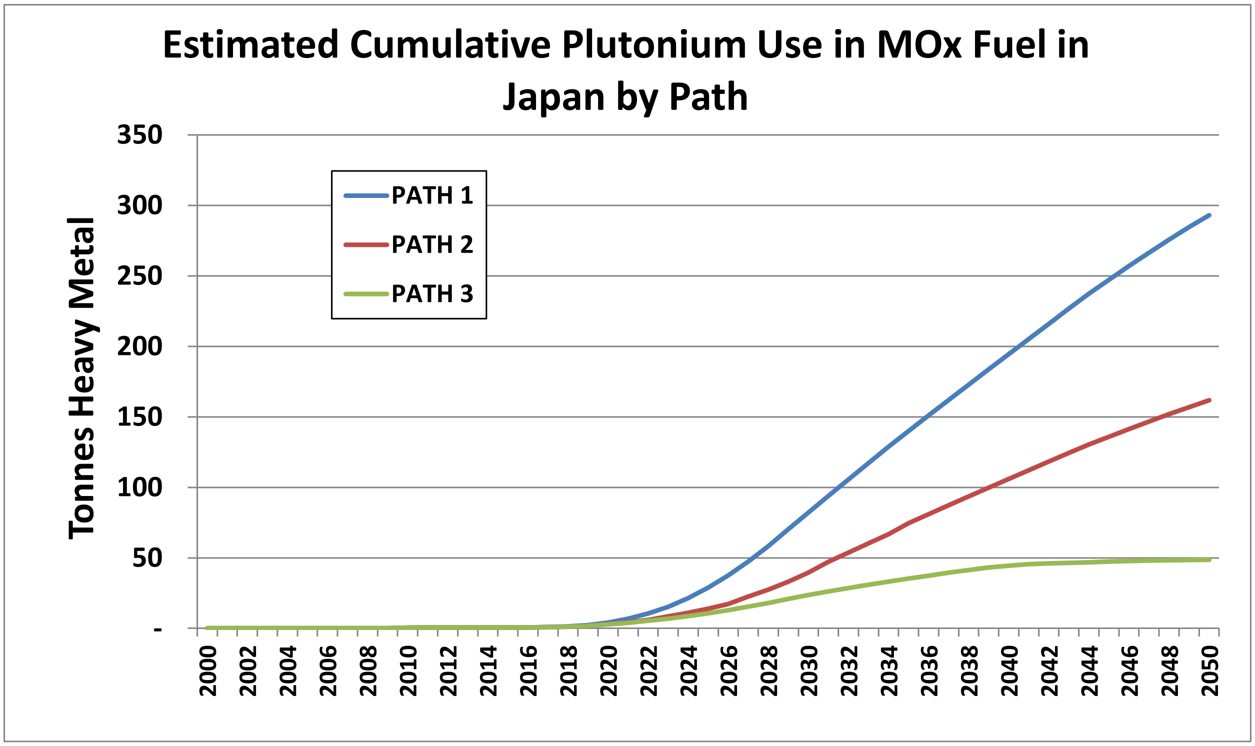


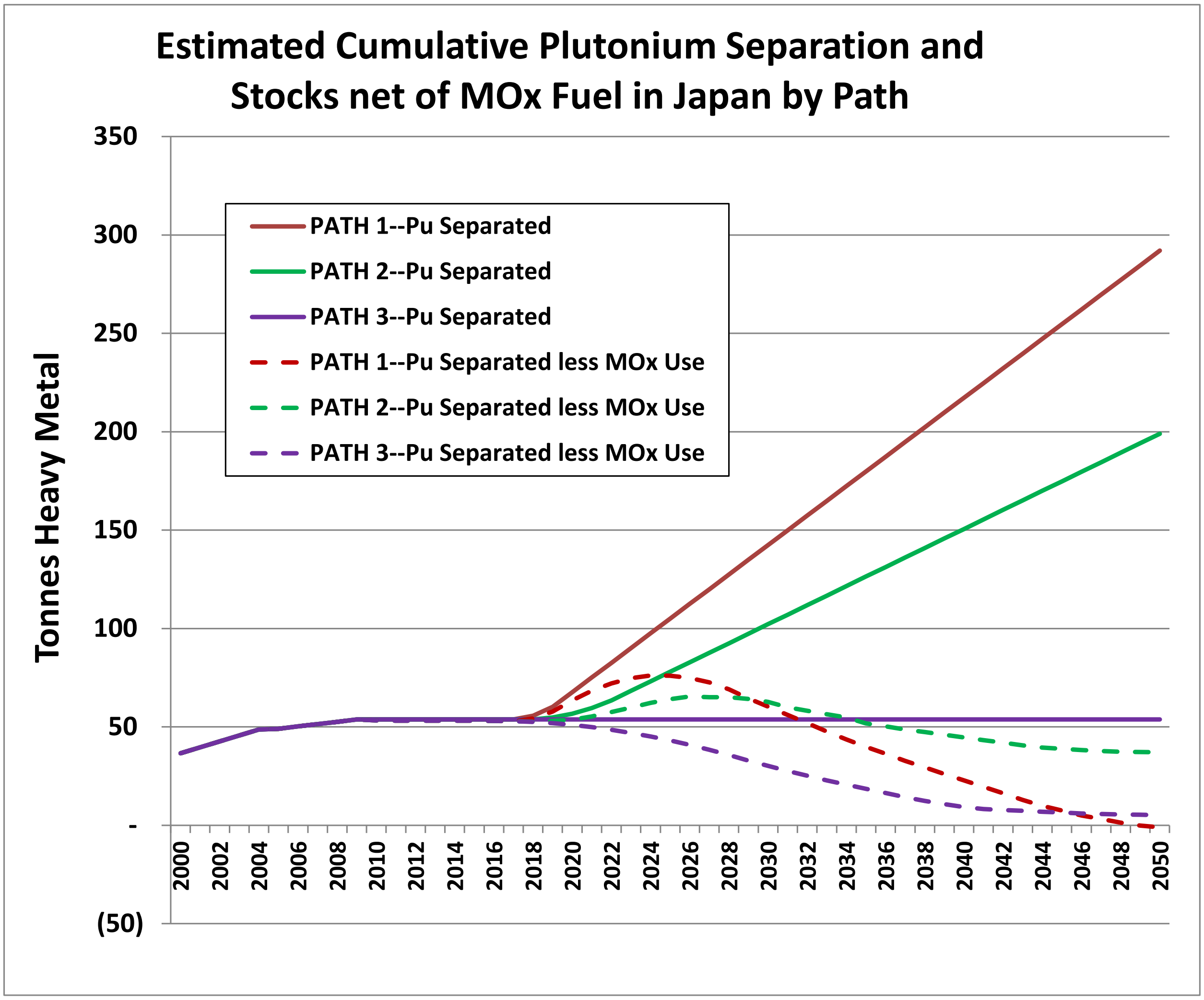

Figure 4-4 combines consideration of Pu separation from spent fuel via reprocessing, including spent fuel reprocessed domestically and internationally before 2000, with the net of plutonium produced and used in LWRs as MOx fuel. In this figure, the solid lines show a cumulative 300 tonnes of Pu separation in Path 1 by 2050, versus 200 tonnes of Pu in Path 2 and just over 50 tonnes in Path 3. Net of MOx fuel use (the dashed lines in Figure 4-4), Path 1 as modeled actually results in slightly negative Pu inventories (that is, slightly more Pu is used as MOx than the sum of existing inventories and annual production) as of 2050, and Path 3 results in the use of nearly all of Japan's domestic and foreign Pu inventory as of 2050. In Path 2, more Pu is used during 2000 through 2050 than is separated via reprocessing, but about 37 tonnes of Pu inventory remain as of 2050.

Note that the depletion of plutonium inventories shown under any of these paths would be a departure from historical experience, and thus could be viewed as optimistic. For example, the International Panel on Fissile Materials, in reviewing France's Pu stockpile over 1995 through 2013, notes "France's own stock-pile of unirradiated plutonium has increased steadily despite an apparently successful MOX program".[46] Put another way, in order for the Pu stockpile draw-downs shown in Figure 4-4 to occur, much has to go smoothly in the Japanese nuclear sector—reprocessing plants and MOx fabrication facilities must run at expected capacity levels, capacity factors for nuclear electricity generation facilities using MOx fuel must be as anticipated, and no significant issues—technical, social, economic, or political, for example—must arise in the

[46] International Panel on Fissile Materials (2015), *Plutonium Separation in Nuclear Power Programs: Status, Problems, and Prospects of Civilian Reprocessing Around the World*, available as http://fissilematerials.org/library/rr14.pdf. See Figure 3.3.

handling of large quantities of MOx fuel that flow through these Paths, and particularly Paths 1 and 2. This sequence of postulated outcomes may thus reasonably be viewed as hypothetical and arguably implausible.

***Figure 4-4: Cumulative Plutonium Separation and Stocks***




## 4.3 Spent Fuel Flows, Reprocessing, and Spent Fuel Storage

The three different restart paths each entail quantitatively and, in Path 3, qualitatively different handling of cooled spent fuel. Paths 1 and 2 differ by the amount of spent fuel reprocessing, as well as by the amount of spent fuel created, since in Path 1 Japan uses nuclear power more heavily than in Path 2. All three paths assume the movement of spent fuel to the Mutsu away-from-reactor intermediate storage facility starting when the first, 3000 tHM capacity phase of Mutsu opens, reportedly in 2016, and when its second, 2000 tHM capacity, phase opens, reportedly planned for 2028. Path 3 also includes the transfer of additional cooled spent fuel from dense-packed spent fuel pools to dry cask storage, assumedly at reactor sites (though development of additional away-from-reactor sites is possible), in order to convert operating spent fuel pools to non-dense-packed configurations, and the transfer of spent fuel from decommissioned reactors to dry cask storage as well. In all three cases, spent fuel from pools at decommissioned reactors is transferred to other storage within 8 years after the reactor is decommissioned.

Figure 4-5, Figure 4-6, and Figure 4-7, respectively, show the production and disposition of spent fuel in each of the three Restart paths. In Path 1, cumulative spent fuel production rises from about 18,600 tHM in 2015—the sum of spent fuel production dating back to the beginning of Japan's commercial nuclear power program—to nearly 40,000 tHM by 2050. About 30,000 tHM of spent fuel is reprocessed by 2050 (including over 8000 tHM reprocessed by 2015, mostly overseas), with the remaining 10,000 tHM housed in existing spent fuel pools and in the Mutsu dry-cask storage facility in roughly equal portions. About 2300 tHM of the 10,000 tHM spent fuel in dry cask storage and spent fuel pools is MOx spent fuel, with more of the MOx spent fuel in pools than in casks (because MOx spent fuel has been cooling for less time, on average). Remaining spent fuel storage capacity in dense-packed spent fuel pools in both Paths 1 and 2 is about 17,000 tHM in 2050. In Path 2, cumulative spent fuel production rises to about 34,000 tHM and cumulative reprocessing rises to 22,000 tHM by 2050. Somewhat under 7000 tHM of spent fuel remains in spent fuel pools as of 2050. The cumulative production of MOx spent fuel in Path 2 from 2015 through 2050 is about 1250 tHM, most of which would be in the spent fuel pools (as opposed to in dry cask storage).[47]

[47] For this analysis, we assume an average of 10 tHM of spent fuel is loaded in each cask, whether the fuel is UOx or MOx fuel. In practice, casks loaded with MOx fuel may need to be more lightly loaded, depending on how long the fuel has cooled, due to the different radiological properties of spent MOx fuel.

*Figure 4-5: Spent Fuel Production and Disposition, Restart Path 1*

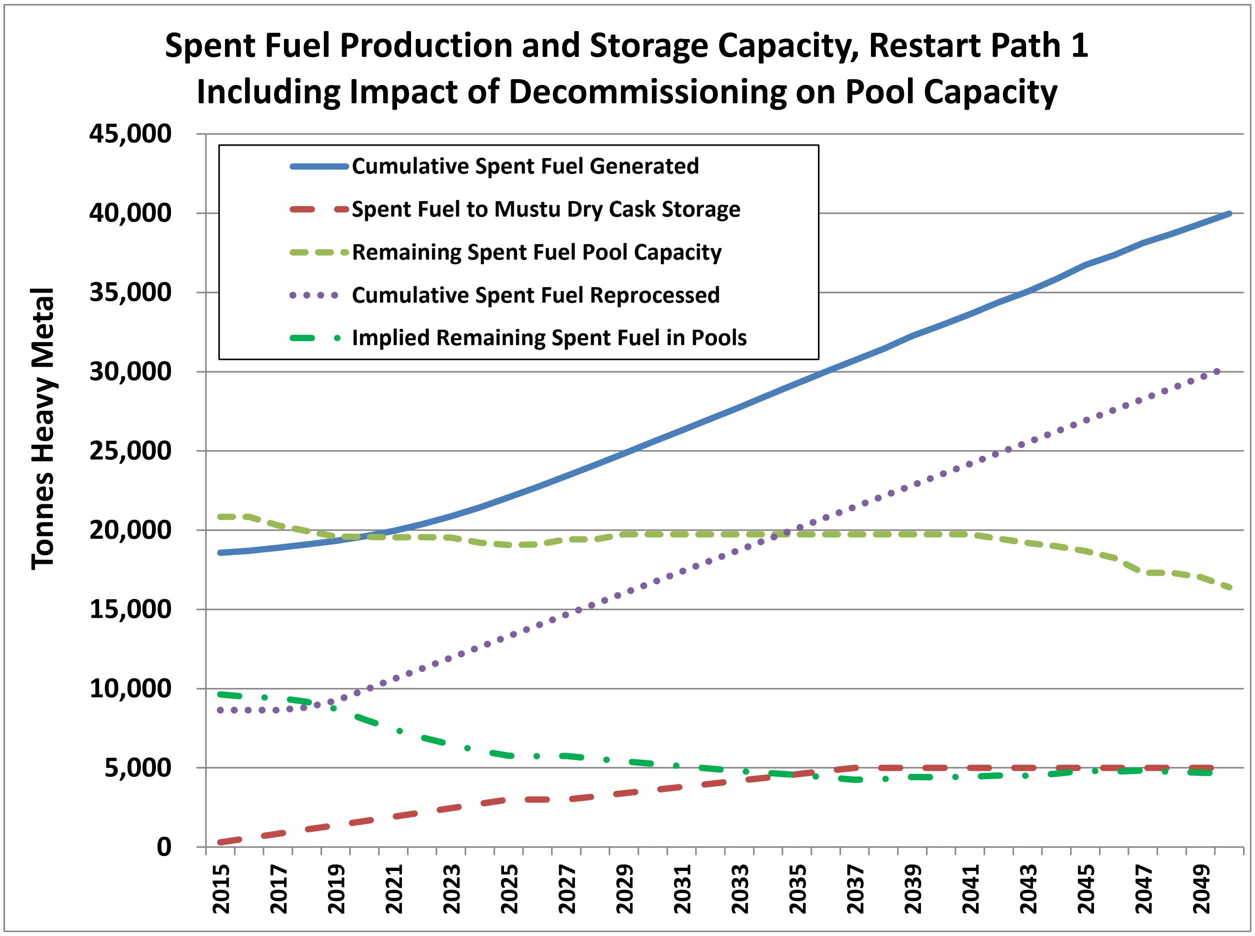
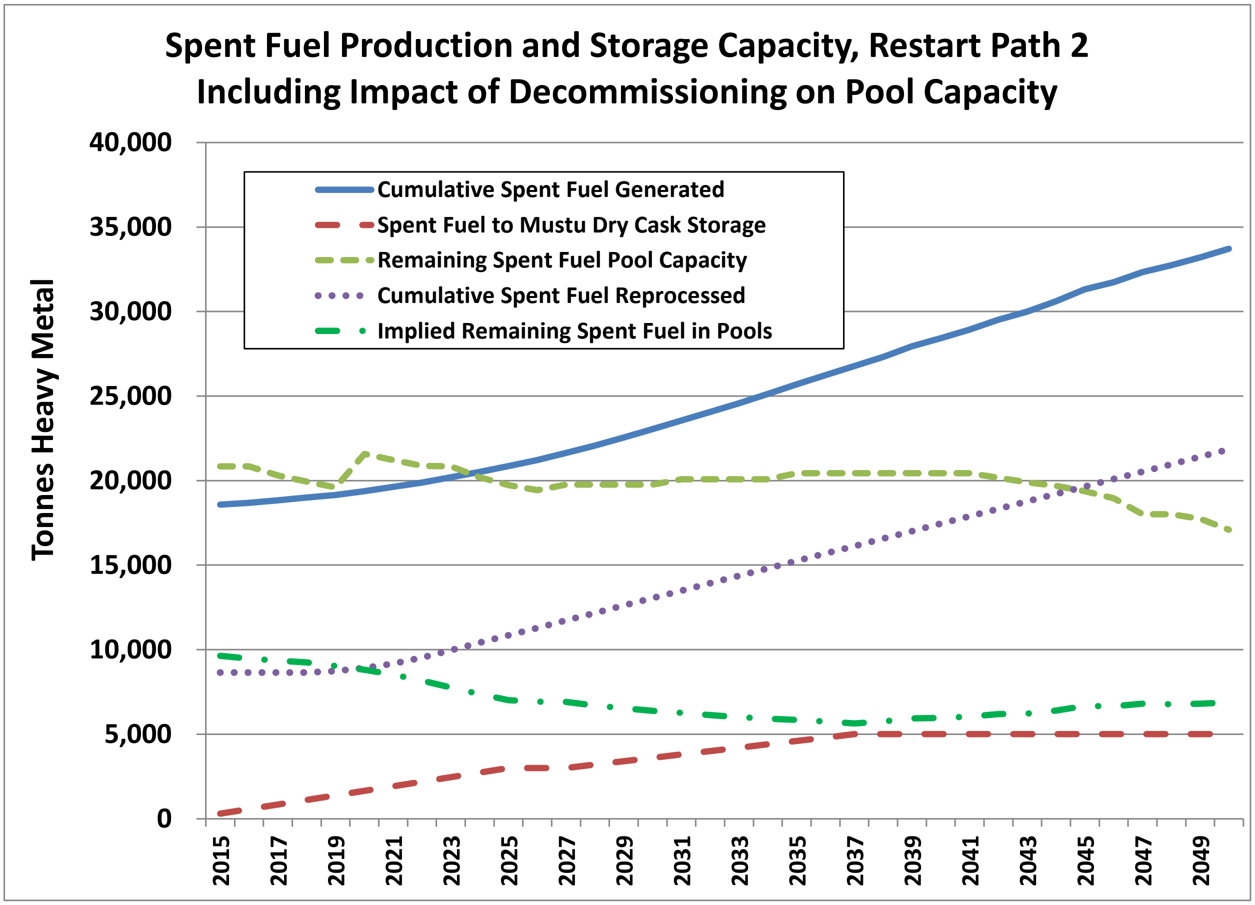


*Figure 4-6: Spent Fuel Production and Disposition, Restart Path 2*




In Path 3, the program of converting dense-packed spent fuel pools, coupled with the decommissioning of older reactors, rapidly drops spent fuel capacity (the orange line in Figure 4-7) from nearly 21,000 tHM in 2015 to just over 8000 tHM by 2022. By 2050, over 13,000 tHM of spent fuel has been placed in dry cask storage, including at the Mutsu facility. Less than 1600 tHM of spent fuel remains in non-dense-packed spent fuel pools by 2050, and the capacity of those pools is only slightly higher—that is, the few spent fuel pools remaining are mostly full (though at the non-dense-packed level) by 2050. Since no reprocessing is included from 2015 on in Path 3, the cumulative total spent fuel pool reprocessed remains at pre-2015 levels through 2050. About 500 tHM of the total spent fuel produced during 2015 through 2050 in Path 3 is MOx spent MOx fuel, most of which would likely be in the spent fuel pools as of 2050.

*Figure 4-7: Spent Fuel Production and Disposition, Restart Path 3*

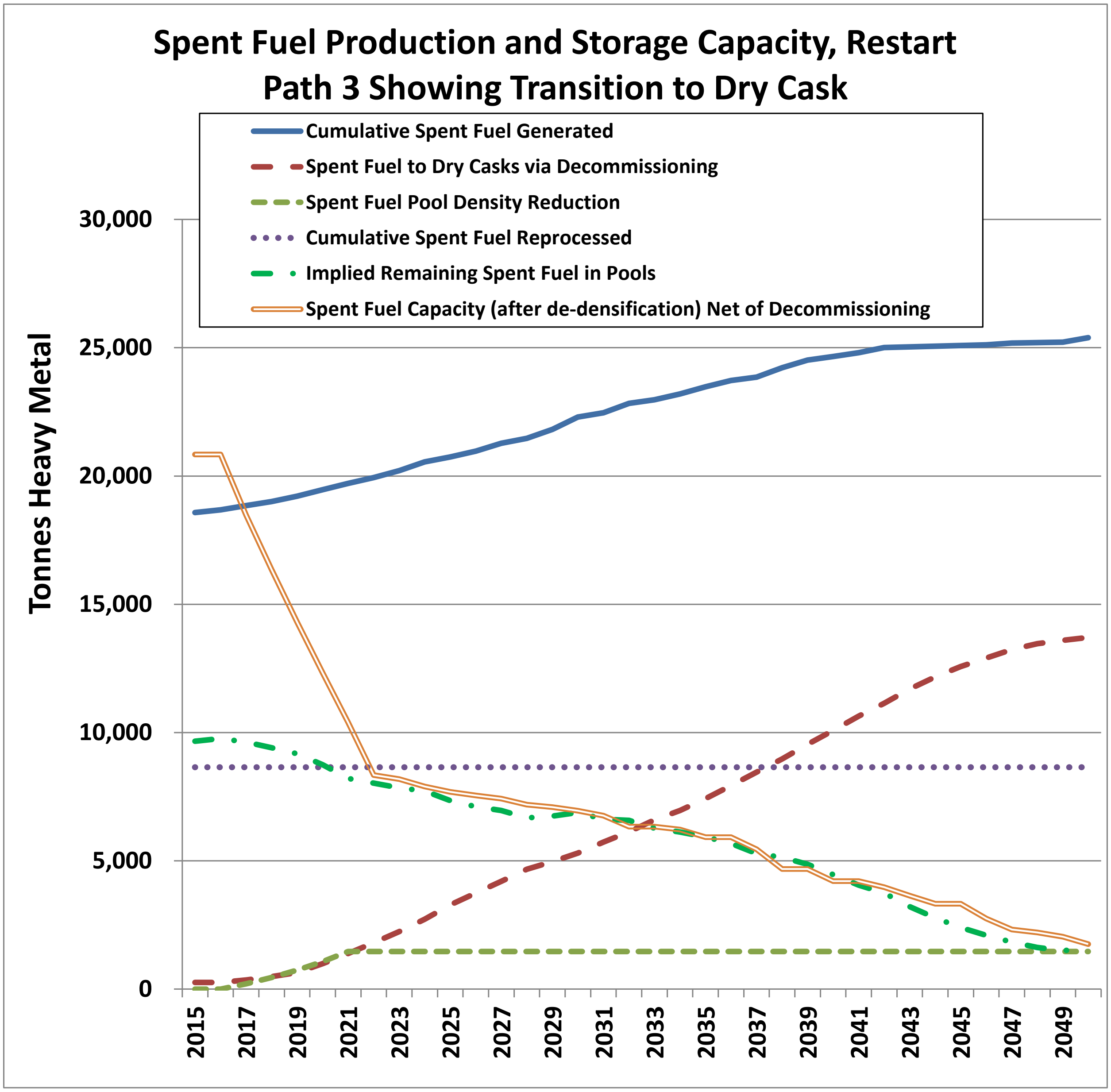



Table 4-5 presents spent fuel production and reprocessing data for selected years and on a cumulative basis for the three Restart Paths. Path 1 results in about 17,000 tHM of cooled spent fuel production by 2050, Path 2 about 13,000 tHM, and Path 3 results about 9000 tHM. Of the total spent fuel cooled, about 14 percent is MOx spent fuel in Path 1, versus 10 percent in Path 2 and 5 percent in Path 3. About 22,000 tHM of spent fuel is reprocessed from 2015 through 2050 in Path 1, versus about 13,000 tHM in Path 2, and none in Path 3. Transporting cooled spent fuel from reactors to Rokkasho will require about 5 ocean voyages per year in Path 1, versus about 3 per year in Path 2 (and none in Path 3).

*Table 4-5: Spent Fuel Flows, Reprocessing, and Spent Fuel Transport for Reprocessing by Restart Path*

| Parameter | YEAR | Path 1 | Path 2 | Path 3 |
|---|---|---|---|---|
| Annual New Spent LWR Fuel Cooled and Available for Reprocessing, Storage, or Disposal (excluding MOx spent fuel), Metric Tonnes Heavy Metal | 2010 | 697 | 697 | 697 |
| | 2030 | 382 | 249 | 215 |
| | 2050 | 651 | 514 | 191 |
| | Cumulative, 2015-2050 | 16,767 | 12,921 | 9,175 |
| Annual Spent MOx Fuel Cooled and Available for Storage or Disposal, Metric Tonnes Heavy Metal | 2010 | - | - | - |
| | 2030 | 39 | 17 | 14 |
| | 2050 | 113 | 65 | 5 |
| | Cumulative, 2015-2050 | 2,273 | 1,245 | 484 |
| Implied Amount of Spent LWR Fuel (UOx only) Reprocessed in Total for Use in Domestic Reactors (Metric tonnes heavy metal) | 2010 | - | - | - |
| | 2030 | 680 | 440 | - |
| | 2050 | 680 | 440 | - |
| | Cumulative, 2015-2050 | 21,658 | 13,200 | - |
| Implied Number of Ocean Voyages Annually for Transport of Cooled Spent LWR Fuel (UOx only) to All Reprocessing Centers | 2010 | - | - | - |
| | 2030 | 5 | 3 | - |
| | 2050 | 5 | 3 | - |
| | Cumulative, 2015-2050 | 161 | 98 | - |

Table 4-6 presents estimates of the reprocessing wastes of various types produced in selected years and cumulatively from 2015 through 2050, along with electricity inputs to high-level wastes (HLW) stabilization in glass (vitrification) and uranium outputs from reprocessing. Also presented are the amounts of reprocessed uranium ("RepU") produced during reprocessing to separate plutonium from spent fuel. Although RepU can be used in the formulation of UOx and MOx fuel, its characteristics—it is slightly enriched in $U_{235}$ and significantly enriched in $U_{232}$ and $U_{236}$ relative to natural uranium, as well as being significantly more radioactive—mean that RepU requires additional technical arrangements (and likely expense) in handling and processing relative to natural uranium.[48] About 20,000 and 12,000 tonnes of RepU are produced in Paths 1 and 2, respectively. The volumes of high-level (HLW), medium-level, and low-level wastes produced from reprocessing operations are not particularly significant relative to, for example, the volumes of coal ash and municipal solid wastes routinely generated, but reprocessing wastes will require special storage or disposal arrangements, particularly for HLW. Path 1 produces over 60 percent more, on a cumulative basis, than does Path 2; Path 3, which lacks reprocessing, does not produce these wastes. The electricity used in "vitrifying" high level wastes, even in Path 1, is not particularly significant on an annual basis, amounting to about 0.3 average megawatts in 2030 and 2050.

238 and 145 tonnes of plutonium are produced by reprocessing operations at Rokkasho from 2015 through 2050 in Paths1 and 2, respectively. Paths 1 and 3 result in near-zero year-2050

[48] See, for example, several of the papers in IAEA (2007), *Use of Reprocessed Uranium: Proceedings of a Technical Committee Meeting Held in Vienna, August 2007*, Report number IAEA-TECDOC-CD-1630, available as http://www-pub.iaea.org/MTCD/publications/PDF/TE_1630_CD/PDF/IAEA-TECDOC-1630.pdf.

plutonium inventories for Japan—that is, about 50 tonnes Pu are used net of Pu produced, or about as much Pu as Japan's estimated inventory of Pu in Japan and in Europe , while in Path 2 a net of 16 tonnes of Japan's 2015 stock of Pu are used for MOx fuel after the Pu produced from reprocessing in 2015 through 2050 is used, meaning that Japan's existing stocks of plutonium are drawn down in Path 2, but not fully depleted by 2050.

The number of casks required for cooled spent fuel not otherwise disposed of, including dry casks stored at the Mutsu facility, is highest by a factor of more than two in Path 3, with a cumulative 1600 casks required through 2050. Assuming an average cask diameter of 2.4 meters,[49] and about a one-cask-diameter spacing between casks placed vertically on a concrete pad, 1600 casks would require less than 4 hectares (less than 40,000 square meters) of storage space, which is modest compared with the several hundred hectares typically used for a nuclear power plant.

[49] See, for example, the 2010 TEPCO table "Specification of Dry Casks", available as https://sanonofresafety.files.wordpress.com/2013/06/fukushimacaskspecifications2010.jpg.

***Table 4-6: Reprocessing Wastes/Outputs and Waste Handling Inputs and Outputs by Restart Path***

| Parameter | YEAR | Path 1 | Path 2 | Path 3 |
|---|---|---|---|---|
| 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 | - | - | - |
| | 2030 | 78.20 | 50.60 | - |
| | 2050 | 78.20 | 50.60 | - |
| | Cumulative, 2015-2050 | 2,490.67 | 1,518.00 | - |
| 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 | - | - | - |
| | 2030 | 2.35 | 1.52 | - |
| | 2050 | 2.35 | 1.52 | - |
| | Cumulative, 2015-2050 | 74.72 | 45.54 | - |
| Implied Volume of Medium-level Waste from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters) | 2010 | - | - | - |
| | 2030 | 136 | 88 | - |
| | 2050 | 136 | 88 | - |
| | Cumulative, 2015-2050 | 4,332 | 2,640 | - |
| Implied Volume of Low-level Waste from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters) | 2010 | - | - | - |
| | 2030 | 952 | 616 | - |
| | 2050 | 952 | 616 | - |
| | Cumulative, 2015-2050 | 30,321 | 18,480 | - |
| Implied Volume of Solid Waste from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters) | 2010 | - | - | - |
| | 2030 | 102 | 66 | - |
| | 2050 | 102 | 66 | - |
| | Cumulative, 2015-2050 | 3,249 | 1,980 | - |
| Total Annual Implied Mass of Uranium Separated during All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Domestic Reactors (metric tonnes) | 2010 | - | - | - |
| | 2030 | 639 | 414 | - |
| | 2050 | 639 | 414 | - |
| | Cumulative, 2015-2050 | 20,359 | 12,408 | - |
| 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 | (0.44) | (0.44) | (0.44) |
| | 2030 | (4.21) | (1.49) | (2.64) |
| | 2050 | (0.93) | (0.13) | (0.23) |
| | Cumulative, 2015-2050 | (54.23) | (16.07) | (48.09) |
| Implied Mass of Plutonium Separated from All Cooled Spent LWR Fuel (UOx only) Reprocessed (metric tonnes heavy metal) | 2010 | - | - | - |
| | 2030 | 7.48 | 4.84 | - |
| | 2050 | 7.48 | 4.84 | - |
| | Cumulative, 2015-2050 | 238.24 | 145.20 | - |
| Total Annual Number of Casks Required for Cooled Spent LWR Fuel, UOx and MOx, for Domestic Reactors (units) | 2010 | - | - | - |
| | 2030 | 24 | 22 | 35 |
| | 2050 | 11 | 7 | 12 |
| | Cumulative, 2015-2050 | 727 | 625 | 1,566 |

## 4.4 Nuclear Sector Costs

Although the costs of uranium purchased by Japan to fuel its reactors, at $4 to $20 billion (0.6 to 2.7 trillion Yen) in the three paths over 2015 to 2050, sound substantial, they are only a fraction of a percent of the total electricity generation costs implied for each path over the same period, as shown in Table 4-7. Given recent trends in uranium prices, we use a “low” price growth trajectory that assumes an average 0.5 percent annual growth in real prices from 2015 through 2050.

***Table 4-7: Costs Associated with Mining and Milling of Uranium in Each Restart Path, 2010 through 2050***

| | (Million 2009 dollars) | | | | Billion 2015 Yen | | | |
|---|---|---|---|---|---|---|---|---|
| **Cost** | YEAR | Path 1 | Path 2 | Path 3 | Path 1 | Path 2 | Path 3 | |
| Annual Total Cost of Uranium Produced Domestically or Imported for Use in Reactors in Japan | 2010 | $ 848 | $ 848 | $ 848 | 2010 | ¥113 | ¥113 | ¥113 |
| | 2030 | $ 708 | $ 496 | $ 160 | 2030 | ¥94 | ¥66 | ¥21 |
| | 2050 | $ 471 | $ 360 | $ 13 | 2050 | ¥63 | ¥48 | ¥2 |
| | Cumulative, 2015-2050 | $ 20,411 | $ 14,177 | $ 4,192 | Cumulative, 2015-2050 | ¥2,719 | ¥1,888 | ¥558 |

The costs associated with uranium enrichment in each Path (Table 4-8) are dominated by the costs of enrichment services, with conversion of UOx to $UF_6$ a smaller portion of the total and the costs of $U_3O_8$ transport, which can be done in drums as regular bulk cargo, essentially negligible, even though Japan imports uranium from far-flung locations.[50] Under base-case assumptions for the costs of enrichment services, using approximate 2015 costs of $72/kg SWU (separation work unit), with a real escalation rate of one percent annually, the total undiscounted cost (2009 USD) of enrichment, including $UF_6$ conversion and transport, is about $3.3 (Path 3) to $16 billion (Path 1), or from 0.44 to 2.1 trillion (2015) Yen. Again, as with uranium costs, these are large absolute costs, but are spread over 3.5 decades and an entire nation, and thus represent, for each path, just a fraction of one percent of overall power sector costs during the same period. All post-restart enrichment services used in Japan in all paths are assumed to be provided by in-country enrichment plants.

[50] Japan sources its uranium from a number of different countries, most notably Australia, Kazakhstan, and Canada. We assume most of this uranium is carried by ship, and an average shipping distance is 8000 km. For information on U origins for Japan, see, for example, World Nuclear Organization (2017), "Japan's Nuclear Fuel Cycle", dated November, 2017, and available as http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/japan-nuclear-fuel-cycle.aspx.

***Table 4-8: Costs Associated with Enrichment of Uranium in Each Restart Path, 2010 through 2050***

| | | Cost in Million 2009 USD | | | Cost in Billion 2015 Yen | | |
|---|---|---|---|---|---|---|---|
| **Cost** | YEAR | Path 1 | Path 2 | Path 3 | Path 1 | Path 2 | Path 3 |
| Implied Cost of U3O8 Transport to In-country and Out-of-country Enrichment for Use in Domestic Reactors | 2010 | $ 0.88 | $ 0.88 | $ 0.88 | ¥0.12 | ¥0.12 | ¥0.12 |
| | 2030 | $ 0.65 | $ 0.46 | $ 0.15 | ¥0.09 | ¥0.06 | ¥0.02 |
| | 2050 | $ 0.47 | $ 0.36 | $ 0.01 | ¥0.06 | ¥0.05 | ¥0.00 |
| | Cumulative, 2015-2050 | $ 19.16 | $ 13.34 | $ 3.85 | ¥2.55 | ¥1.78 | ¥0.51 |
| Annual Total Cost of Conversion of U3O8 to UF6 for Uranium Enriched In-country or Out-of-country | 2010 | $ 100 | $ 100 | $ 100 | ¥13.3 | ¥13.3 | ¥13.3 |
| | 2030 | $ 90 | $ 63 | $ 20 | ¥12.0 | ¥8.4 | ¥2.7 |
| | 2050 | $ 65 | $ 50 | $ 2 | ¥8.6 | ¥6.6 | ¥0.2 |
| | Cumulative, 2015-2050 | $ 2,637 | $ 1,836 | $ 529 | ¥351.2 | ¥244.5 | ¥70.5 |
| Annual Total Cost of Uranium Enrichment Services In-country or Imported for Fuel Used in Domestic Reactors | 2010 | $ 820 | $ 820 | $ 820 | ¥109.2 | ¥109.2 | ¥109.2 |
| | 2030 | $ 549 | $ 385 | $ 124 | ¥73.2 | ¥51.3 | ¥16.5 |
| | 2050 | $ 364 | $ 279 | $ 10 | ¥48.5 | ¥37.1 | ¥1.3 |
| | Cumulative, 2015-2050 | $ 15,827 | $ 10,992 | $ 3,254 | ¥2,108.1 | ¥1,464.1 | ¥433.5 |

Table 4-9 presents the costs associated with fuel fabrication and transport by Restart Path in selected years and on a cumulative basis. Although fuel transport is complex and requires special-made and expensive vessels, trucks, casks and other equipment, the small volumes and limited number of shipments means that total costs are modest relative to other nuclear fuel cycle costs. Fuel fabrication costs are more significant, totaling hundreds of millions of dollars, or tens of billions of Yen, per year. Fuel fabrication costs in Path 1 are about 60 percent higher than in Path 2, and more than five times that in Path 3, because of greater use of nuclear power in Paths 1 and 2.[51]

[51] We assumed fuel fabrication costs of $272 per kg HM (2009 USD) for UOx fuel, based on data in World Nuclear Association (2010) "The Economics of Nuclear Power", available as http://www.world-nuclear.org/info/inf02.html.The quoted cost of $240 per kg UO2 fuel as of January 2010 was converted to a $ per kg heavy metal (U) basis. For fabrication of MOx fuel, we assumed a cost of $1800 per kgHM (again, 2009 USD) based on a value (in 2002 dollars) in *The Future of Nuclear Power, An Interdisciplinary MIT Study* (2003) compiled by a team of researchers mostly from the Massachusetts Institute of Technology (MIT), Cambridge, MA USA, and available as http://web.mit.edu/nuclearpower/pdf/nuclearpower-full.pdf.

***Table 4-9: Costs Associated with UOx and MOx Fuel Fabrication in Each Restart Path, 2010 through 2050***

| | | Cost in Million 2009 USD | | | Cost in Billion 2015 Yen | | |
|---|---|---|---|---|---|---|---|
| **Cost Element** | YEAR | Path 1 | Path 2 | Path 3 | Path 1 | Path 2 | Path 3 |
| Implied Transport Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated for Use in Domestic Reactors, All Sources | 2010 | $ 58.06 | $ 58.06 | $ 58.06 | ¥7.73 | ¥7.73 | ¥7.73 |
| | 2030 | $ 2.40 | $ 1.68 | $ 0.54 | ¥0.32 | ¥0.22 | ¥0.07 |
| | 2050 | $ 1.73 | $ 1.32 | $ 0.05 | ¥0.23 | ¥0.18 | ¥0.01 |
| | Cumulative, 2015-2050 | $ 70.28 | $ 48.93 | $ 14.11 | ¥9.36 | ¥6.52 | ¥1.88 |
| Implied Transport Costs for MOx Fuel for Fuel Enriched and Fabricated for Use in Domestic Reactors, All Sources | 2010 | $ 0.53 | $ 0.53 | $ 0.53 | ¥0.1 | ¥0.1 | ¥0.1 |
| | 2030 | $ 0.64 | $ 0.34 | $ 0.14 | ¥0.1 | ¥0.0 | ¥0.0 |
| | 2050 | $ 0.46 | $ 0.27 | $ 0.01 | ¥0.1 | ¥0.0 | ¥0.0 |
| | Cumulative, 2015-2050 | $ 15.89 | $ 8.76 | $ 2.61 | ¥2.1 | ¥1.2 | ¥0.3 |
| Implied Fuel Fabrication Costs for UOx Fuel (excluding MOx) for Fuel Enriched and Fabricated, All Sources, for Use in Domestic Reactors | 2010 | $ 210.45 | $ 210.45 | $ 210.45 | ¥28.0 | ¥28.0 | ¥28.0 |
| | 2030 | $ 189.89 | $ 133.01 | $ 42.93 | ¥25.3 | ¥17.7 | ¥5.7 |
| | 2050 | $ 136.56 | $ 104.43 | $ 3.74 | ¥18.2 | ¥13.9 | ¥0.5 |
| | Cumulative, 2015-2050 | $ 5,562 | $ 3,872 | $ 1,117 | ¥740.8 | ¥515.8 | ¥148.7 |
| Implied Fuel Fabrication Costs for MOx Fuel, All Sources, for Use in Domestic Reactors | 2010 | $ 8.40 | $ 8.40 | $ 8.40 | ¥1.1 | ¥1.1 | ¥1.1 |
| | 2030 | $ 221.54 | $ 119.91 | $ 50.09 | ¥29.5 | ¥16.0 | ¥6.7 |
| | 2050 | $ 159.32 | $ 94.15 | $ 4.36 | ¥21.2 | ¥12.5 | ¥0.6 |
| | Cumulative, 2015-2050 | $ 5,541 | $ 3,056 | $ 911 | ¥738.1 | ¥407.0 | ¥121.4 |

The costs associated with spent fuel reprocessing and related activities are presented in Table 4-10. Here the costs for reprocessing are dominant,[52] at 45 to 74 billion dollars (6 to 10 trillion yen) with costs for treatment and storage of HLW[53] and for storing/safeguarding Pu also significant, but roughly an order of magnitude less than reprocessing costs.

[52] Per-unit, all-inclusive costs of reprocessing in Japan were estimated by Tadahiro Katsuta in 2009 for the East Asia Science and Security (EASS) project at $3400 per kgU, based on projections of total Rokkasho costs and lifetime throughput.
[53] Costs listed as "disposal" costs for HLW in Table 4-10 represent costs for treatment and medium- or long-term storage of high-level wastes, not disposal in a final repository.

*Table 4-10: Costs Associated with Reprocessing of Spent Fuel in Each Restart Path, 2010 through 2050*

| | | Cost in Million 2009 USD | | | Cost in Billion 2015 Yen | | |
|---|---|---|---|---|---|---|---|
| **Cost Element** | YEAR | Path 1 | Path 2 | Path 3 | Path 1 | Path 2 | Path 3 |
| Implied Transport Costs for All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors | 2010 | $ - | $ - | $ - | ¥0.0 | ¥0.0 | ¥0.0 |
| | 2030 | $ 13.43 | $ 8.69 | $ - | ¥1.8 | ¥1.2 | ¥0.0 |
| | 2050 | $ 13.43 | $ 8.69 | $ - | ¥1.8 | ¥1.2 | ¥0.0 |
| | Cumulative, 2015-2050 | $ 427.75 | $ 260.70 | $ - | ¥57.0 | ¥34.7 | ¥0.0 |
| Implied Costs for All Reprocessing of Cooled Spent LWR Fuel (UOx only) for Use in Domestic Reactors | 2010 | $ - | $ - | $ - | ¥0 | ¥0 | ¥0 |
| | 2030 | $ 2,312 | $ 1,496 | $ - | ¥308 | ¥199 | ¥0 |
| | 2050 | $ 2,312 | $ 1,496 | $ - | ¥308 | ¥199 | ¥0 |
| | Cumulative, 2015-2050 | $ 73,637 | $ 44,880 | $ - | ¥9,808 | ¥5,978 | ¥0 |
| Total Annual Cost/Benefit of Storage/ safeguarding/ disposal of Plutonium from Reprocessing Operations (fraction not used as MOx) | 2010 | $ 159.96 | $ 159.96 | $ 159.96 | ¥21 | ¥21 | ¥21 |
| | 2030 | $ 180.83 | $ 188.19 | $ 90.65 | ¥24 | ¥25 | ¥12 |
| | 2050 | $ (3.19) | $ 111.29 | $ 15.22 | ¥0 | ¥15 | ¥2 |
| | Cumulative, 2015-2050 | $ 4,511 | $ 5,549 | $ 2,904 | ¥601 | ¥739 | ¥387 |
| Total Annual Cost of Disposal of High-level Wastes from Reprocessing Operations | 2010 | $ - | $ - | $ - | ¥0 | ¥0 | ¥0 |
| | 2030 | $ 102.00 | $ 66.00 | $ - | ¥14 | ¥9 | ¥0 |
| | 2050 | $ 102.00 | $ 66.00 | $ - | ¥14 | ¥9 | ¥0 |
| | Cumulative, 2015-2050 | $ 3,249 | $ 1,980 | $ - | ¥433 | ¥264 | ¥0 |
| Implied Costs for Treatment and Disposal/Storage of Medium-level Wastes from All Reprocessing | 2010 | $ - | $ - | $ - | ¥0 | ¥0 | ¥0 |
| | 2030 | $ 42.28 | $ 27.36 | $ - | ¥6 | ¥4 | ¥0 |
| | 2050 | $ 42.28 | $ 27.36 | $ - | ¥6 | ¥4 | ¥0 |
| | Cumulative, 2015-2050 | $ 1,347 | $ 821 | $ - | ¥179 | ¥109 | ¥0 |
| Implied Costs for Treatment and Disposal/Storage of Low-level Wastes from All Reprocessing | 2010 | $ - | $ - | $ - | ¥0.0 | ¥0.0 | ¥0.0 |
| | 2030 | $ 18.02 | $ 11.66 | $ - | ¥2.4 | ¥1.6 | ¥0.0 |
| | 2050 | $ 18.02 | $ 11.66 | $ - | ¥2.4 | ¥1.6 | ¥0.0 |
| | Cumulative, 2015-2050 | $ 573.94 | $ 349.80 | $ - | ¥76.4 | ¥46.6 | ¥0.0 |
| Implied Costs for Treatment and Disposal/Storage of Solid Wastes from All Reprocessing | 2010 | $ - | $ - | $ - | ¥0.0 | ¥0.0 | ¥0.0 |
| | 2030 | $ 0.10 | $ 0.06 | $ - | ¥0.0 | ¥0.0 | ¥0.0 |
| | 2050 | $ 0.10 | $ 0.06 | $ - | ¥0.0 | ¥0.0 | ¥0.0 |
| | Cumulative, 2015-2050 | $ 3.13 | $ 1.90 | $ - | ¥0.4 | ¥0.3 | ¥0.0 |
| Implied Costs for Treatment and Disposal/Storage of Uranium Separated During from All Reprocessing | 2010 | $ (0.04) | $ (0.04) | $ (0.04) | ¥0.0 | ¥0.0 | ¥0.0 |
| | 2030 | $ 4.52 | $ 3.03 | $ (0.22) | ¥0.6 | ¥0.4 | ¥0.0 |
| | 2050 | $ 4.79 | $ 3.14 | $ (0.02) | ¥0.6 | ¥0.4 | ¥0.0 |
| | Cumulative, 2015-2050 | $ 150.63 | $ 93.19 | $ (3.93) | ¥20.1 | ¥12.4 | -¥0.5 |

The costs of dry cask and spent fuel pool storage of spent fuel by Restart Path are provided in Table 4-11. Total costs as estimated to be on the order of 0.9 to 1.9 billion dollars (110 to 260 billion Yen) for dry cask storage, and similar costs (1.4 to 1.9 billion dollars, or 190 to 250 billion Yen) for storage of cooled spent fuel in spent fuel pools,[54] with costs being higher in Path 3 because more spent fuel is moved to dry casks sooner than in the other paths, and because no spent fuel is taken out of spent fuel pools for reprocessing, as it is in Paths 1 and 2.

[54] Note that only costs for storing cooled spent fuel in at-reactor pools (or in the spent fuel pool at the Rokkasho plant) are counted here, because costs for storing not-yet-cooled spent fuel are assumed to be included in O&M costs for nuclear power plant operation (and/or in decommissioning costs, for reactors recently closed).

*Table 4-11: Costs Associated with Dry Cask and Spent Fuel Pool Storage of Spent Fuel in Each Restart Path, 2010 through 2050*

| | | Cost in Million 2009 USD | | | Cost in Billion 2015 Yen | | |
|---|---|---|---|---|---|---|---|
| **Cost Element** | YEAR | Path 1 | Path 2 | Path 3 | Path 1 | Path 2 | Path 3 |
| Total Annual Cost of Casks Required for Dry Cask Storage of Cooled Spent LWR UOx and MOx Fuel for Storage/Disposal | 2010 | $ - | $ - | $ - | ¥0.0 | ¥0.0 | ¥0.0 |
| | 2030 | $ 19.13 | $ 17.33 | $ 28.10 | ¥2.5 | ¥2.3 | ¥3.7 |
| | 2050 | $ 9.08 | $ 5.21 | $ 9.41 | ¥1.2 | ¥0.7 | ¥1.3 |
| | Cumulative, 2015-2050 | $ 582 | $ 500 | $ 1,253 | ¥78 | ¥67 | ¥167 |
| Total Annual Operating and Maintenance Cost for Casks Required for Dry Cask Storage of All Cooled Spent LWR Fuel for Storage/Disposal | 2010 | $ - | $ - | $ - | ¥0.0 | ¥0.0 | ¥0.0 |
| | 2030 | $ 8.59 | $ 8.54 | $ 15.99 | ¥1.1 | ¥1.1 | ¥2.1 |
| | 2050 | $ 14.05 | $ 13.02 | $ 36.22 | ¥1.9 | ¥1.7 | ¥4.8 |
| | Cumulative, 2015-2050 | $ 330 | $ 319 | $ 681 | ¥44 | ¥42 | ¥91 |
| Implied Total Cost of Dry Cask Storage/Disposal of All Cooled Spent Fuel | 2010 | $ - | $ - | $ - | ¥0.0 | ¥0.0 | ¥0.0 |
| | 2030 | $ 27.72 | $ 25.87 | $ 44.09 | ¥3.7 | ¥3.4 | ¥5.9 |
| | 2050 | $ 23.12 | $ 18.23 | $ 45.62 | ¥3.1 | ¥2.4 | ¥6.1 |
| | Cumulative, 2015-2050 | $ 912 | $ 819 | $ 1,934 | ¥121 | ¥109 | ¥258 |
| Implied Operating and Maintenance Cost of Spent Fuel Pool Storage of All Cooled Fuel after Other Storage/Disposal Implemented | 2010 | $ 48.25 | $ 48.25 | $ 48.25 | ¥6.4 | ¥6.4 | ¥6.4 |
| | 2030 | $ 3.19 | $ 39.76 | $ 54.76 | ¥0.4 | ¥5.3 | ¥7.3 |
| | 2050 | $ 53.23 | $ 46.88 | $ 20.65 | ¥7.1 | ¥6.2 | ¥2.8 |
| | Cumulative, 2015-2050 | $ 1,412 | $ 1,812 | $ 1,897 | ¥188 | ¥241 | ¥253 |

Figure 4-8 and Figure 4-9 show total cumulative nuclear fuel cycle costs, in USD and Yen, respectively, from 2015 through 2050 for the three Restart Paths. Reprocessing costs are by far the single largest set of costs in Restart Paths 1 and 2, with costs for uranium purchase and enrichment the next most significant sets of costs in those paths. In Path 3, cumulative costs for uranium purchase are the single largest set of costs, followed by costs for plutonium storage, uranium enrichment, and dry cask and pool storage of spent fuel, though each of these costs are on the same order of magnitude (a few billion dollars, or a few hundred million yen. The overall costs for fuel cycle activities in Path 3 are on the order of one-sixth the costs in Path 1, and one-quarter the costs in Path 2, but of course Path 3, in particular, provides significantly less nuclear generation than the other two paths. On a per-MWh basis, however, the cost of Paths 1 and 2 are still somewhat higher than in Path 3, at about $16.3 and $15.8 per MWh (2.2 and 2.1 Yen/kWh) for Paths 1 and 2, respectively, versus about $9.8 per MWh (1.3 Yen/kWh) for Path 3, based on the total 2015 undiscounted nuclear fuel cycle costs divided by the total nuclear output for those years.

*Figure 4-8: Cumulative Nuclear Fuel Cycle Costs By Restart Path, 2015 – 2050, Million 2015 US Dollars*

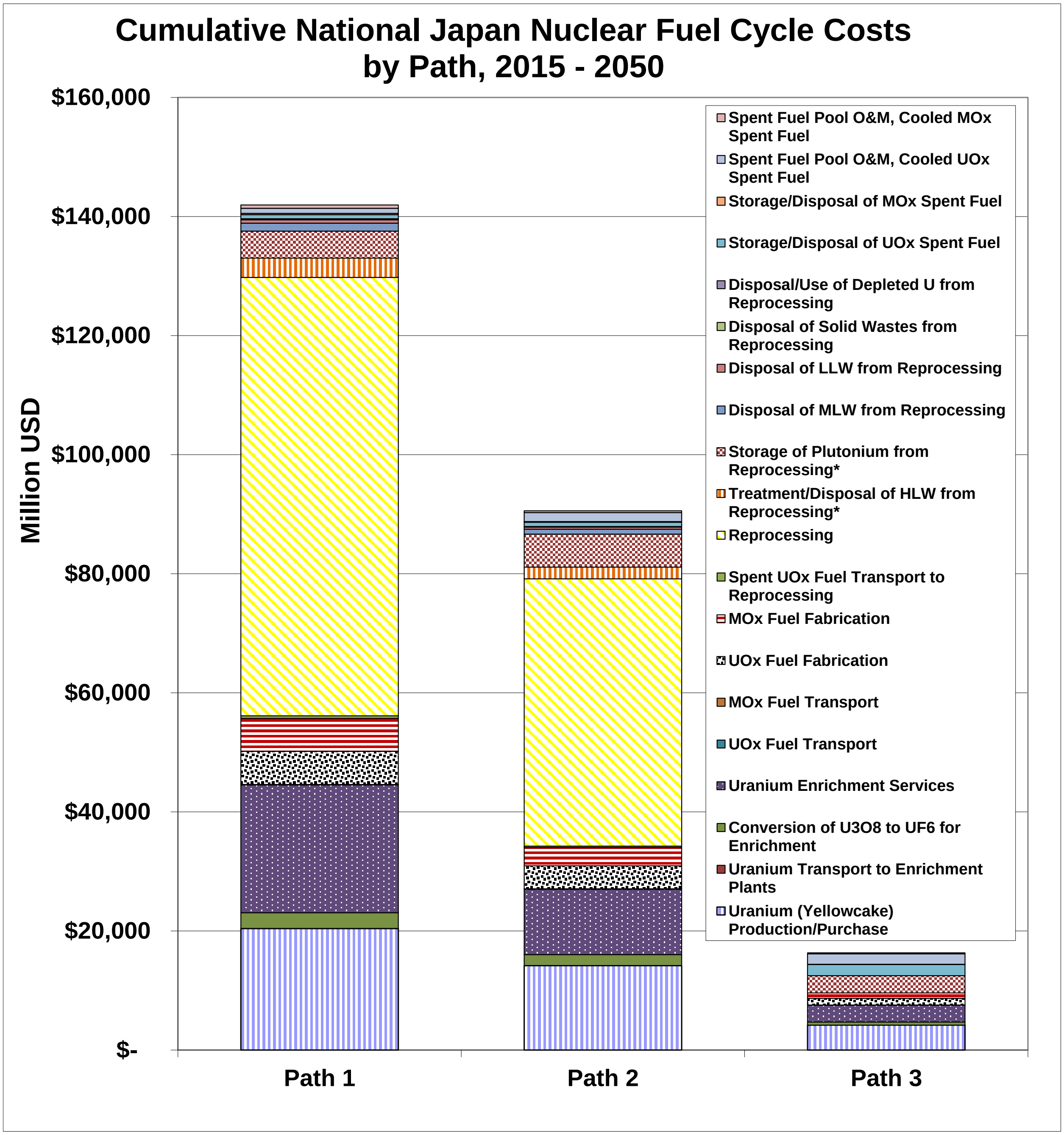
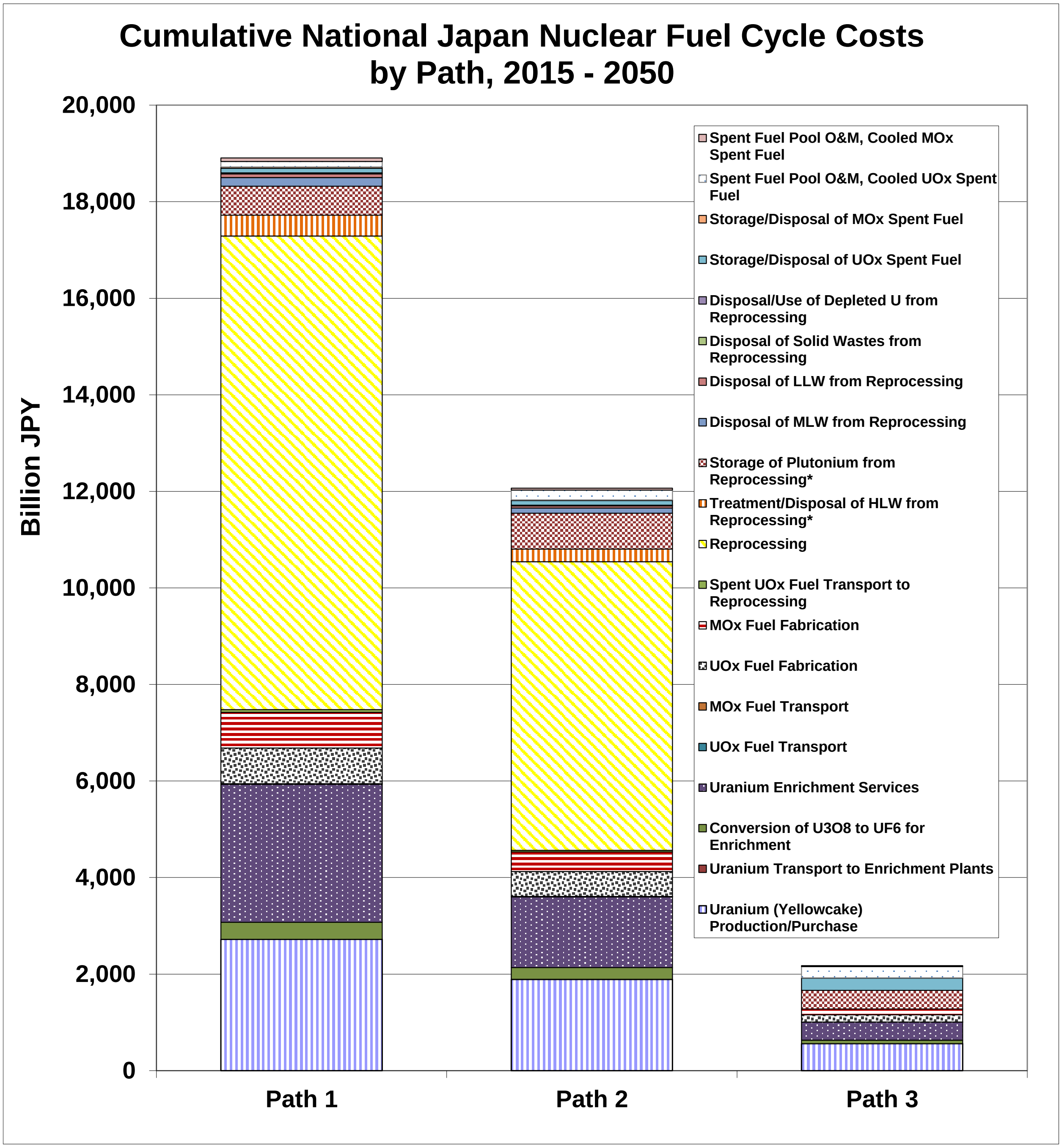


*Figure 4-9: Cumulative Nuclear Fuel Cycle Costs By Restart Path, 2015 – 2050, Billion 2015 Japanese Yen*




## 4.5 Sensitivity Analysis

We performed sensitivity analysis on the results of the overall cost comparisons between the Restart Paths by varying three key parameters—the cost projections for uranium (yellowcake) and for uranium enrichment, and the cost of spent fuel reprocessing.

We prepared three projections for uranium costs as shown in Figure 4-10 . No recent long-term projections of Uranium costs were immediately available, but an older (2001) IAEA report[55] suggested that in a medium nuclear fuels demand scenario, uranium resources with production costs of $130 would become economic in 2034 (assuming known resource development only), and in a high demand scenario, those resources would become economic in 2026. Converting this cost to 2009 dollars yields $163.80 per kg U. Starting with actual 2015 Uranium spot prices,[56] these estimates suggest an annual average growth rate in Uranium prices of 2.9% under a medium demand scenario, and 5.06% under a high demand scenario. These very rough estimates, extrapolated to 2050, yielded the "medium" and "high" price trends shown. Note that in the high demand case, by 2050 Uranium prices approach recent estimates of the costs of extracting Uranium from seawater. For 2016-2020, the medium demand case assumptions yield values fairly close to the UxC Uranium Futures Quotes for that period as of August 2015. For the "low demand" trajectory case below, we assume a modest 0.5% annual real increase in Uranium costs, which is the same escalation rate used by a team of MIT researchers in preparing *Update of the MIT 2003 Future of Nuclear Power Study*.[57] We use this low-case projection as the "base case" estimate of uranium prices for this study, as it seems most consistent with recent trends and the relatively modest activity in the nuclear sector worldwide in recent years (with the exception of China).

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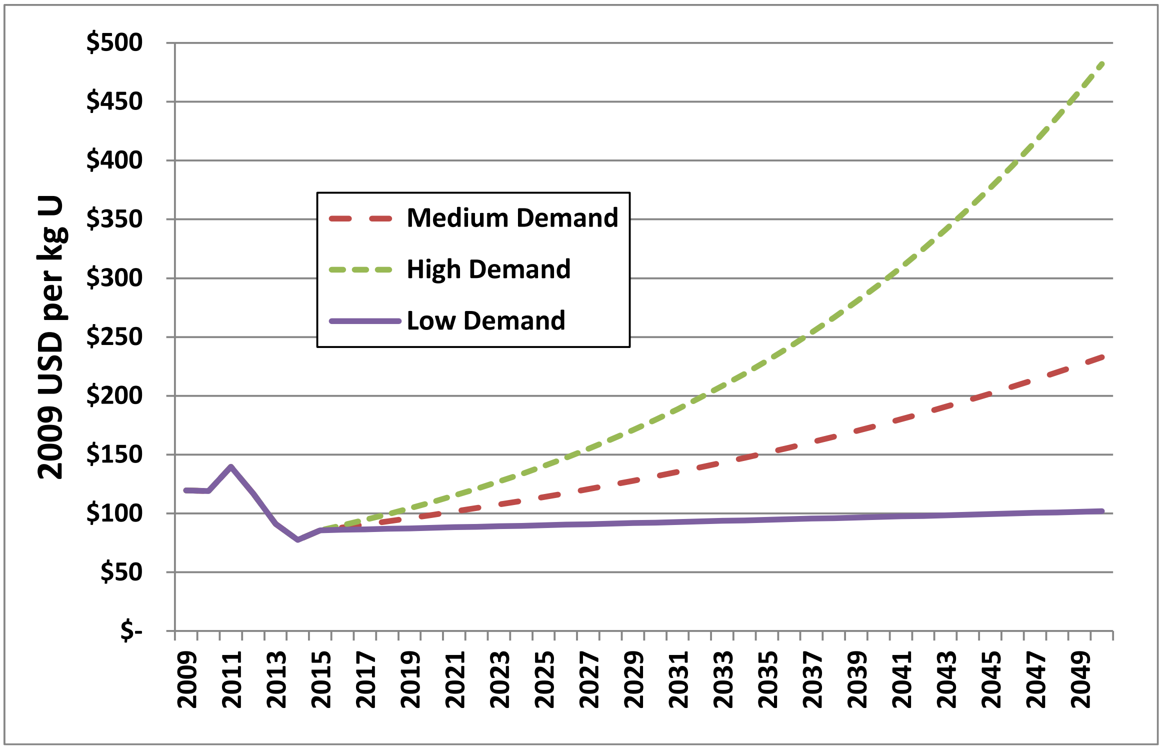
[55] International Atomic Energy Agency (2001), *Analysis of Uranium Supply to 2050*, dated May 2001, Report # STI/PUB/1104.

[56] Historical prices from Cameco "URANIUM PRICES, Uranium Spot Price History", though July, 2015. Available as http://www.cameco.com/invest/markets/uranium-price.

[57] John M. Deutch, Charles W. Forsberg, Andrew C. Kadak, Mujid S. Kazimi, Ernest J. Moniz, John E. Parsons, Du Yangbo, And Lara Pierpoint (2009), *Update of the MIT 2003 Future of Nuclear Power Study*. Available as http://web.mit.edu/nuclearpower/pdf/nuclearpower-update2009.pdf.

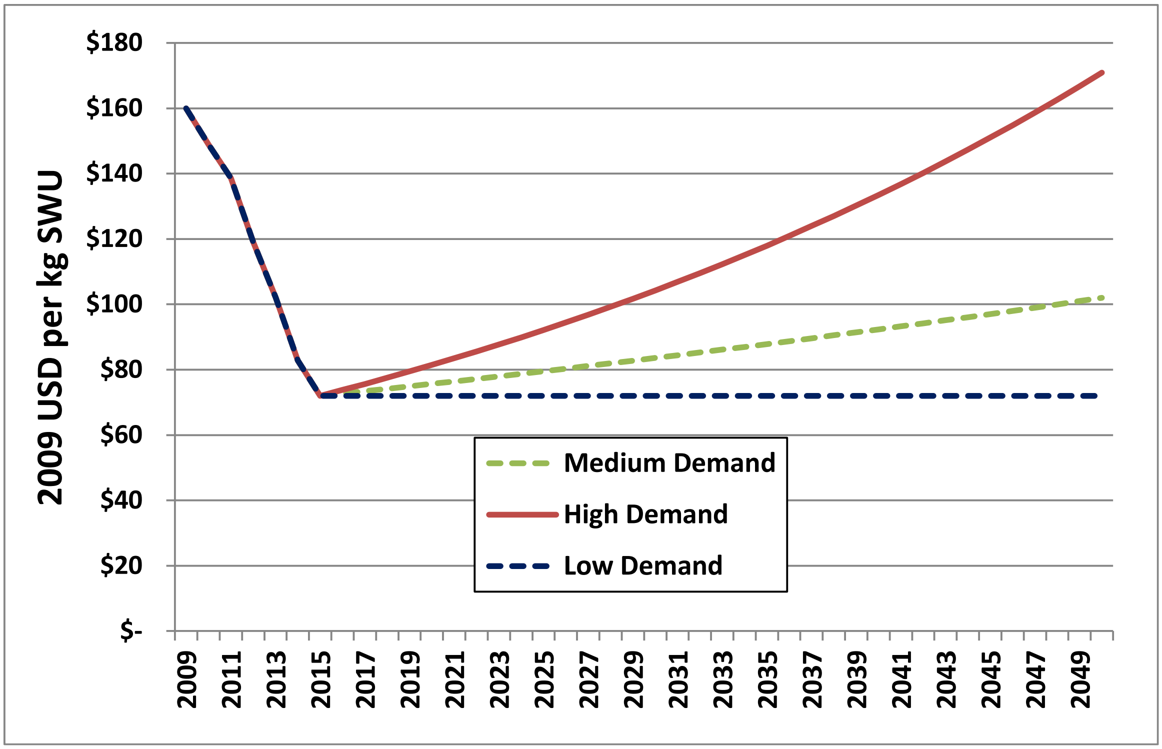
*Figure 4-10: Uranium Price Projections Used in This Study*




Similarly, we prepared three different projections for uranium enrichment costs. As with uranium prices, no recent long-term projections of uranium enrichment costs were immediately available. We thus used historical data with three assumed growth rates to produce three candidate cost trajectories.[58] We use an average real escalation rate for enrichment prices of 1.0% annually as a reference case (medium demand) assumption, with 2.5% annually for a high demand case, and 0.0% annual growth used as a low-case projection of enrichment value. Note that only in the high demand case (see Figure 4-11) do enrichment prices rise to the 2009 level in real terms. 2008-2010 enrichment prices were the highest prices experienced in both real and current-dollar terms since at least 1995.

[58] Historical data on enrichment costs were taken from TradeTech and its Web site, http://www.uranium.info, accessed as of 2009 via http://www.uranium.info/index.cfm?go=c.page&id=34.

*Figure 4-11: Uranium Enrichment Cost Projections Used in This Study*



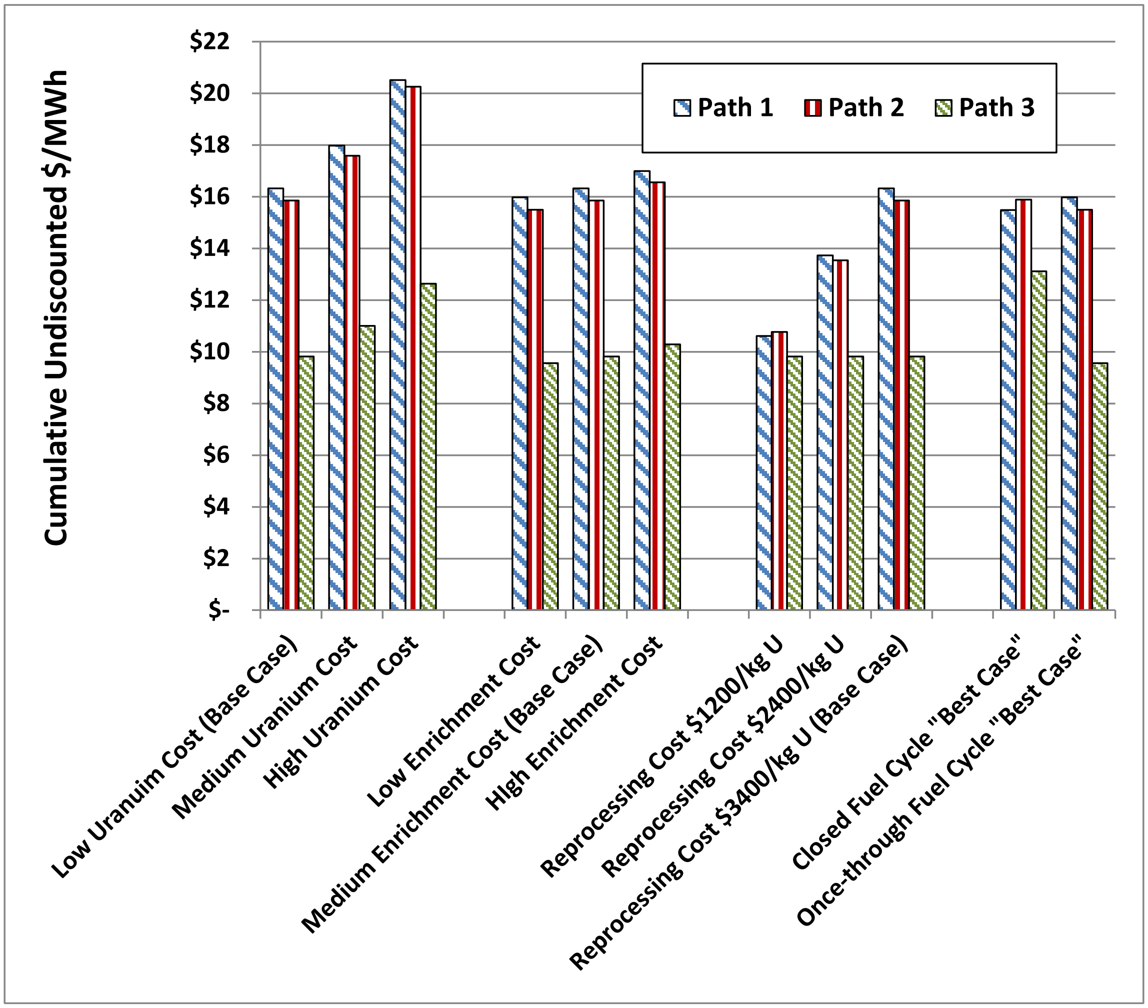

For the cost of spent fuel reprocessing, we use three different costs per kg heavy metal in spent fuel reprocessed (kgHM). $1200 per kgHM is used as a low estimate, based on international sources,[59] $3400, based on a study of Rokkasho costs by Tadahiro Katsuta, is used as the high case estimate, and as the base case estimate for Japan in this study, and an intermediate value of $2400 per kgHM is used as a medium case.

The results of the analysis of the sensitivity of the costs of the three Restart Paths to the changes in the three parameters described above are presented in Figure 4-12 on an undiscounted basis, and in Figure 4-13 using a discount rate of 5 percent annually for costs. In both cases results are presented in USD per megawatt-hour of nuclear electricity generated, as the three paths each provide different amounts of nuclear generation over time. Moving from the low to the high estimate of future uranium costs raises the overall costs per MWh of nuclear electricity by on the order of 26-29 percent in all three paths, with a slightly higher proportionate effect on Restart Path 3 because no reprocessing costs are included in Path 3, so uranium costs are a higher proportion of overall costs. Moving from the low to the high projection of enrichment costs has a much more modest effect—six to eight percent—but the difference between the low and high

[59] The "MIT Report", *The Future of Nuclear Power, An Interdisciplinary MIT Study*, 2003, compiled by a team of researchers mostly from the Massachusetts Institute of Technology (MIT), Cambridge, MA USA, and available as http://web.mit.edu/nuclearpower/pdf/nuclearpower-full.pdf, lists an estimated reprocessing cost of $1000 per kg heavy metal, presumably in approximately 2002 dollars (p. 147). This value, equivalent to $1,200 in 2009 dollars, is very similar to (in comparable dollars) to the value from the 1994OECD/NEA (Nuclear Energy Agency of the Organization for Economic Cooperation and Development) document *The Economics of the Nuclear Fuel Cycle*, OECD/NEA (1994).

enrichment cost projections is much less than that between the low and high uranium cost projections. Moving from low to high reprocessing costs has the most significant effect of the three parameters on Restart Paths 1 and 2—54 and 47 percent, respectively—but has no effect on Path 3, which lacks reprocessing. Under the assumption of low reprocessing costs, the cost per MWh of nuclear output is nearly the same for the three restart cases. Given the reported costs of the Rokkasho facility, however, it seems unlikely that Japan could achieve reprocessing for a cost of $1200 per kgHM.

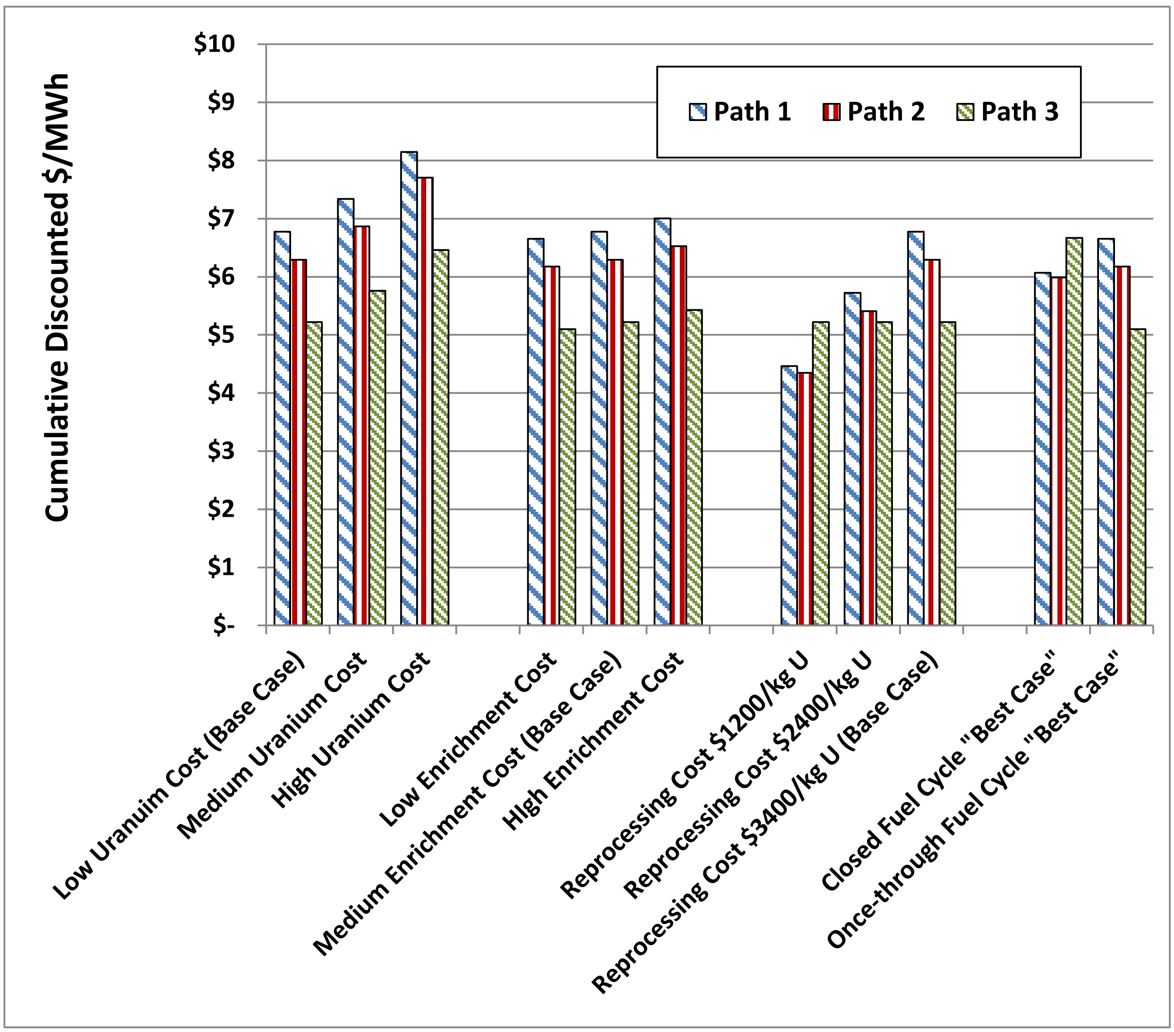
***Figure 4-12: Sensitivity of Nuclear Fuel Cycle Costs of Restart Paths to Variation in Key Parameters: Undiscounted 2015-2050 Costs per MWh of Nuclear Generation***




Also included in the sensitivity analysis is the evaluation of the impact of two "mixed" cases. The first, called the "Closed Fuel Cycle 'Best Case'", includes low reprocessing costs and high uranium and enrichment costs. Under this combination of parameters, Path 1 becomes slightly less expensive, per MWh of output, then Path 2, and Path 3, while still less costly per unit output than the other two paths, is closer in cost to Paths 1 and 2. Conversely, the second mixed case, "Open Fuel Cycle 'Best Case'", includes high reprocessing costs and low uranium and enrichment costs. Here Paths 1 and 2 are 62 to 67 percent more expensive than Path 3.

Figure 4-13, in effect, tests the sensitivity of the per-MWh result to discounting of cash flows at 5 percent annually in real terms.[60] Here the impact of discounting has a greater effect across the board on the costs of Path 3 relative to Paths 1 and 2, because many of the nuclear sector costs in Path 3, including movement of spent fuel to dry cask storage, occur sooner in Path 3, and nuclear generation falls off more abruptly over time in Path 3. Under cases with low reprocessing costs, Path 3 becomes slightly more expensive than Paths 1 and 2. It should be remembered, however, that only nuclear fuel cycle costs are shown in the figures in this Chapter, and that nuclear fuel cycle costs are only a portion of total nuclear generation costs, which in turn are only a portion of the full costs of Japan's electricity sector shown in Chapter 4.

***Figure 4-13: Sensitivity of Nuclear Fuel Cycle Costs of Restart Paths to Variation in Key Parameters: Discounted 2015-2050 Costs per MWh of Nuclear Generation***




[60] In fact, given the near-zero interest rates that have prevailed in Japan for some time, a five percent annual real discount rate may be unrealistically high, though it is difficult to know what the next 35 years will bring with regard to interest rates.

# 5 Energy Security and Terrorism Vulnerability Comparisons between Paths

In recognition that "energy security" should mean more than just sufficient access to key fuels at reasonable prices, as it has often, at least in effect, been defined, Nautilus set out to work with colleagues in Japan to prepare a more inclusive definition of energy security, and a methodology for comparing the energy security attributes in a way that is as transparent as possible. The initial result of that effort, the Pacific Asia Regional Energy Security (PARES) project,[61] was used in 1998 to prepare and compare different future energy paths for Japan. The energy security analysis methods developed in the PARES project have subsequently been revised and updated, and have been used in comparisons of energy security attributes for other national and regional energy paths.[62]

In the remainder of this Chapter, we offer a comparison of the three Restart Paths using an adaptation of the overall energy security (broadly construed) assessment framework developed as described above. As noted in Chapter 1 of this report, this comparison is vital because it compares both the quantifiable attributes of each path—that is, the "countable"—and many of the non-quantifiable or difficult-to-quantify attributes that may, in the end, prove more important to Japan's nuclear energy (and electricity sector) decisions—that is, the "things that count". We also provide, in this Chapter, a summary of our assessment of the relative qualitative vulnerability of Japan's nuclear energy sector to terrorism directed at nuclear facilities under each Restart Path.

## 5.1 Comparison of Energy Security Attributes

We compared the three Restart Paths with regards to energy security attributes in six categories:

- **Energy Supply**, including the security of domestic versus imported supplies, considerations of the possibility of absolute scarcity, and considerations of technology, energy intensity, supply diversity, cost, speed of deployment, and sustainability.
- **Economics**, including potential price volatility, cost-benefit and risk-benefit ratios of approaches to energy sector development, social costs of supply disruptions, local versus

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[61] See Tatsujiro Suzuki, David von Hippel, Ken Wilkening, and James Nickum (1998), *Synthesis Report for the Pacific Asia Regional Energy Security (PARES) Project, Phase I: A Framework for Energy Security Analysis and Application to a Case Study in Japan*, dated June 9, 1998, and available as http://oldsite.nautilus.org/archives/pares/PARES_Synthesis_Report.PDF.

[62] See, for example, David von Hippel, Tatsujiro Suzuki, James H. Williams, Timothy Savage, and Peter Hayes (2011), "Energy Security and Sustainability in Northeast Asia", *Energy Policy*, volume 39, pp. 6719-6730, available as http://dx.doi.org/10.1016/j.enpol.2009.07.001; David von Hippel, Tatsujiro Suzuki, James H. Williams, Timothy Savage, and Peter Hayes (2011), "Evaluating the Energy Security Impacts of Energy Policies", Chapter 3 in *The Routledge Handbook of Energy Security*, edited by Benjamin K. Sovacool, Routledge Publishers; David F. von Hippel, James H. Williams, Fritz Kahrl, and Peter Hayes (2012), "Energy Security—East Asia", in Volume 7 of *Berkshire Encyclopedia of Sustainability: China, India, and East and Southeast Asia: Assessing Sustainability*, Berkshire Publishing Group; and David F. von Hippel (2014), *Energy Security Concepts for Sustainable Development in Northeast Asia*, prepared for the Hanyang University Energy Security and Governance (EGS) Center, dated March 18, 2014, and available as EGS Working Paper Number 2014-06, http://www.egskorea.org/common/download.asp?downfile=Working_Paper_2014_60.pdf&path=board, and http://nautilus.org/napsnet/napsnet-special-reports/energy-security-concepts-for-sustainable-development-in-northeast-asia-2/.

foreign manufacturing of equipment, labor costs and requirements, financing aspects, and benefits of "no regrets" strategies.

- **Technology**, including consideration of the risk of failure of research and development programs, the costs and benefits of technological focus versus technological diversification, new materials dependency in technological substitution strategies, potential for catastrophic failure of technologies, and exposure to risk of adoption/diffusion or commercialization failure of key technologies.
- **Environmental**, including consideration of local externalities, regional externalities (for example, both atmospheric pollutants and maritime externalities), global externalities such as greenhouse gases, and the degree to which an energy path pursues the "precautionary principle" (for example, avoids the risks of technology deployment in the absence of consensus as to the magnitude of those risks).
- **Social-Cultural**, including managing/minimizing consensus and conflict in domestic or foreign policy making among different actors, the current and future capacities of institutions to address problems, the siting and downwind distributional impacts of key energy facilities, the potential populist resistance to or rejection of particularly energy strategies, and existing perceptions and lessons from history with regard to different energy systems, and within different social groups.
- **International Military/Security**, including national and international management of plutonium stocks, the proliferation potential of the nuclear fuel cycle, the security of sea lanes and energy shipping amid a period of rising regional powers and changing relations among regional neighbors, and the geopolitics of oil and gas supplies.

Below, and summarized in Table 5-1, we briefly explore the relative characteristics of the three Restart Paths with regard to selected measures of each of the energy security attributes described above.

### 5.1.1 Energy Supply

The cumulative overall 2015 through 2050 fossil fuel use—coal, oil products, and natural gas—for electricity generation is highest in Restart Path 2 (195 Exajoules, or $10^{18}$ Joules), lowest in Restart Path 1 (174 EJ), and in the middle in Restart Path 3 (186 EJ), though as a result of more aggressive energy efficiency and renewable energy investments, annual fossil fuel use in Path 3 is lower than in the other two paths in the later years of the modeling period. Conventional wisdom would say that it will likely be an advantage to have lower fossil fuel requirements for electricity generation later in the period, when supplies of fossil fuel will presumably be more uncertain and efforts to reduce greenhouse gas emissions through, for example, carbon taxes will presumably be increase the cost of fossil fuels. The converse argument could also be made, however—fossil fuel prices will remain low because fuel demand will fall in many countries due to GHG emissions reduction efforts. Higher fossil fuel use renders the Japanese economy somewhat more vulnerable to supply disruptions in Paths 2 and 3 than in Path 1, but as the overall fossil fuel use only differs 5 to 10 percent between the two paths, and fossil fuel use in total in other sectors in Japan exceed fossil fuel use in the electricity sector, the difference in vulnerability to supply disruptions between the three Restart Paths is not likely to be highly significant. It can also be argued that with a greater diversity of fossil fuel suppliers on the world market today than was the case during the time of the oil crises in the 1970s, it will continue to be much less likely in future years that Japan's fossil fuel supplies can be physically disrupted than it was 10 or more years ago.

Path 3, with more wind and solar power, and more energy efficiency (though less nuclear power) arguably will provide greater energy supply diversity than Paths 1 and 2 in the later years of the modeling period, though possibly less supply diversity in the earlier years of the period, when lower nuclear generation must be made up for by increased fossil fuel use.

With regard to the security of uranium supply (as yellowcake, $U_3O_8$), Path 1, though it offers reduced dependence on U imports via MOx use and reprocessing) than if the same nuclear generation were provided in a once-through fuel cycle, still has significantly higher (188 thousand tonnes, or kte) overall raw uranium requirements from 2015 through 2050 than do Paths 2 and 3. This means that Path 1 is more vulnerable to uranium supply disruptions than the other two paths, with 131 kte (Path 2) and 37 kte (Path 3) over 2015-2050, although Path 2 and, especially, Path 3 feature less nuclear generation than Path 1. In general, a disruption in raw uranium supplies seems unlikely, unless there is a general disruption in international shipping (which would have much more dire impacts for the Japanese and most other economies), given the diversity of uranium suppliers, the availability of uranium from typically very stable countries (such as Australia and Canada), and the relatively small amounts of uranium needed each year.

#### 5.1.2 Economy

On an undiscounted basis, the overall costs of electricity generation in the three restart paths are within about 2.5 percent of each other over the period 2015 through 2050, at 530, 544, and 531 trillion Yen for Paths 1 through 3, respectively. On a discounted (5 percent annually in real terms) basis, the cumulative costs are even closer in percentage terms—243, 248, and 244 trillion Yen for Paths 1 through 3. This variation in overall estimated electricity sector costs, though it is in the trillions of Yen, is insignificant compared with the uncertainties involved in estimating costs over a period of 35 years. In addition, the total magnitude of electricity sector costs over 2015 through 2050, which we estimate, as above, to be in the vicinity of 500 trillion Yen, is similar to a single year of Japan's gross national product (GNP), which has averaged over 500 trillion Yen annually in recent years. As a consequence, difference in overall costs between the three paths is unlikely to much affect the general economy one way or another.

Similarly, there are tradeoffs between the paths in terms of imported and domestic components, both between technologies and over time. Path 1, and, to a lesser extent, Path 2, involve more U imports than Path 3. As noted above, the three Paths require different amounts of fuel imports, and thus vary in imported fuel costs, but not substantially. Path 2 has the highest undiscounted or discounted fossil fuel costs over 2015 through 2050, at 232 trillion Yen undiscounted/113 T Yen discounted, with Path 3 having the next highest imported fossil fuel costs (219 T Yen undiscounted, 110 T Yen discounted), and Path 1 having the lowest fossil fuel costs (206 T Yen/103 T Yen). Paths 1 and, to a lesser extent, Path 2 have higher uranium import costs, but greater activity in domestic enrichment and reprocessing than in Path 3. Path 3 has more activity in the renewable energy and energy efficiency sectors than Paths 1 and 2, and though it does not include reprocessing, may partially make up for jobs not created (or not continued) in reprocessing by increasing employment related to dry cask storage and by moving up decommissioning activities in time for Japan's reactor fleet, relative to Paths 1 and 2. It is well beyond the scope of this Report to perform a macroeconomic analysis of the three paths with respect to changes in net national income and employment between the three paths, but our guess is that overall changes in GNP and employment between the paths might, if anything, slightly favor Path 3 because of its renewable energy and energy efficiency components, as both involve mostly domestic industries and both tend to be more labor-intensive than other sources of electricity.

As described in section 4.4, above, overall 2015 - 2050 nuclear fuel cycle costs for Path 1 are higher than in Path 2, which in turn are substantially higher than in Path 3, but much of the difference stems from the different levels of nuclear generation between the three paths. On a per MWh generated basis, Paths 1 and 2 are quite similar, at 2.2 and 2.1 Yen per nuclear kWh generated, respectively, while Path 3, because it excludes reprocessing, is less expensive on that basis, at 1.3 Yen/kWh. Again, these costs are for fuel cycle activities exclusive of purchasing and operating the nuclear reactors themselves.

#### 5.1.3 Technology

From the perspective of the technology-related attributes associated with a broad definition of energy security, Paths 1 and 2 both provide practical experience for Japan in operating and research and development (R&D) in closed nuclear fuel cycle technologies, most specifically, in reprocessing. Path 3 largely does not provide much experience for Japanese scientists in closed fuel cycle technologies. Though it is possible that some closed fuel cycle R&D would take place under Restart Path 3, it seems likely that without reprocessing ongoing, R&D on closed fuel cycle technologies would receive less financial support and thus be less extensive. In contrast, R&D and commercialization of renewable energy and energy efficiency technologies in Japan could be expected to be significantly higher in Path 3 than in Paths 1 and 2, possibly giving Japan an additional edge in exporting goods and services related to renewable energy and energy efficiency, as well as in integrating RE electricity sources into electricity grids, in developing and operating "smart grids" that coordinate electricity supplies and demand at the local level, and similar technologies.

Technological risks are also a part of the consideration of technical energy security attributes. Path 1, and to a lesser extent, Path 2, rely heavily on a single technology, and, in fact, a single huge factory—the Rokkasho reprocessing center—to operate effectively in order to build toward a closed nuclear fuel cycle. Rokkasho has an operations history that is decidedly mixed with regard to reliability, so it seems reasonable to be concerned about its future performance. If Rokkasho fails to operate as planned, Paths 1 and 2 either become once-through paths requiring greater inputs of imported uranium (and attendant higher uranium costs, but presumably lower reprocessing costs), or must rely on reprocessing services provided abroad, with their attendant reprocessing service costs and greater spent fuel/plutonium transportation requirements. If Rokkasho fails to operate as planned, it seems likely that closed fuel cycle research and development may be delayed as a whole, though that depends on the organization of closed fuel cycle R&D in Japan. Path 3 had a greater dependence than Paths 1 or 2 on the effective operation and smooth integration with electricity grids of renewable energy sources, and the effectiveness of energy efficiency programs in Japan. Although there are risks that these technologies will not perform as expected, the great diversity of RE/EE technologies, and the much smaller scale of their individual applications relative to reprocessing and other closed fuel cycle technologies, would seem to render the RE and EE technologies in Path 3 more robust to potential technological failure than the nuclear technologies that play a greater role in Paths 1 and 2.

### 5.1.4 Environment

The three Restart Paths have somewhat different environmental footprints, principally because of the difference in fossil fuel use between the paths, but also due to the generation of reprocessing and other wastes from the nuclear fuel cycle. Of the three paths, Path 2 has the greatest greenhouse gas (GHG) emissions in most years from 2015 through 2050, as well as on a cumulative basis. As a result of its greater nuclear generation, Path 1 has the least cumulative GHG emissions, and the least emissions in most years, but by 2045 annual emissions in Path 3 fall below those in Path 1. Although we have not explicitly modeled emissions of conventional air pollutants such as nitrogen oxides, sulfur oxides, and particulate matter, we would expect that emissions of these pollutants from the electricity sector will generally follow emissions of GHGs, thus Path 1 will offer the lowest cumulative emissions, with annual emissions in Path 3 being lower than in the other two paths by the mid-2040s, due to greater use of EE and RE in Path 3.

As noted in Chapter 5 of this Report, Paths 1 and 2 produce high-, medium-, and low-level wastes, as well as solid wastes, with Path 1 producing on the order of 60 percent greater volumes of wastes than Path 2 due to the higher level of reprocessing in Path 1. Although the volumes of these wastes are not large, compared with, for example, the volume of ash from coal combustion, (of which on the order of one hundred million tonnes will be produced in each Path over 2015-2050), wastes from reprocessing that must be carefully disposed of in (at least) special landfills, and in the case of high-level wastes, require very special storage/disposal facilities, as HLW must be isolated from the biosphere for "hundreds of thousands of years".[63]

Other nuclear fuel cycle solid wastes produced in quantities that vary between the three Restart Paths are the "tailings" –waste rock depleted of U that is produced when uranium ore is milled—and uranium depleted of $U_{235}$ during enrichment activities. These will be produced in proportion to uranium and enriched uranium needs, respectively, in the three Restart Paths, and thus will be significantly higher in Paths 1 and 2 than in Path 3. As little or no uranium mining occurs in Japan, uranium tailings will likely be disposed of outside Japan. Depleted uranium has some other uses, (mostly in munitions), but must typically be disposed of as low-level radioactive waste after conversion to uranium oxides. Reprocessed uranium, which is produced in Paths 1 and 2 but not Path 3, may to some extent be recycled, but must otherwise be carefully stored or disposed of due to its content of radioactive uranium isotopes.

The three different Restart Paths have somewhat different attributes with regard to land use for non-nuclear sector activities. Perhaps the major land use impact of the three paths has to do with coal mining. An aggregate 1.7 to 1.9 billion tonnes of coal are mined for use for electricity generation in Japan—although almost all not in Japan—in each path over 2015 through 2050. In addition, as noted above, on the order of a hundred million tonnes of coal ash will be produced in all of the Restart Paths. Some of this material may be reused as a fill for civil works or a

[63] See, for example, the U.S. Nuclear Regulatory Commission (2015), "High-Level Waste", dated April 8, 2015, and available as http://www.nrc.gov/waste/high-level-waste.html.

blending agent for cement, for example, but likely not all.[64] The quantities of coal mined coal ash produced vary on the order of 10 percent between scenarios, with Path 2 having the highest cumulative coal mining requirements and ash production, Path 1 having the lowest, and Path 3 intermediate. Path 3, with its greater emphasis on wind and solar power, will have more land taken up with solar and wind systems, though in both cases some or much of the land used for these systems can be used concurrently for other purposes—for example, wind turbines can be installed on working farms, and solar PV systems can be installed over parking lots, on building roofs, and on other structures.

Although all three paths utilize mostly the same, existing nuclear facilities, Path 1, and to a lesser extent Path 2, involve the completion of under-construction nuclear power plants that are not included in Path 3, although most of the units added are on existing nuclear plants sites. In Path 3, slightly more land is required for dry cask storage, though the land used would likely be well within existing sites for nuclear facilities. In Path 3, the decommissioning of nuclear plants occurs about 15 years sooner than in Paths 1 and 2, nominally meaning that decommissioned sites, or parts of them, might be available for other uses, or to be returned to an approximation of their natural state, sooner, though that would depend on a number of decisions regarding, for example, any residual hazards on-site and/or the long-term uses of the sites for storing spent fuel (if any). Also, the earlier decommissioning of reactors means the need to move up the disposal of a variety of radioactive and conventional solid wastes, creating an earlier need for disposal space for these materials.

As the Fukushima accident, and the Chernobyl accident before it, vividly illustrated, there is some risk of significant radiation release associated with natural disaster-caused and human-error-origin accidents involving nuclear reactors and spent fuel pools. Although significant upgrades in safety equipment and procedures have been and are being undertaken by nuclear plant operators in Japan, the greater numbers of nuclear plants operating in Path 1 than in Path 2, and the significantly greater number of plants operating in both of those Paths than in Path 3, mean that the relative risk of significant releases of radioactive materials will be higher in Paths 1 and 2 than in Path 3, though the overall absolute risk of releases may be low in all cases. In addition, the conversion of spent fuel pools in Path 3 to non-dense-racked configurations will markedly reduce the risk of catastrophic releases of radiation from spent fuel pools, which are often the largest potential sources of radioactivity releases under an accident (or attack) scenario, as demonstrated in the results shown in Chapter 2.

### 5.1.5 Social/Cultural

The relative social/cultural impacts of the three Restart Paths in Japan are probably among the most difficult energy security parameters to estimate, particularly for authors who are not Japanese, so we would encourage Japanese colleagues to review and augment correct our thoughts below. Several categories of social/cultural impacts that may differ among the three Restart Paths can be considered, including the impact on those working in the nuclear industry in Japan, the impacts of nuclear policies on public perceptions of radiation risks, and the impacts of

[64] See, for example, New Energy and Industrial Technology Development Organization (NEDO, 2006), *Clean Coal Technologies in Japan: Technological Innovation in the Coal Industry*, available as http://www.nedo.go.jp/content/100079772.pdf.

policies on public perceptions of Japan's energy future and as a global leader in sustainable development.

The activities of scientists and technicians in the nuclear industry and those that support them in Japan, including nuclear industry workers in utilities and other private sector organizations, and those working in government ministries and institutes tied to the nuclear industry, will be similar in scope in both Restart Paths 1 and 2. In both paths, closed-fuel-cycle R&D continues, reprocessing work continues, and nuclear power plants restart and bring more power plants workers back to work. The additional reactor restarts in Path 1 mean a higher level of activity for the nuclear sector in Path 1 than in Path 2, but little qualitative change in the types of activities that will be required. Path 3 is a significantly different from Paths 1 and 2 in this regard. Although some close-fuel cycle R&D is included in Path 3, the combination of limited reactor restarts, earlier decommissioning through only modest life extension of existing plants, no use of reprocessing, and dry cask storage replacing dense-packed spent fuel pools means a significant change in mission for those in the nuclear sector. Rather than being responsible for a key, perhaps central, component of Japan's electricity generation system in the past, present and future, as well as a center of focus for Japan's energy security policy, the nuclear sector would evolve in Path 3 into a role that focuses on stewardship of nuclear waste and safe decommissioning of existing facilities. The latter is a worthy and crucial role to be sure, but may not offer the type of fulfillment that nuclear sector workers were seeking and expecting when they started their careers. As such, Path 3 represents a significant re-setting of the roles and goals of many of the individuals and organizations that comprise Japan's nuclear sector. Whether and how many of those individuals and organizations can or will smoothly adapt to new roles and goals is an open question.

Similarly, Paths 1 and, to a lesser extent, 2 offer relatively little change from current policies in terms of risk of radiation releases through accidents or attack, as most of the same technologies continue to be used in both Paths, including dense-packed spent fuel pools. The main changes from pre-Fukushima conditions associated with Restart Paths 1 and 2 are those common to all three paths, that is, the additional safety measures—improvement of redundant power and cooling systems, reinforcement of seawalls and other physical protections, and security upgrades—that are being implemented at all nuclear facilities in Japan (and in other nations) as a result of the lessons of Fukushima. As such Paths 1 and 2 arguably offer no substantial additional reassurance to the public that the risks of radiation exposure that became real with the Fukushima accident will become qualitatively significantly lower. Because it restarts only a few reactors, includes the de-densification of spent fuel pools, decommissions reactors earlier, and does not operate Rokkasho, with its attendant need for handling and securing nuclear materials, and its mixed history of technical success, Path 3 arguably provides a tangible demonstration to the public of an ongoing policy commitment to significantly reducing radiological risks. Although the reduction in risk by Path 3 is significant, it is probably the public <u>perception</u> of that reduction in risk that would be more important in terms of its social and cultural impact.

All three paths include a significant amount of renewable energy deployment. The additional deployment of solar, wind, and other (small hydroelectric and geothermal, mostly) electricity sources in Path 3, however, would demonstrate a greater policy commitment by Japan's leaders to focus on Japan's long-term greenhouse gas reduction and other sustainability goals, as well as to refocus Japan's energy sector and indeed, economy, on technologies that will be "green" and sustainable for the long-term. This revised focus might be more consistent with Japan's historical cultural identity than the closed-fuel-cycle path in Paths 1 and 2, though we would look to Japanese colleagues to more fully flesh out (or refute) this argument.

### 5.1.6 International Military/Security

The different Restart Paths impose different types and levels of international relations risks and military security risks and requirements.

From an international relations perspective, Paths 1 and 2, in which Japan continues to use reprocessing, arguably offer greater risks of conflict with China and the two Koreas over nuclear issues. In the case of Japan/ROK relations, ROK nuclear policymakers are likely to continue to feel that Japan's use of reprocessing, and, by extension, the United States' policy allowing Japan to use reprocessing while the ROK does not, as yet, have the clearance to do so, is unfair to the ROK. With Japan continuing to use reprocessing, as in Paths 1 and 2, key nuclear sector actors in the ROK may continue to push for the right to pursue the ROK's variant of reprocessing, "pyroprocessing", and a Korean version of a closed fuel cycle. If the United States is convinced to modify its nuclear agreement with the ROK to allow it to pursue pyroprocessing, it seems likely that the combination of reprocessing in both Japan and the ROK will if anything, retard, and possibly fully derail, the process of reaching an agreement with the DPRK such that the DPRK gives up its existing weapons and future nuclear weapons programs. So long as reprocessing remains active in Japan, and plutonium stockpiles remain in Japan, it will be difficult to convince the DPRK (and ROK) that Japan is not reserving at least the technical opportunity to build nuclear weapons rapidly if needed. In Path 3 (and in Path 1, though via a different trajectory), Japan's stockpile of plutonium is used up, reducing the risk of diversion of portions of the existing stockpile (if not, in Path 1, the continued annual flows from reprocessing) for use in nuclear explosives or radiological weapons.

Conversely, Path 3, in which reprocessing is not pursued, would likely help to reduce pressure in the ROK to pursue pyroprocessing, and serve as a positive example to help induce the DPRK toward negotiations to give up its own nuclear weapons program. In addition, a commitment to an energy future such as that suggested in Path 3 would also help Japan to induce other nations to focus on lower-carbon development with limited use of nuclear power, helping Japan to further demonstrate its international commitments under international climate agreements.

China has raised concerns about Japan's "excess plutonium" and the risk that it may proliferate its own nuclear weapons, in part due to reference to Japan's "technological deterrent" by a few Japanese policymakers.[65] However, Japan's propensity to proliferate its own nuclear weapons appears to be separate from its absolute stocks of plutonium and enriched uranium. Japan can produce a significant number of warheads from a small fraction of its fissile material stocks in all three pathways (at least until the last years of pathway 3, decades in the future). Thus, the risk that Japan would proliferate is largely invariant with respect to the pathway adopted for reasons of energy security or to minimize the threat of attack or catastrophic failure to manage safely Japan's spent fuel. In Sino-Japanese geo-strategic relations, the absolute quantity of fissile

**65** See, for example, "Japan's huge stockpiles of plutonium pose risks," *China Daily*, October 22, 2015, at: http://usa.chinadaily.com.cn/opinion/2015-10/22/content_22250018.htm.

material available to Japan is more a perceptual and political indicator of intention than it is a strictly technical matter at this stage of Japan's technological development.

From a national military/security perspective, the flows of nuclear materials in Paths 1 and, somewhat less, in Path 2, require a significantly greater effort to secure spent fuel, plutonium, and other dangerous materials, as described below. These additional efforts, in arguably more places in Japan than in Path 3, will likely, through their very presence have an effect on perceived safety and security if the general public. Paths 1 and 3 involve similar movements of plutonium back from Europe to Japan, and thus have similar security requirements in that regard. All three paths require security for MOx fuel preparation and transport, but the higher volumes of MOx fuel required in Path 1 than in Path 2 imply that securing of MOx fuel preparation and movement takes place in more places and more frequently. The much-reduced use of MOx fuel in Path 3 implies lower levels of security associated with MOx than the other two paths, but the type of security required is still qualitatively similar.

For Japan, which imports virtually all of its fossil energy supplies (as well as all of its uranium), another military/security element of its broader energy security picture is securing trade routes for the imports of conventional fuel supplies. Although at present, and likely for the foreseeable future, trade routes in East Asia and beyond are largely secured by the US military, a significant change (reduction or increase) in the flows of oil and gas through narrow seaways in the region could have the potential for reducing or increasing flash points for conflict in seas that are increasingly conflict prone. Although Restart Path 1 uses less imported oil, gas, and coal cumulatively than Paths 2 and 3, the difference in volumes (5 – 10 percent) are not significant enough to allow security arrangements for energy product trade routes to be qualitatively different. For example, an overall change of a few percent in energy use would probably not allow Japan to switch away from a major fuel supplier simply to avoid trade routes that had become problematic. Restart Path 3 similarly uses slightly less fossil fuel overall than Path 2, but not enough less to be a factor in military security associated with energy flows. After about 2045, Path 3 uses increasingly less fossil fuel annually than both other Paths, which may put Japan on course to a qualitatively different level of energy imports, but only beyond 2050. The difference between the three paths with regard to uranium imports, though substantial, is unlikely to affect military security arrangements for trade routes because the bulk volume of uranium imported is small relative to other energy and non-energy commodities, and uranium (yellowcake) typically does not require special ships for transport.

### 5.1.7 Overall Energy Security Comparison of Paths by Attribute

As we have described in previous publications focused on the multi-attribute analysis of energy security impacts (see above), it is possible to develop a weighing and ranking system to attempt to sum all of the different attributes of energy security, both quantitative and qualitative, into a common metric, and thus to produce an aggregate "score" for each of several alternative energy paths or scenarios. Although doing so offers the prospect of objective decisions involving multiple parameters and attributes, we feel that it in fact obscures what is invariably a largely subjective process of developing weightings for different attributes, and at its worst distorts and magnifies what are often small differences in specific attributes—such as the small differences in total costs we see across the three Restart Paths over time—as well as distorting and reducing the significance of potentially large differences between Paths, both quantitative and qualitative. As a consequence, and particularly in this case when it is really for Japanese policymakers and their public to decide what is most important in terms of Japan's nuclear energy future, we prefer to lay out the different attributes of different Paths directly in a "matrix" format, and let readers decide which attributes in what combinations mean the most for the energy policy decisions at hand. Table 5-1, below, summarizes the comparison of the three Restart paths as described above with regard to the six categories of attributes included in this analysis.

*Table 5-1: Summary Comparison of Restart Paths with Regard to Energy Security Attributes*

| Energy Security Attribute | Path 1: Return to Closed Fuel Cycle Trajectory | Path 2: Slower Return to Closed Fuel Cycle | Path 3: Limited Restart/Once-through Cycle |
|---|---|---|---|
| Energy Supply Security--Overall | Lower 2015-2050 imported fossil fuels use for generation than in Path 2 or Path 3 (174 EJ); higher supply diversity in early years than Path 3, less in later years | Higher 2015-2050 imported fossil fuels than Path 1 (195 EJ); higher supply diversity in early years than Path 3, less in later years | Ultimately lower fossil fuels imports, higher use of domestic resources, than Paths 1 and 2 (due to EE/RE), but higher fossil fuel use initially and over 2015-2050 than in Path 1 (186 EJ); lower supply diversity in early years than Paths 1 and 2, less in later years |
| Energy Supply Security—U purchases | Reduced dependence on U imports (via MOx, Reprocessing) than for same generation in a once-through fuel cycle, but overall significantly more (188 kte) than Paths 2 and 3 | Reduced U imports dependence (via MOx) than similar output without MOx use, less overall use than Path 1 (131 kte over 2015-2050) | Less U requirements overall than Paths 1 and 2 (37 kte over 2015-2050), but much less nuclear generation |
| Economy—Total Electricity Sector Costs | 2.6 % lower than Path 2 (530 Trillion Yen) | 544 Trillion Yen, 2015-2050 (undiscounted) | 2.3 % lower than Path 2 (531 Trillion Yen) |
| Economy—Nuclear Fuel Cycle Costs | 2.2 Yen per nuclear kWh (undiscounted) | 2.1 Yen per nuclear kWh (undiscounted) | 1.3 Yen per nuclear kWh (undiscounted) |

| Energy Security Attribute | Path 1: Return to Closed Fuel Cycle Trajectory | Path 2: Slower Return to Closed Fuel Cycle | Path 3: Limited Restart/Once-through Cycle |
|---|---|---|---|
| Economic—Impact on GNP and Employment | Greater activity in reprocessing and enrichment than other Paths, somewhat less activity in fossil fuel imports/handling and fossil generation | Somewhat less activity in reprocessing and enrichment than Path 1, but more activity in fossil generation and fossil fuel imports | More activity in renewable energy and energy efficiency, less in some nuclear subsectors (reprocessing), more in others (dry cask storage, decommissioning) |
| Technology—R&D | Builds closed fuel cycle expertise | Builds closed fuel cycle expertise | More experience with RE/EE |
| Technology—Risk of Dependence | Depends on performance of SF reprocessing (Rokkasho) | Depends on performance of SF reprocessing (Rokkasho) | Depends on performance of RE/EE (but many different technologies included) |
| Technical—Grid Stability | Similar to Path 2 | Similar to Path 1 | Possibly more difficult to assure due to addition of more RE |
| Environment—Electricity $CO_2e$ Greenhouse Gas Emission | 2035—256 Mt<br>2050—141 Mt<br>2015–2050—10,800 Mt | 2035—294 Mt<br>2050—164 Mt<br>2015–2050—12,100 Mt | 2035—288 Mt<br>2050—105 Mt<br>2015–2050—11,500 Mt |
| Environment—Electricity other Air Pollutant Emissions | Roughly proportional to GHG emissions, thus lower cumulative than Paths 2 and 3, but higher after 2044 than Path 3 | Roughly proportional to GHG emissions, thus higher cumulative and per year than Paths 1 and 3 | Roughly proportional to GHG emissions, thus lower cumulative and most years than Path 2, lower after 2044 than Path 1 |
| Environment—Non-nuclear solid wastes/land use | About 10% less coal mined, coal ash than Path 2 | On the order of 100 Mte coal ash, 1.9 Gte coal mining, 2015 - 2050 | About 4% less coal mined, coal ash than Path 2; More space needed for RE |

| **Energy Security Attribute** | **Path 1: Return to Closed Fuel Cycle Trajectory** | **Path 2: Slower Return to Closed Fuel Cycle** | **Path 3: Limited Restart/Once-through Cycle** |
|---|---|---|---|
| Environment—Nuclear Sector Solid Wastes | Highest wastes from reprocessing, Rep U, depleted U, U tailings | Wastes from reprocessing, Rep U, depleted U, U tailings ~ 40% less than Path 1 | No wastes from Reprocessing; U tailings ~30% of Path 2, ~20% of Path 1 |
| Environment—Nuclear Sector Land Use | Highest due to additional reactors (but most at current sites), reprocessing waste landfill needs | Fewer reactors than Path 1, less reprocessing waste, therefore lower landfill requirements | No additional reactor land use, earlier decommissioning may free up land earlier, slightly more land for dry cask storage |
| Social/Cultural—Nuclear Sector Identity | More and longer-term employment for nuclear sector workers, consistent with recent decades | Similar to Path 1, but at somewhat lower levels for some nuclear activities | Significant change in focus of nuclear sector actors from future fuel cycle-oriented to stewardship and decommissioning of existing materials and sites |
| Social/Cultural—Radiological Risks | Improvement in public perception due to post-Fukushima upgrades, but otherwise little change | Similar to but slightly less than Path 1 | Change in actual and public perception of risk levels due to earlier decommissioning, retirement of facilities, de-densification of spent fuel pools |
| Military Security—International | Continued use of reprocessing promotes call for reprocessing in ROK, nuclear weapons in DPRK, may exacerbate Chinese suspicions of Japanese proliferation intentions | Similar to Path 1, except some Pu stockpiles remain, may exacerbate Chinese suspicions of Japanese proliferation intentions | Rejection of reprocessing, consumption of Pu improves odds that ROK can be induced not to reprocess, may help in negotiations with DPRK, may reduce somewhat Chinese suspicions of Japanese proliferation |

| Energy Security Attribute | Path 1: Return to Closed Fuel Cycle Trajectory | Path 2: Slower Return to Closed Fuel Cycle | Path 3: Limited Restart/Once-through Cycle |
|---|---|---|---|
| Military Security—Nuclear Sector | More nuclear facilities, Fuel/SF transport to secure, more Pu handling to secure | Somewhat less quantitatively than Path 1, but qualitatively the same | Arguably less than Paths 1 and 2 |
| Military Security—Conventional Fuel Supply | Less cumulatively than Paths 2 and 3, but not significant enough to allow different security arrangements | More than Paths 1 and 3 overall | Less than Path 2 after ~2045, slightly more earlier; not significantly different for ~3 decades |

## 5.2 Vulnerability to Terrorist Attack under Different Restart Pathways

The three Restart Pathways, in part by design, have different types and levels of vulnerabilities to terrorist attack on nuclear facilities or diversion of nuclear materials. As summarized in Table 5-2, these vulnerabilities can be categorized as those related to existing plutonium stocks, to new separation of plutonium, to spent fuel pools, to reactors, and to spent fuel and MOx fuel handling.

In both Paths 1 and 3 Japan's existing plutonium stocks, including stocks held in Japan and stock held in Europe as following reprocessing of Japanese spent fuel in France and the United Kingdom, are essentially all blended into MOx fuel and irradiated in reactors. In Path 2, some of the stocks are consumed—or more accurately, the use of Pu in MOx fuel in Path 2 exceeds the new separation of Pu in domestic reprocessing from 2015 through 2050—but tens of tons of excess Pu remain in Path 2 as of 2050. These additional stocks, over and above those drawn down over time in Paths 1 and 3, constitute a risk for terrorist attack or diversion that is therefore greater in Path 2.

As Path 3 includes no reprocessing, no additional or new stocks of Pu are created. New stocks would probably, at least temporarily, be stored in what would probably be a different location—although possibly only a different location within the same facility—from where Japan's existing Pu stocks are stored. As such, Paths 1 and 2 would provide new locations that could be targets for terrorist attack and/or diversion of Pu, possibly with the help of industry insiders. Paths 1 and 2 also include higher maximum Pu stocks than in Path 3 (see Figure 4-4), though, again, existing and new Pu stocks may not be in a single place. Although the absolute probability of attack on or diversion of Pu stocks at existing or new facilities cannot be known, clearly the creation of new Pu stocks through reprocessing creates a qualitatively different risk in Paths 1 and 2 than that in Path 3.

Path 3 also includes an aggressive program to de-densify spent fuel pools in Japan, such that within a decade the vulnerability of spent fuel pools to terrorist attack (or accident) yielding very large releases of radioactivity would be significantly less than in Paths 1 and 2. The conversion of spent fuel pools to non-dense-packed configurations means that a pool fire in Path 3 is far less likely to occur, and makes the spent fuel pools in Japan much less of a terrorist target. Spent fuel pools in Path1, and to a somewhat lesser extent in Path 2, also will over time contain more MOx fuel than spent fuel pools in Path 3, resulting in, on average, a different thermal and radiological profile for the contents of spent fuel pools under those paths. It is not entirely clear to us whether the different thermal and radiological profile of spent fuel pools containing significant amounts of MOx spent fuel will increase the potential impact if those pools are targeted by terrorists relative to pools containing little MOx spent fuel—the difference will depend on how MOx spent fuel of differing burnup is distributed in a given pool, among other factors—but more MOx spent fuel in pools, overall, seems likely to increase the risks of larger radiological releases from a given attack.

With more reactors in operation than in the other two Paths, and thus more reactors with higher radioactive inventories within reactor containment vessels, Path 1 offers the highest risk of significant radiological releases from a terrorist attack of the three Paths. Path 3, with relatively few reactors returned to operation, offers the lowest risk of significant radioactivity releases terrorist attack, and Path 2 is more similar to Path 1 than Path 3. With more reactors in operation, Path 1, and to a lesser extent Path 2, arguably offer more paths, as well as more locations for terrorist attack on reactors than Path 3, including attacks initiated with the assistance of personnel working inside reactor complexes. By decommissioning reactors earlier, Path 3 also removes more reactors as potential targets sooner than in Paths 1 and 2.

Consideration of the relative terrorism risks related to spent fuel transfer in the three paths yields results that are not entirely clear-cut. Although significantly less spent fuel is created overall is in Path 3 than in the other two paths (and to a lesser extent, in Path 2 relative to Path 1), the earlier decommissioning of reactors and the de-densification of spent fuel pools in Path 3 mean that more fuel is moved between modes (transferred from at-reactor pools to dry casks either at reactor sites or off-site) earlier. On the other hand, spent fuel is moved to reprocessing in Path 1 and Path 2 (but not in Path 3), requiring transfer from reactor pools to transport casks and then to holding facilities at Rokkasho. Each point of transfer is, in theory, a point at which spent fuel is vulnerable to terrorist attack, potentially resulting in the release of radioactivity if fuel assemblies are damaged or destroyed by terrorist actions.

Finally, since all three paths include the use of MOx fuel, all three paths theoretically could be vulnerable to terrorist diversion of fresh MOx fuel assemblies. Fresh MOx fuel, lacking the high radioactivity of spent fuel, could be chemically processed by terrorists for use in “dirty bombs” or in nuclear weapons. The relative vulnerability of the three paths would, with security arrangements in fuel handling being equal, scale with the total MOx use in the three paths, with Paths 1 and 2 having many times higher MOx use than Path 3. Path 3 generates much more spent fuel in dry cask storage, but dry casks require considerably more effort for terrorists to release and broadcast radioactivity than other forms of spent fuel storage.

***Table 5-2: Comparison of Attributes of Vulnerability to Terrorism under Different Restart Paths***

| Terrorism Vulnerability Attribute | Path 1: Return to Closed Fuel Cycle Trajectory | Path 2: Slower Return to Closed Fuel Cycle | Path 3: Limited Restart/Once-through Cycle |
|---|---|---|---|
| Pu (or Pu/U mixed) Stocks | Existing Pu used up by 2050, but separation of Pu continues | Existing Pu not fully used up by 2050, new separation slower than Path 1 | Existing Pu used, but only by 2050; no new production |
| New Production of Pu/U mixed | Rokkasho in full service by 2020, highest maximum total Pu stocks | Slower production and thus less than Path 1, lower maximum stocks | None |
| Spent Fuel Pools | Dense-packed, more hot fuel | Dense-packed, less hot fuel | Converted to non-dense-packed by 2022 |
| Reactors | More operating, more thermally and radiologically "hot" fuel than Paths 2 and 3 | Somewhat less than Path 1 | Considerably less than Paths 1 and 2 |
| Spent Fuel Handling | More movement to/from reactors, storage, transport casks, reprocessing, transport creates more opportunities for attack/diversion | Somewhat less than Path 1 | More spent fuel movement earlier to dry cask storage (but cooler fuels on average) |
| MOx Fuel Handling | More MOx use, thus More MOx fuel movement, more risk of diversion than Paths 2 and 3 | Somewhat less than Path 1 | Considerably less than Paths 1 and 2 |

# 6 Conclusions: Of the Many Considerations in Setting Nuclear Spent Fuel Management Policy, Cost is Insignificant

Based on the analysis shown here, it appears that there are no clear and significant differences between the three restart cases presented on an economic cost basis. This result implies that if Japan is to choose a future for its nuclear policy, it will have to do so largely on the basis of non-cost considerations. These considerations include the radiological risk associated with an accident at or attack on one or more nuclear facilities, a consideration that is complex because it includes both components that are controllable—for example, how the nuclear spent fuel management system is configured, and what security and safety measures are in place—and those that are mostly not—the probability of an accident-triggering natural disaster or a terrorist attack. Other considerations, perhaps equally complex and with deep roots in Japan's nuclear policy, include the ongoing support of, roles for, and prominence associated with Japan's nuclear researchers and industry, the allocation of Japan's energy research and development budgets among different priorities (such between nuclear and renewable energy options), the Japanese public's view of nuclear power in the wake of the Fukushima accident, and Japan's leadership in addressing climate change by reducing greenhouse gas emissions.

The three different Restart Paths presented in this Report imply significantly different futures for the Japanese electricity sector. Path 1 and, to a slightly lesser extent, Path 2 continue the vision of an eventual closed fuel cycle and offer essentially the same risks of accidental or terrorist-caused releases of radiological materials that are present today—though today's risks have been reduced somewhat from pre-Fukushima risks by post-Fukushima actions to add redundancy of key systems, physically harden, and improve security at nuclear facilities. Path 3, by converting dense-packed spent fuel pools to non-dense-packed configuration, substantially reduces the risk of large radiological releases from spent fuel pools due to accident or attack within the next decade, relative to the other two Paths. Path 3 also decommissions existing reactors sooner, and does not include any new reactors, resulting in a near phase-out of nuclear power in Japan by 2050. This, plus a larger commitment to renewable energy and energy efficiency than in the other two paths, makes Path 3 a qualitatively different direction for Japan's energy system than Paths 2 or 3.

The three Restart Paths described are, of course, just examples chosen to illustrate a range of possible options for Japan, and each could be changed to test the impact of additional policy assumptions. For example, adopting alternative fuel cycle management options can reduce exposure to potential terrorist incidents (and associated radiological risk) in any of the paths, but there are tradeoffs—different approaches lead to different exposures. For example, the Limited Restart Path (Path 3) includes some MOx use, but policymakers might also reasonably decide not to use MOx in a limited restart regime. Not using MOx fuel avoids the handling of plutonium when it is blended with uranium oxides to produce MOx, and as such arguably avoids a potential point of diversion of plutonium by for use in weapons (or for extortion), also avoids the production of MOx spent fuel, which has thermal and radiological properties that make it more difficult and expensive to manage than UOx spent fuel. On the other hand, not using MOx fuel relinquishes the opportunity to use up existing stockpiles of plutonium, thereby failing to reduce the risk of proliferation associated with the diversion of Pu now in storage, and/or forcing a different solution to Pu disposal. As another example, policymakers and nuclear operators could choose to reduce the density of spent fuel storage as a part of Paths 1 and 2, which might be done, albeit on a more drawn-out schedule than in Path 3, even without much additional deployment of dry cask storage (beyond that planned at the Mutsu facility).

In each of the three Paths, and in Path 3 in particular, both policy changes and considerable work with community hosts will be needed to allow a change spent fuel management practices in Japan. Path 3 will involve dry cask storage of spent fuel, in many cases likely at reactor sites, that will require renegotiation of the "deals" between nuclear reactor operators and their community hosts, as well as, in some cases, changes in laws to allow on-site dry cask storage. This will likely require renegotiating compensation agreements with local communities—some of which may lose a significant source of income if reactors are decommissioned. Another requirement that should not be underestimated is the need to provide opportunities for conversations with local communities about the facilities they are hosting, to educate community members regarding options for spent fuel management and their relative risks, and to provide communities with the technical assistance needed to meaningfully engage in conversations and, when needed, negotiations with reactor operators and national government agencies about the facilities they are hosting and the risks and benefits associated with those facilities.

Exposure to potential future high costs for uranium is often cited as a key reason to pursue a closed nuclear fuel cycle. Our analysis of the three Restart Paths considered in this Report suggest that even if uranium costs ramp up considerably over the next three decades, the per-unit (Yen/kWh) cost of nuclear fuel cycle activities—themselves a relatively small part of overall nuclear power costs—will be higher in Paths including reprocessing than Paths without reprocessing. Moreover nuclear fuel cycle costs in general, though they appear large in absolute terms, at 2 to 18 trillion Yen over 2015-2050, are dwarfed by the overall costs of providing electricity for Japan over that period, which are in the range of 500 trillion Yen, and vary, on a cumulative basis, only a few percent between Paths. Even aggregate greenhouse gas emissions, despite the required higher use of fossil fuels in Path 3 (and to a lesser extent, Path 2) to compensate for nuclear power not generated, are not very different between the three paths over the next 35 years, and the difference is likely well within the substantial range of uncertainty for projections of this type.

This lack of difference between Paths in costs and other more-or-less easily quantifiable metrics means that Japanese policymakers, institutions, and the general public must implicitly or explicitly choose a future nuclear energy and broader energy path for the nation based on criteria that are much more difficult to measure, consider, and come to agreement on. Are differences in the potential risks of radiological release caused by accidents or terrorists attacks worth a significant change in how spent fuel is managed in Japan? Can Japan's nuclear sector accept a change in role from focusing on nuclear energy systems of the future to being largely stewards of the safe handling and storage of nuclear materials? How important to is it to Japan to retain an edge in nuclear technology over other regional powers, including the usually unspoken (but apparently not disregarded) issue of retaining a route to nuclear weapons, in the event that nuclear threats from other nations and/or U.S. assurances of support propel Japan in that direction? Will Japan's policymakers, institutions, and public be ready, willing, and/or able to make a transition to reliance on non-nuclear energy sources, and in particular, renewable energy sources? These are not questions that the authors of this Report can possibly answer, but they must be, and doubtless are being, considered as Japan decides on the future of its nuclear energy system.