Nuclear Fuel Cycle Cooperation Scenarios for East Asia and the Pacific: Analytical Approach and Initial Results

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FUEL CYCLE COOPERATION: OUTLINE OF PRESENTATION

- Overall East Asia Science and Society (EASS) Project Approach, Organization
- Nuclear Capacity “Paths” for East Asia and the Pacific
- “Scenarios” of Regional Nuclear Fuel Cycle Cooperation
- Analytical Approach, and Key Results
- Conclusions and Next Steps

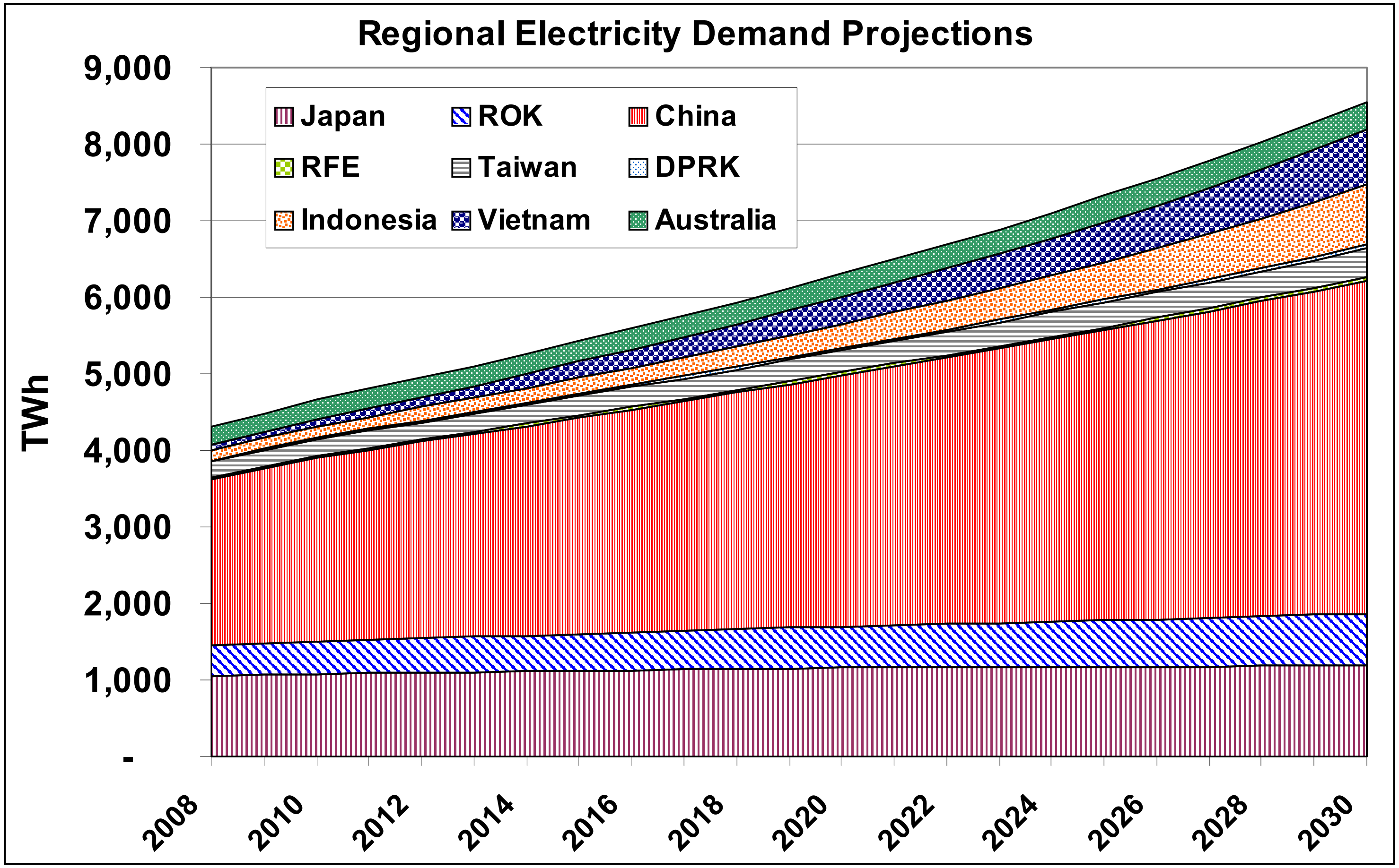
Overall EASS Project Organization and Approach

- 10 Country Working Groups in East Asia/Pacific nations
  - Modeling energy paths, including BAU, “maximum nuclear”, “minimum nuclear”
  - Using common software (LEAP) and analysis methods
  - Models nuclear energy paths in context of full energy sector, economy of each country
- Group of nuclear specialists advising/contributing on formulation and analysis of regional scenarios for nuclear fuel cycle cooperation
  - Including J. Kang (ROK), T. Suzuki and T. Katsuta (Japan), A. Dmitriev (RF), and others

Overall EASS Project Organization and Approach

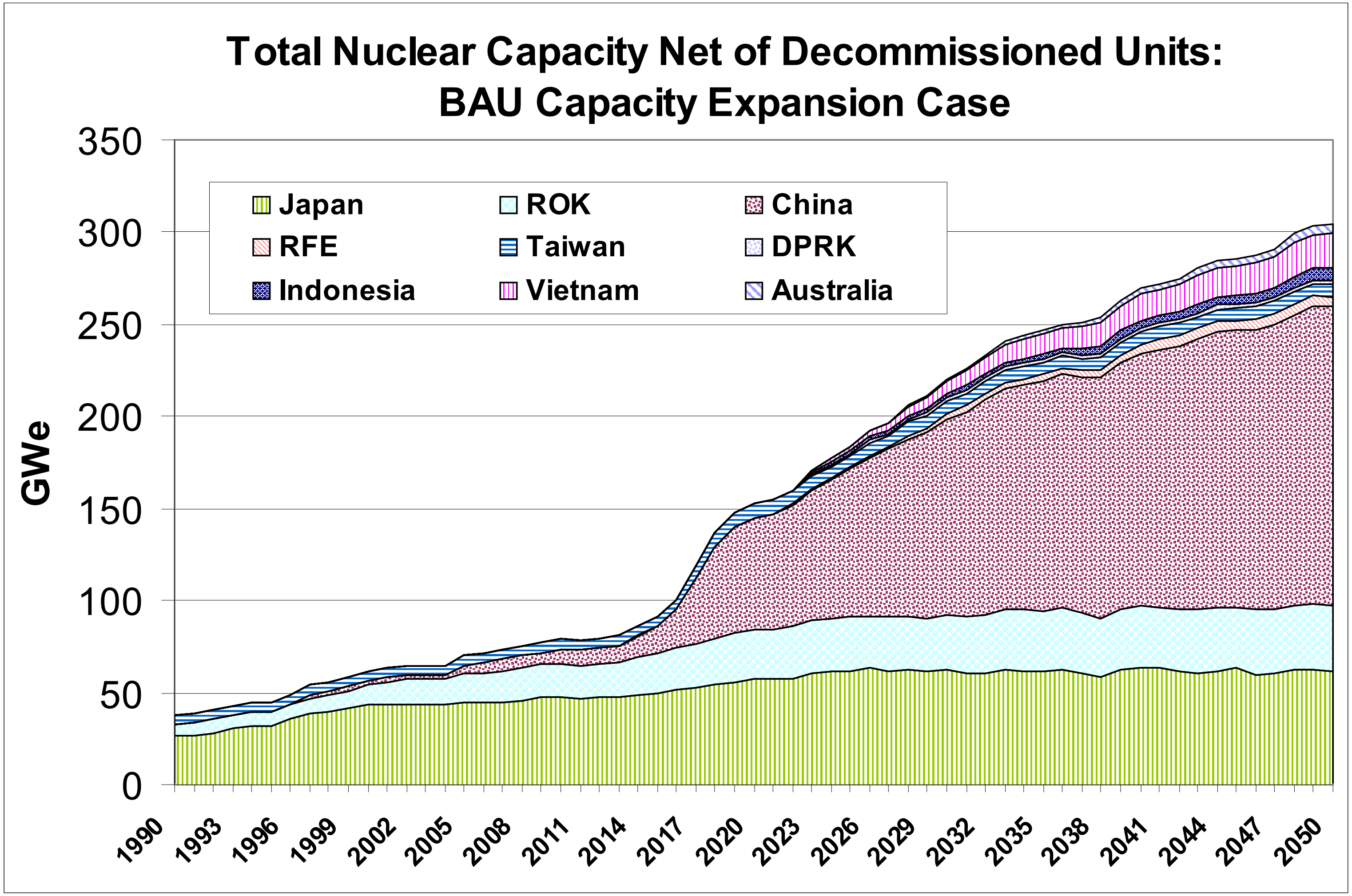
- Nuclear paths by country specified by working groups, in some cases modified/updated somewhat, serve as basis for calculating fuel requirements, spent fuel arisings
- Apply to nuclear paths four scenarios of regional cooperation (or lack of cooperation) on nuclear fuel cycle issues
  - Evaluate required inputs, implied outputs, costs, and other key Energy Security (broadly defined) attributes (quantitative and qualitative)

GROWTH IN ELECTRICITY DEMAND IN EAST ASIA/PACIFIC

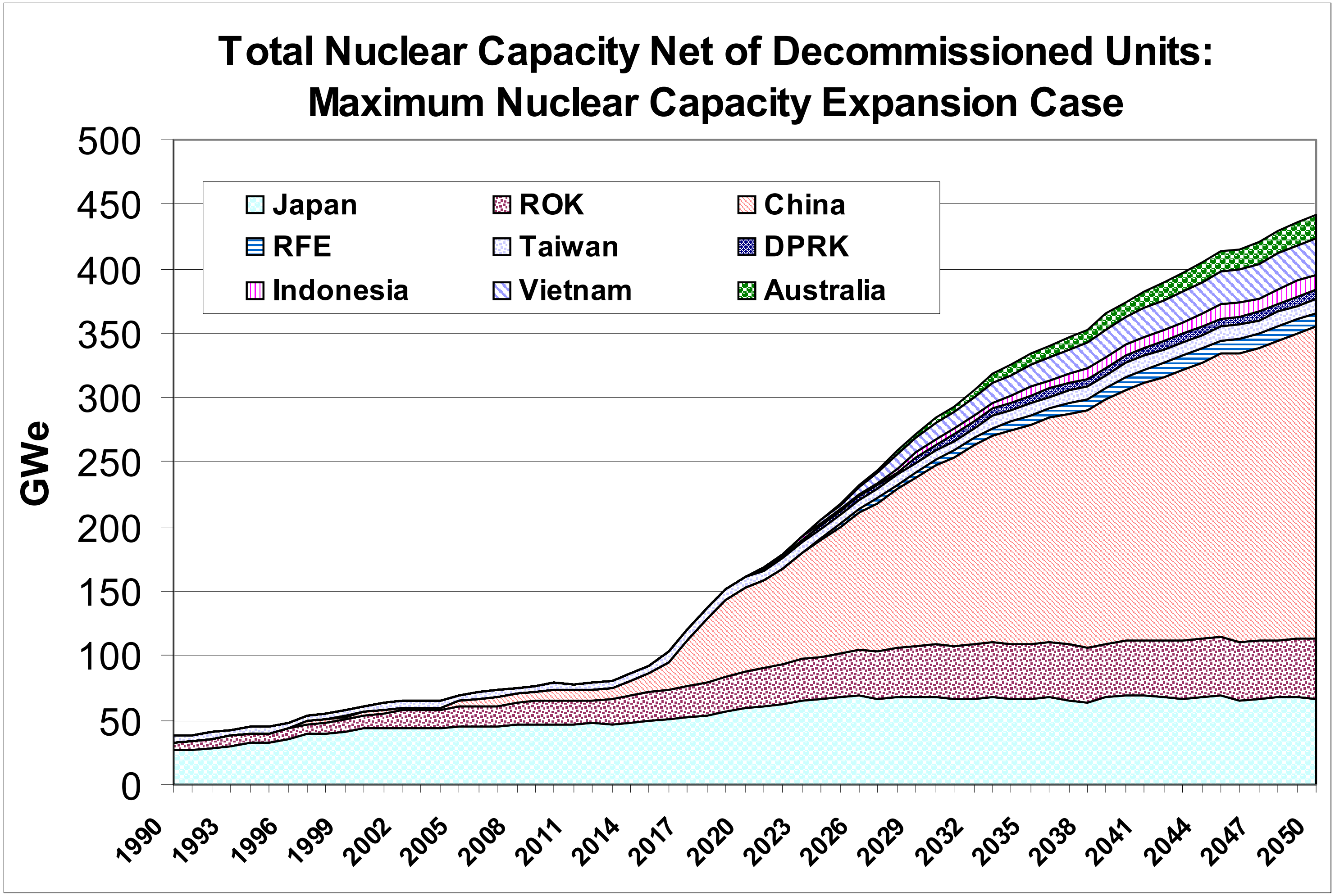


- Projections from EASS LEAP data and other sources

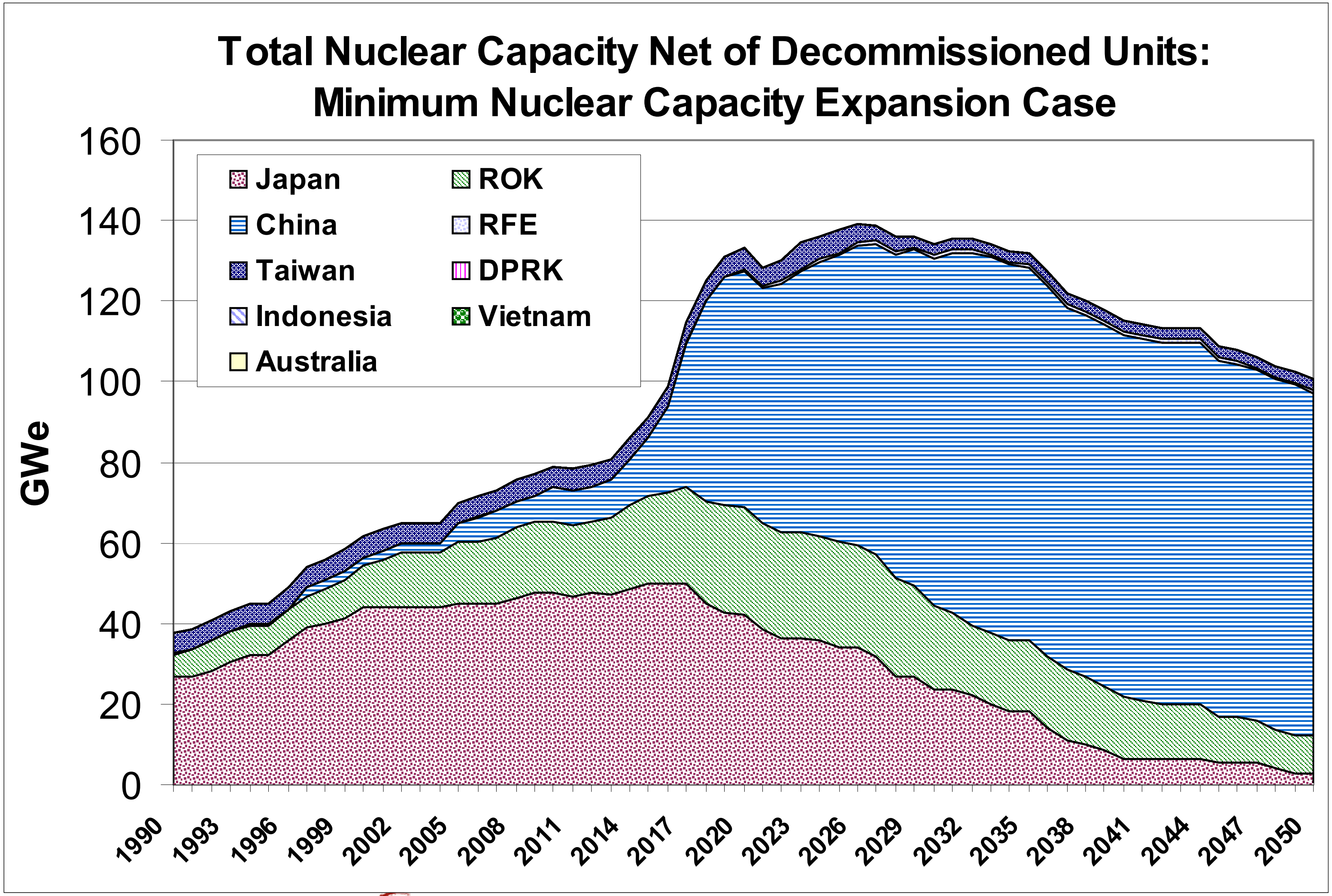
Nuclear Capacity Paths in East Asia/Pacific: BAU Paths



Nuclear Capacity Paths in East Asia/Pacific: Maximum Nuclear Paths



Nuclear Capacity Paths in East Asia/Pacific: Minimum Nuclear Paths



"Scenarios" of Regional Nuclear Fuel Cycle Cooperation

- Four "Scenarios" of regional nuclear fuel cycle cooperation (or lack of cooperation) evaluated
  1. **"National Enrichment, National Reprocessing"**
  2. **"Regional Center(s)"**
  3. **"Fuel Stockpile/Market Reprocessing"**
  4. **"Market Enrichment/Dry Cask Storage"**
- Scenarios chosen not necessarily as most **likely**, but as **illustrations** of possible cooperation arrangements
  - To allow for analysis by country, many assumptions as to individual national activities go into each scenario
  - Common assumptions across scenarios (such as U, SWU costs)
- In general, where scenarios include regionally-shared fuel cycle facilities, locations of facilities are not specified
  - In some cases, more than one facility could serve the region
  - In practice, choices of countries to host regional facilities will be limited by multiple considerations (geological, political, social…)

"Scenarios" of Regional Nuclear Fuel Cycle Cooperation

Scenario 1: "National Enrichment, National Reprocessing"

- Major current nuclear energy users (Japan, China, the ROK) each pursue their own enrichment and reprocessing programs
  - Japan, ROK import U; other nations eventually produce 50% of U needs domestically (except Australia, 100%, RFE, 100% from RF)
  - All required enrichment in Japan, China, ROK accomplished domestically by 2025 or 2030 (other countries import enrichment services)
  - Nuclear fuel is fabricated where U is enriched
  - Reprocessing, using 80, 60, and 50 percent of spent fuel (SF) in Japan/ROK/China, respectively, is in place in Japan by 2020, in ROK/China by 2030
  - 50% of reactors in Japan, China, ROK eventually use 20% MOx fuel, but starting earlier in Japan
  - Disposal of spent fuel/high-level nuclear wastes from reprocessing done each individual country (interim storage or dry cask assumed → 2050)
  - Security arrangements made by individual countries

"Scenarios" of Regional Nuclear Fuel Cycle Cooperation

Scenario 2: "Regional Center(s)"

- Uses one or more regional centers for enrichment/reprocessing/waste management, operated by international consortium, drawn upon and shared by all nuclear energy users in region
  - Consortium imports U for enrichment from international market, shares costs; China limits own production to current levels
  - Nuclear fuel (including MOx) is fabricated at regional center(s)
  - Reprocessing of SF from Japan/ROK/China in same amounts as in Scenario 1, but in regional center(s) by 2025; reprocessing of 50% SF from other nations by 2050
  - MOx use as in Scenario 1
  - Disposal of spent fuel and high-level nuclear wastes from reprocessing in coordinated regional interim storage facilities, pending development of permanent regional storage post-2050

“Scenarios” of Regional Nuclear Fuel Cycle Cooperation

Scenario 3: “Fuel Stockpile/Market Reprocessing”

- Regional U purchase, use of international enrichment, but countries cooperate to create a fuel stockpile (one year’s consumption, natural U and enriched fuel); reprocessing services purchased from international sources
  - Enrichment from international sources except for existing Japanese, Chinese capacity
  - Nuclear fuel (**excluding** MOx) is fabricated where enriched
  - Reprocessing of SF from in same amounts as in Scenario 2, but at international center(s), where MOx fuel is fabricated for use in region (MOx use is as in Scenarios 1 and 2)
  - Disposal of spent fuel and high-level nuclear wastes from reprocessing in international interim storage facilities, possibly including facilities in the region, pending development of permanent regional storage post-2050

"Scenarios" of Regional Nuclear Fuel Cycle Cooperation

Scenario 4: "Market Enrichment/Dry Cask Storage"

- Almost all countries continue to purchase enrichment services from international suppliers; all spent fuel goes into dry cask storage at reactor sites or interim storage facilities
  - U resources purchased by regional consortium
  - Enrichment from international sources except for existing Chinese capacity; existing Japanese capacity closed after 2020
  - Japan's MOx use phased out by 2013; no MOx use elsewhere
  - Japan and China cease reprocessing in 2015—no other countries reprocess SF (at international or in-region facilities)
  - Cooled spent fuel stored at reactor sites in dry casks, or in national interim storage facilities (Japan, RFE); high-level wastes from reprocessing (before 2016) placed in interim storage facilities

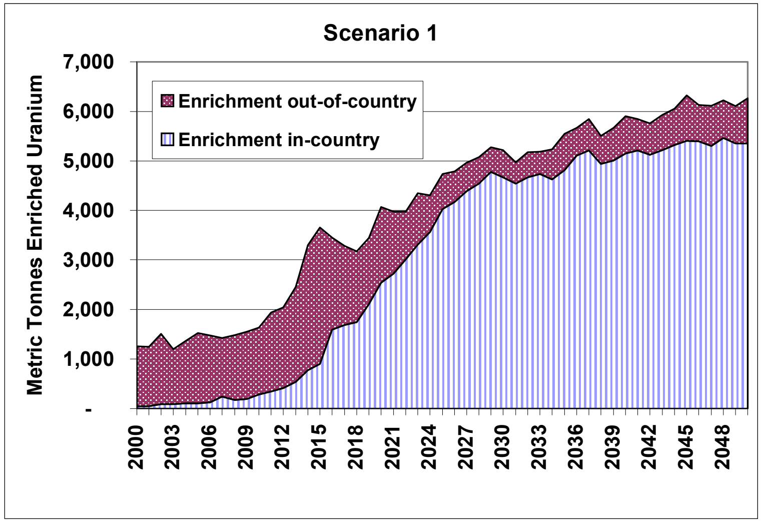
Analytical Approach, and Key Results

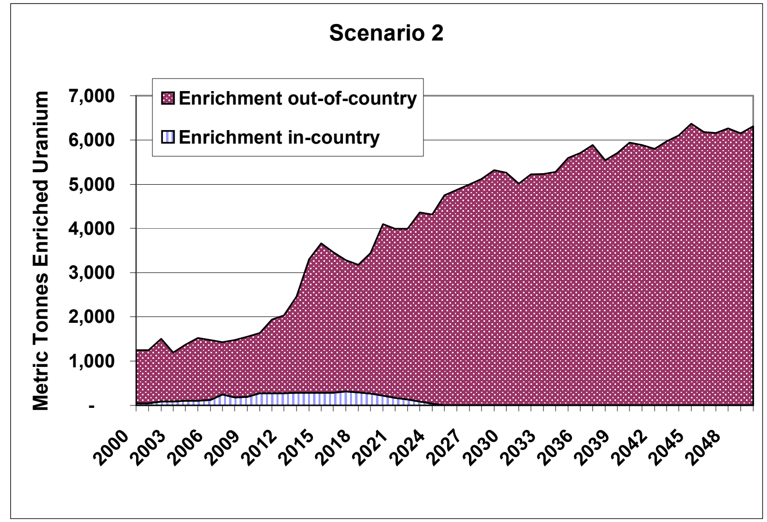
- Nuclear paths specified by EASS country working groups, in some cases modified, serve as basis for calculating fuel requirements, spent fuel arisings
- Apply to each nuclear path, in each country, 4 scenarios of regional cooperation (or lack of cooperation) on nuclear fuel cycle issues
  - Timeline: 2000 through 2050
  - Stock and flow accounting to generate estimates of major required inputs/outputs of to nuclear fleet in each country
  - Fuel cycle nodes modeled: U mining/milling, U transportation/enrichment, fuel fabrication/reactor fuel transport, reprocessing/spent fuel management

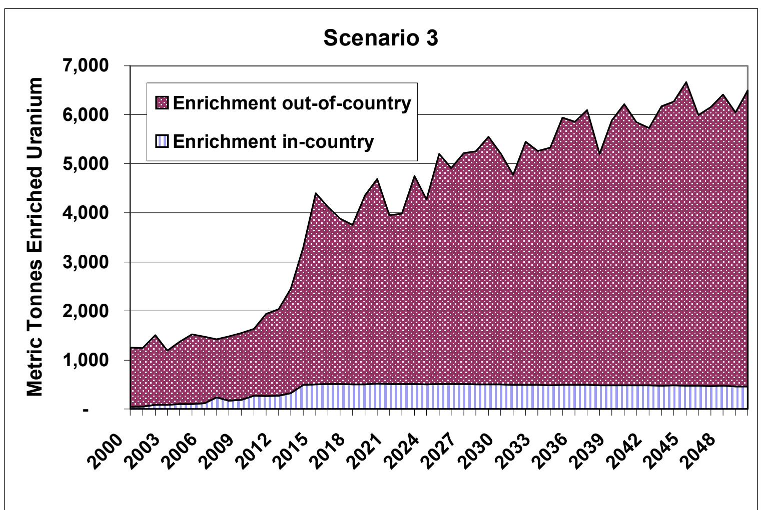
Analytical Approach, and Key Results

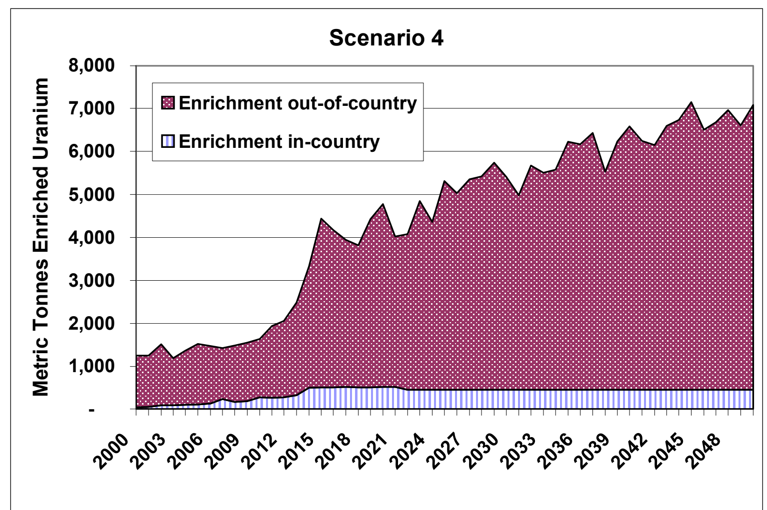
- Key inputs at each node:
  - U and Pu, energy, enrichment services, transport services, money, by country/year
- Key outputs at each node:
  - U, Pu, spent UOx and MOx fuel, major waste products, by country/year
- Results for 12 different regional cooperation scenario and nuclear power development path combinations
  - Quantitative results coupled with qualitative considerations to provide a side-by-side comparison of Energy Security attributes of four cooperation scenarios
  - Energy Security comparison methodology as developed by Nautilus and partners starting in 1998

Analytical Approach, and Key Results: Enrichment needs net of MOx use





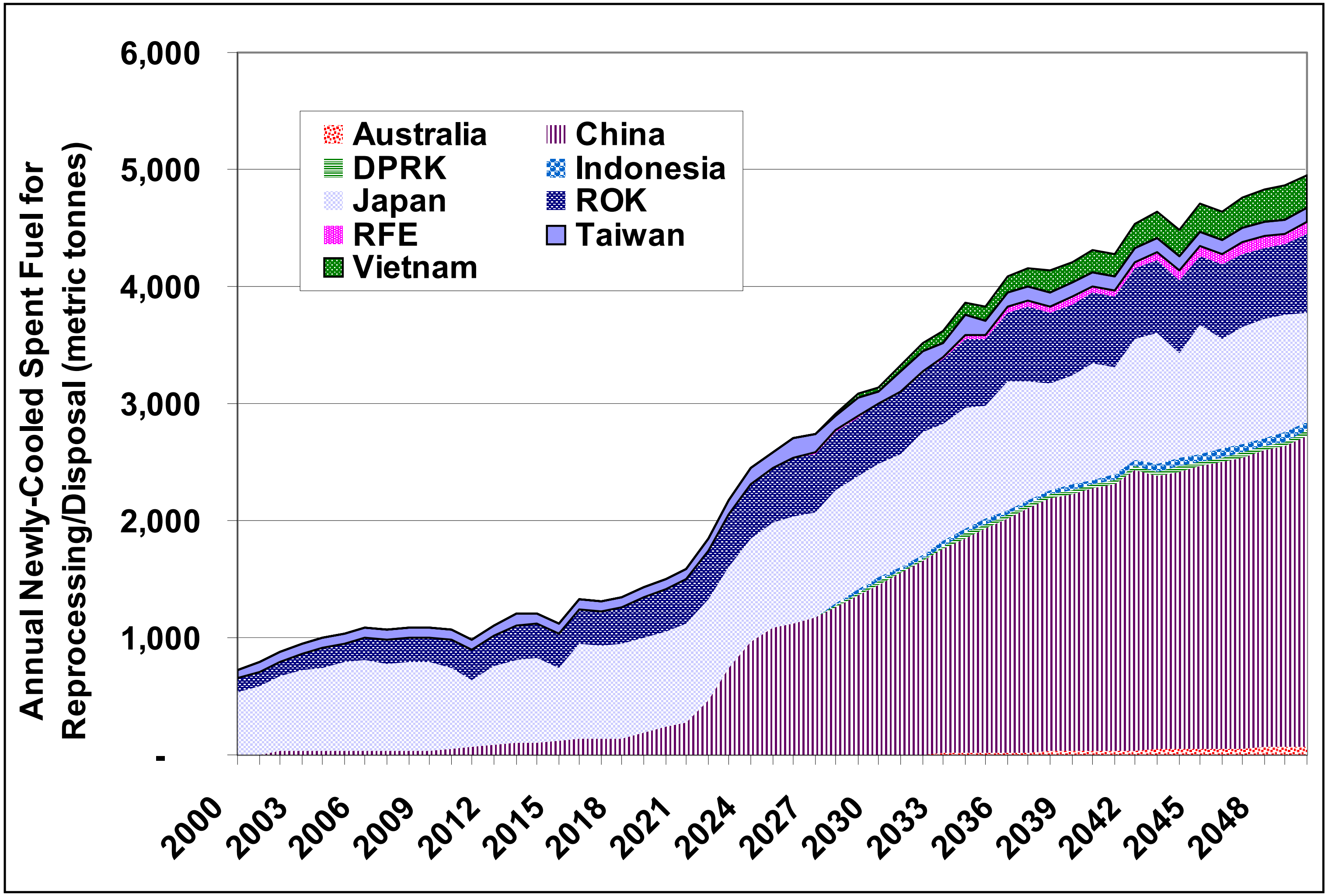




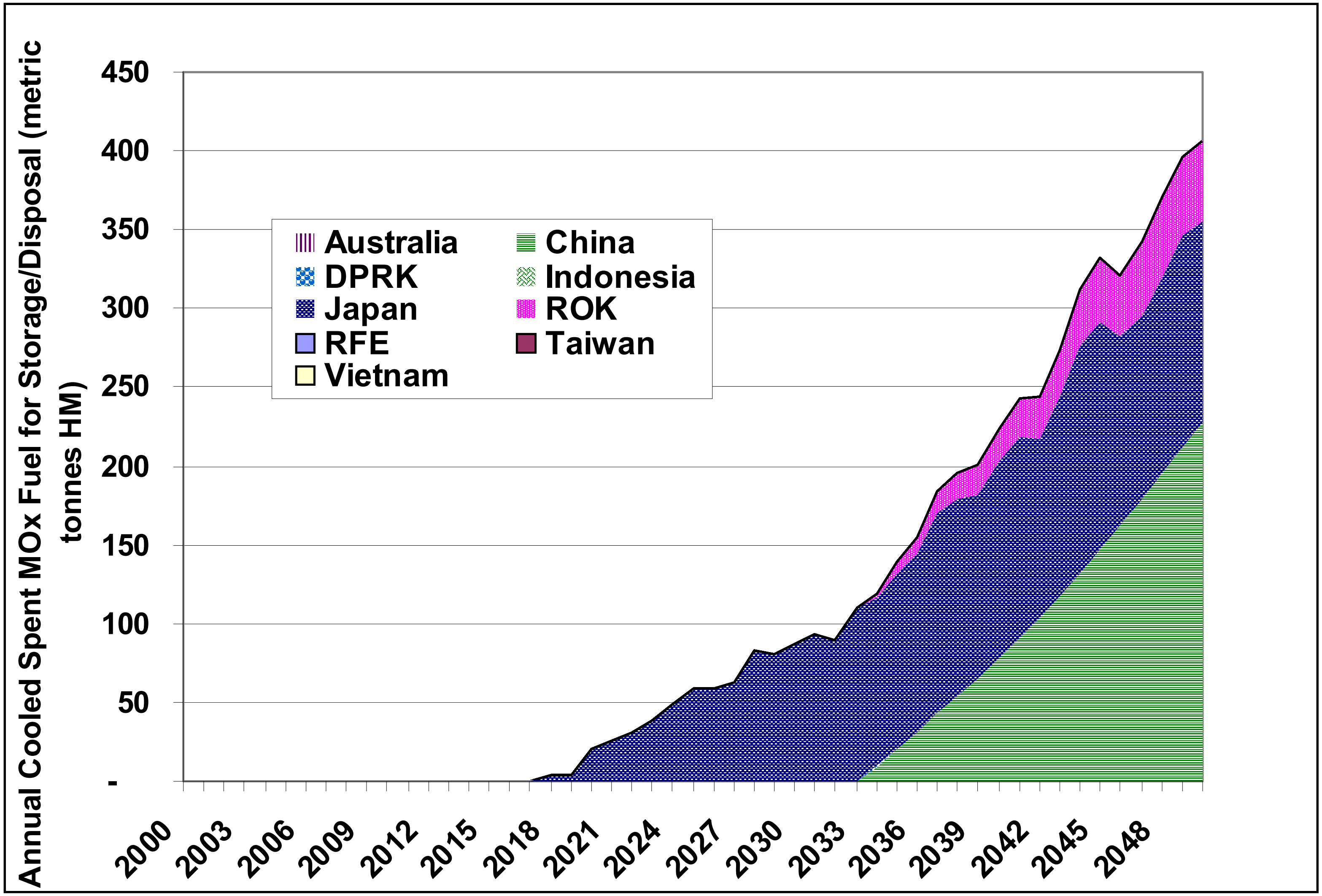
Analytical Approach, and Key Results: Enrichment needs net of MOx use

- Total enrichment services requirements for BAU paths are about 45 M kg SWU in 2050 in Scenarios 1-3, about 50 M for Scenario 4 (no MOx use)
  - For MAX path, needs rise to about 70 M SWU/yr in scenarios without substantial MOx use, about 10% less in scenarios with MOx use
  - For MIN path, requirements fall from a maximum of about 20 million SWU in 2020s to about 15 million SWU in 2050.
- Under Scenario 1, additional enrichment capacity in the countries of the region will need be required under all nuclear capacity expansion paths
  - Under other scenarios, global enrichment capacity by 2015 would need to be expanded significantly to meet 2050 regional plus out-of-region enrichment demand under BAU or MAX expansion paths
  - Under MAX expansion path and Scenario 1, China alone would need to build new enrichment capacity by 2050 approximately equal to 60 percent of today's global capacity
  - Under MIN expansion path, international enrichment facilities as of 2015 are likely sufficient to meet regional and out-of-region demand without significant expansion

Analytical Approach, and Key Results: Annual Cooled UOx SF (Scen-1, BAU path)

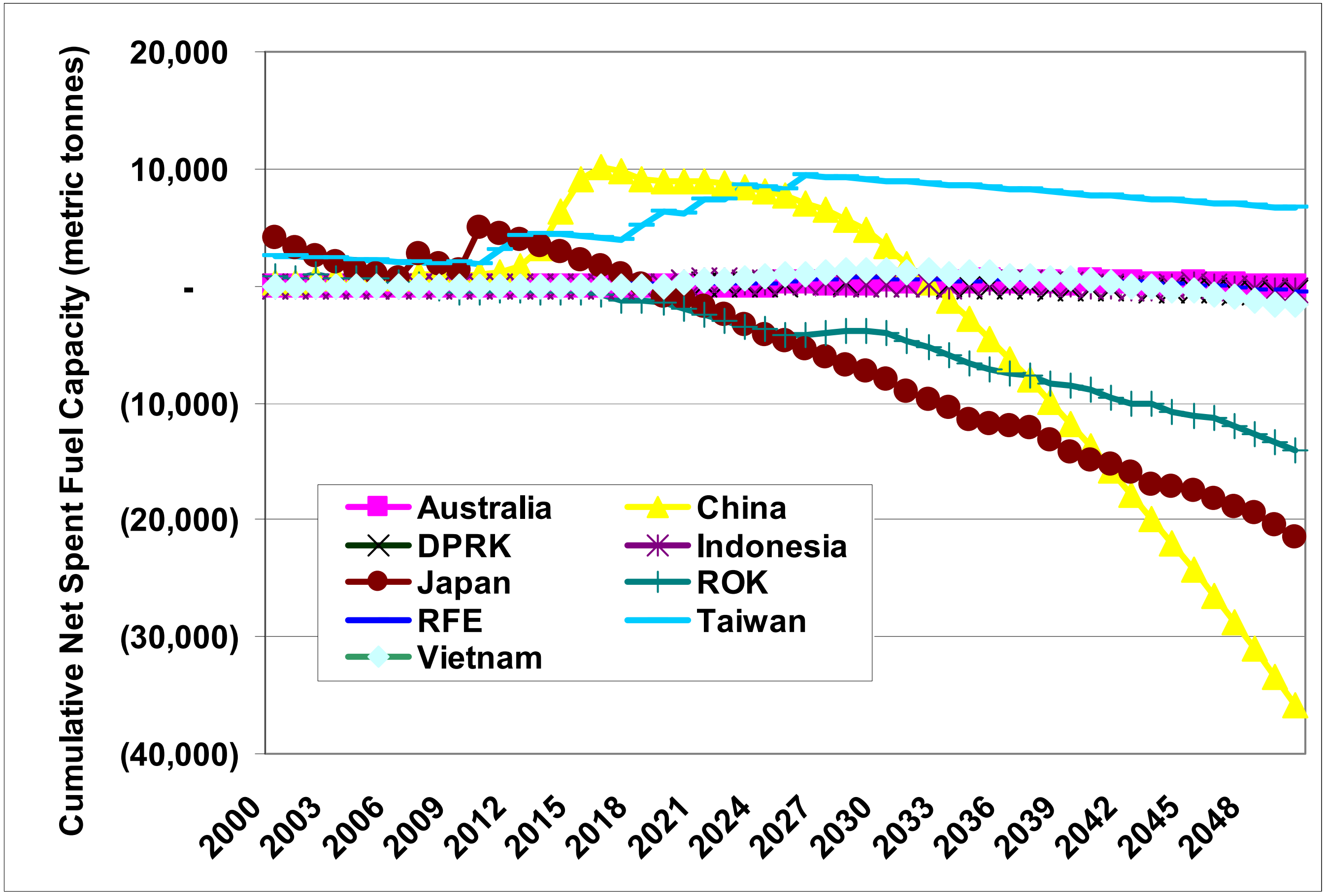


Analytical Approach, and Key Results: Annual Cooled MOx SF (Scen-1, BAU path)



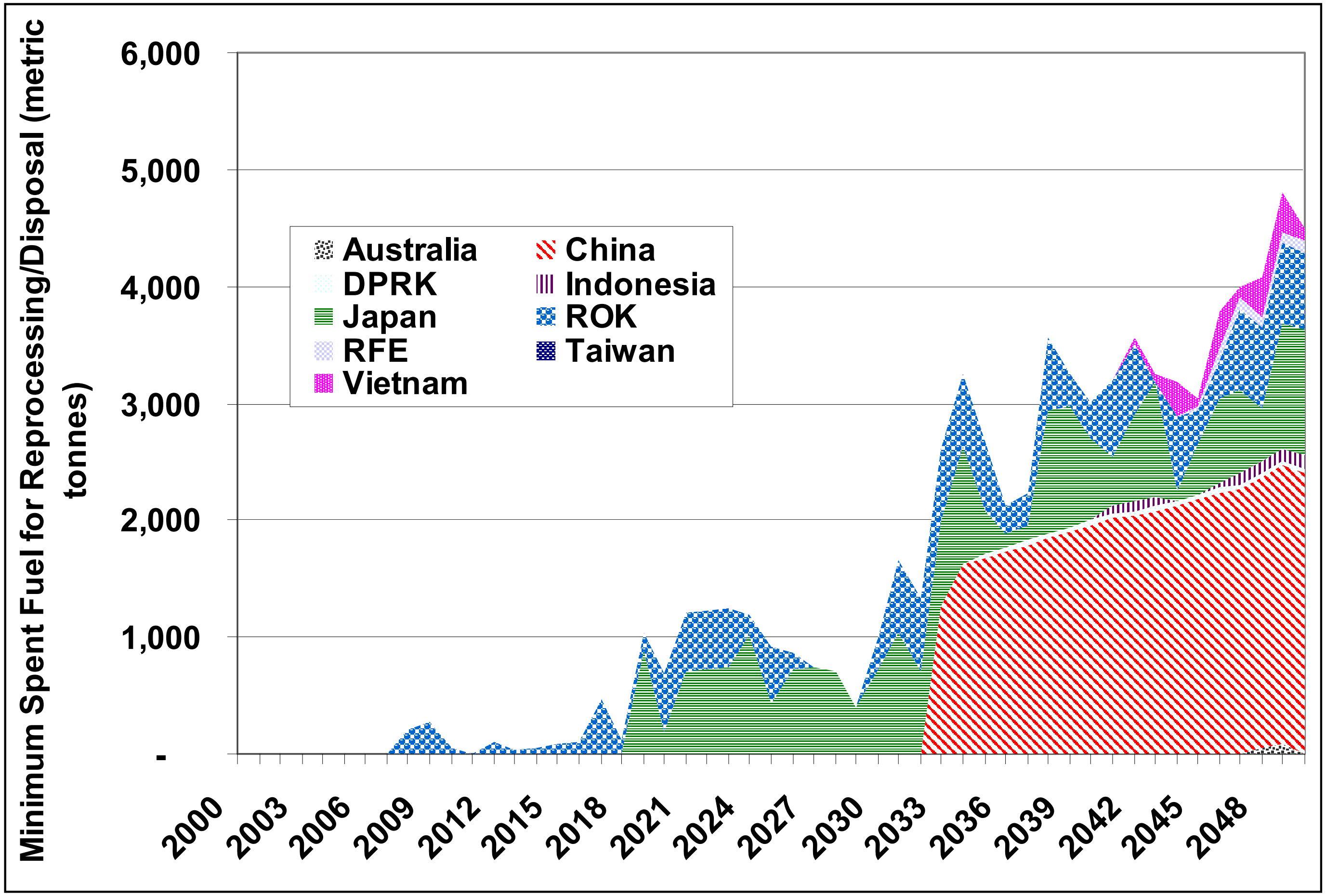
Analytical Approach, and Key Results

- Cumulative difference between 90% of capacity in spent fuel pools at domestic reactors and cumulative amount of spent fuel produced, BAU Nuclear Capacity Expansion Path and Regional Scenario 1



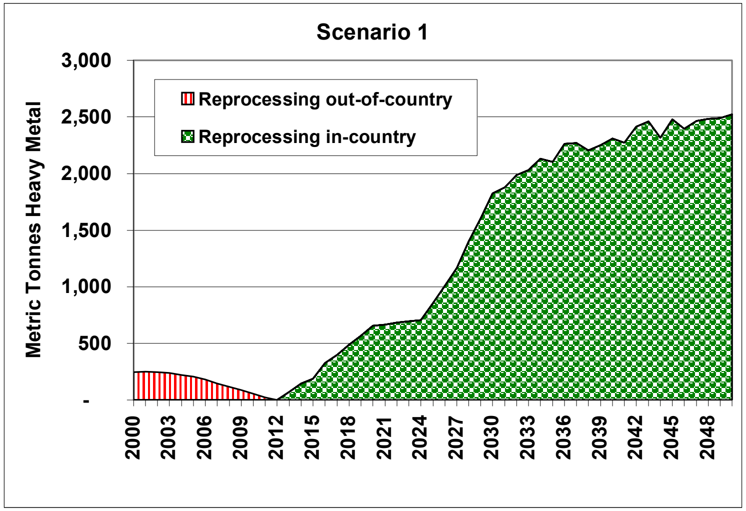
Analytical Approach, and Key Results

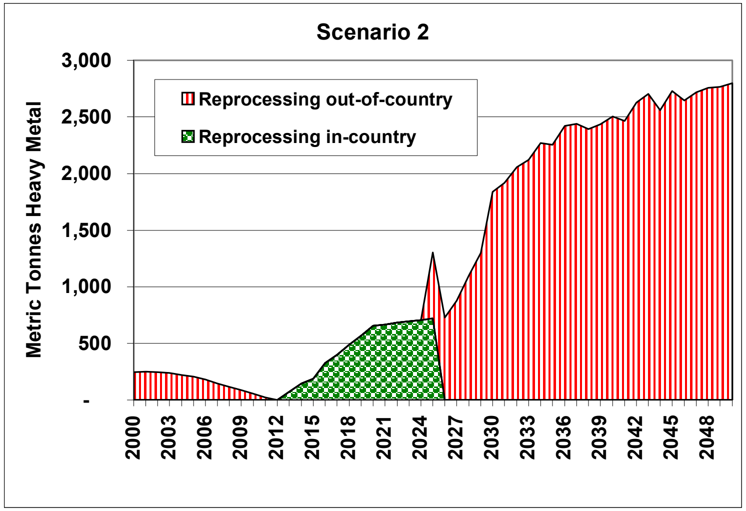
- Implied Minimum Annual New Requirements for Out-of-reactor-pool Storage, Disposal, or Reprocessing, BAU Nuclear Capacity Expansion Path and Regional Scenario 1

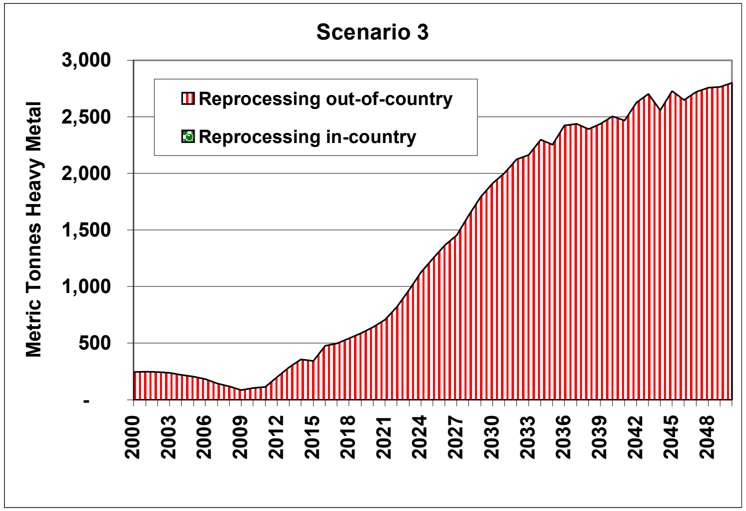


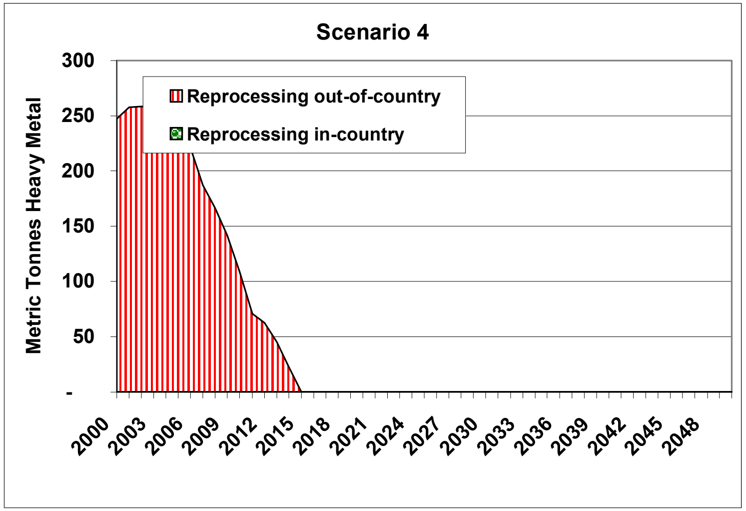
Analytical Approach, and Key Results

- Cooled spent LWR fuel reprocessed in-country and out-of-country from regional spent fuel, by scenario, BAU Capacity Expansion Path



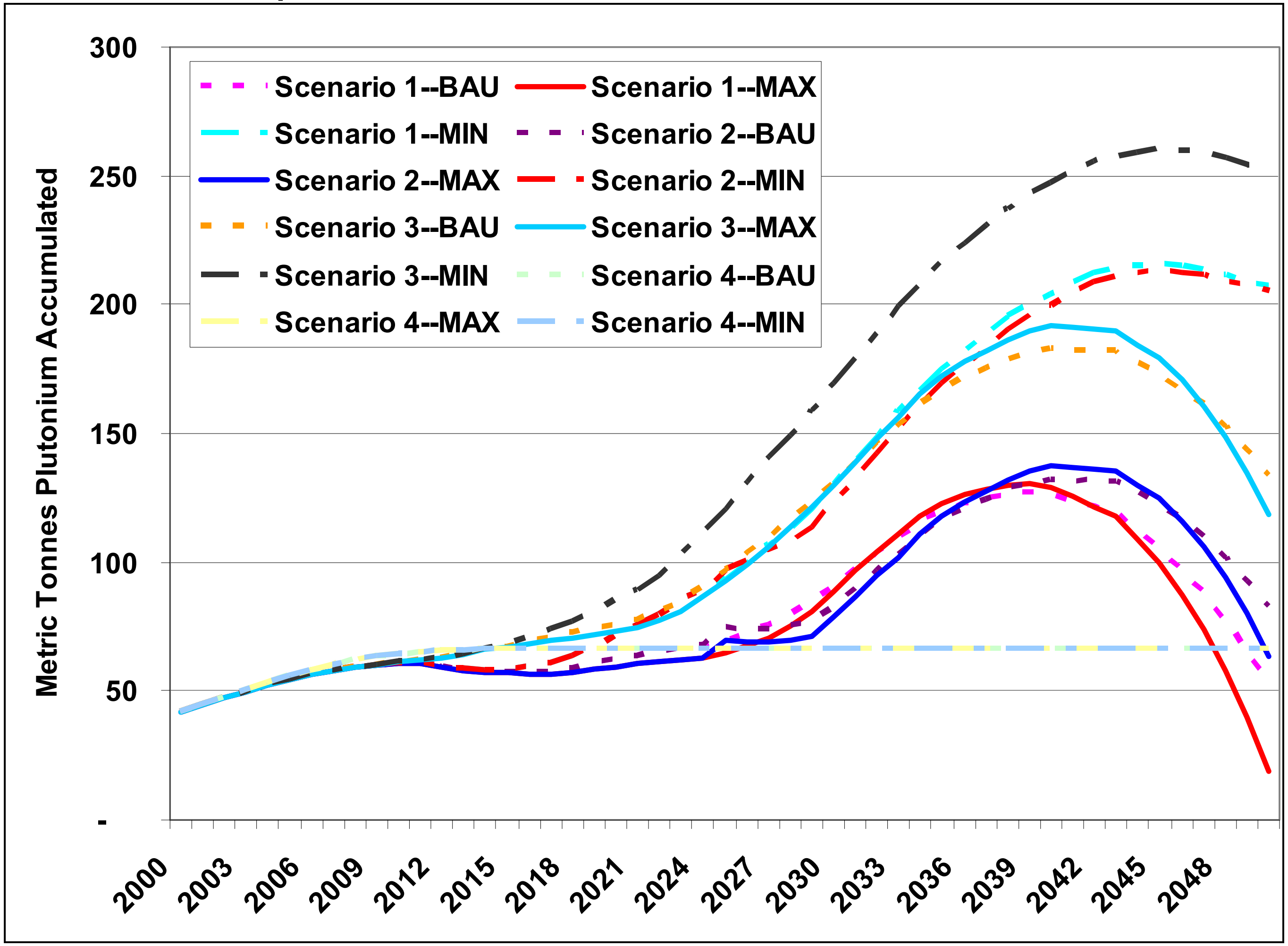






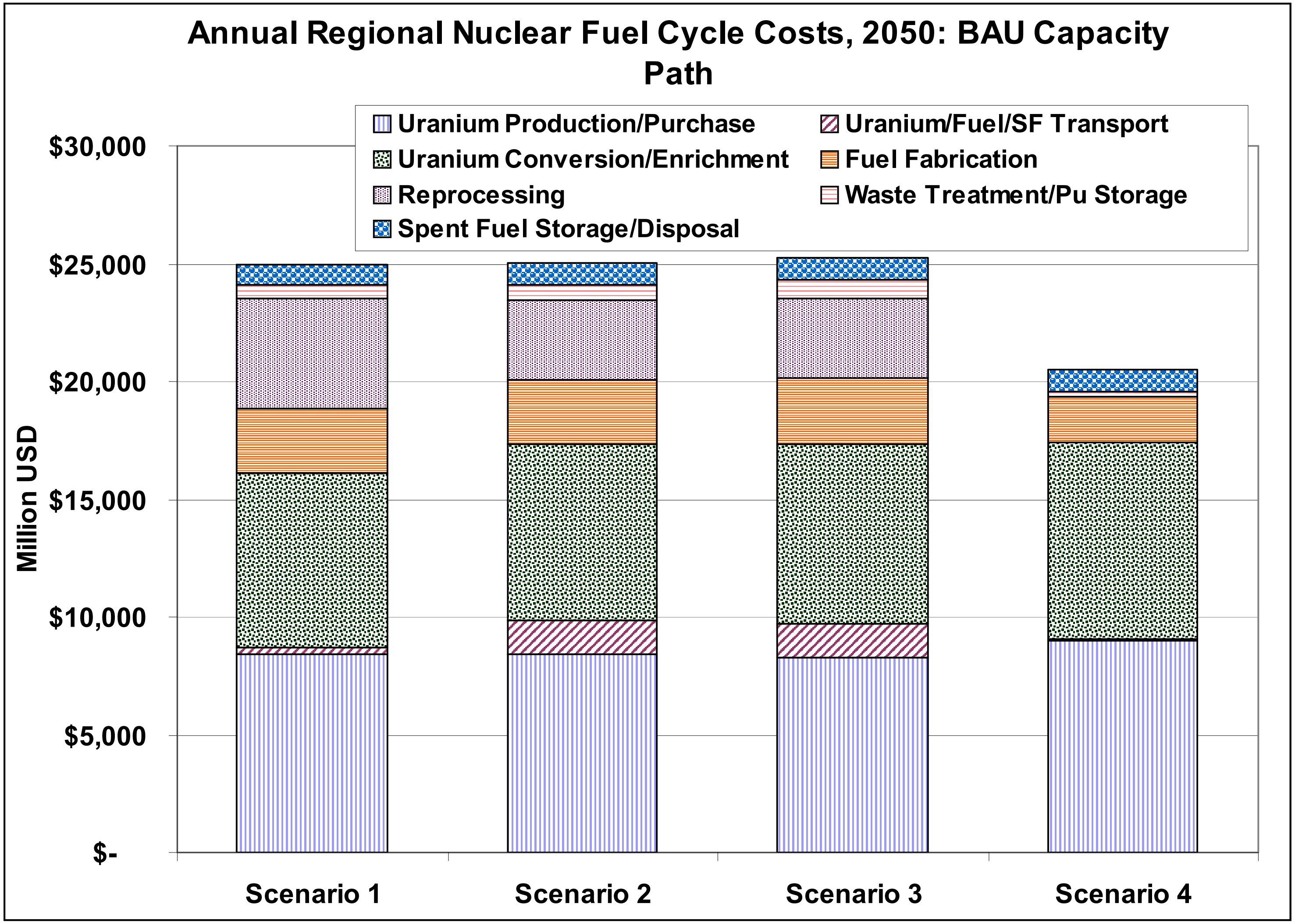
Analytical Approach, and Key Results

- Cumulative mass of Pu separated from SF reprocessed (all locations), less Pu used to make MOx fuel, by Regional Scenario and Nuclear Expansion Path



Analytical Approach, and Key Results

- Annual fuel cycle costs in 2050, not including generation costs



Analytical Approach, and Key Results

Energy Security Attributes of Regional Nuclear Fuel Cycle Cooperation Options: Summary Results

- **Energy Supply Security**
  - Scenario 1, with individual nations running enrichment and reprocessing facilities, provides greater energy supply security at the national level
  - On a regional level, scenarios 2, 3, possibly 4 may offer better energy supply security, including stockpiles aspect of scenarios 3 and 4
- **Economic Security**
  - Scenarios including reprocessing have significantly higher annual costs over entire fuel cycle than scenario 4, but additional cost is a small fraction of overall cost of nuclear power
  - Use of reprocessing and related required waste-management technologies may expose countries of the region to risks of unexpectedly high technology costs
  - Required additional (government/government-backed) investment, (tens of billions of dollars, at least) in reprocessing may divert investment from other activities, within the energy sector and without
  - Development of in-country and in-region nuclear facilities will have its own job-creation benefits in the nuclear industry and related industries

Analytical Approach, and Key Results

Energy Security Attributes of Regional Nuclear Fuel Cycle Cooperation Options: Summary Results

- **Technological Security**
  - Scenario 1 makes nations dependent on specific technologies and plants for the operation of their nuclear energy sector
  - Scenario 4, using dry-cask storage, depends least on performance of complex technologies, but depends on future generations to manage today's wastes (but so do other scenarios)
- **Environmental Security**
  - Scenarios 1 through 3 offer ~10% less Uranium mining and processing, with attendant impacts/waste streams, relative to scenario 4
  - Reduced U mining/milling/enrichment offset by additional environmental burden of need to dispose of solid, liquid, radioactive wastes from reprocessing
  - Differences between scenarios in generation of greenhouse gases, more conventional air/water pollutants likely to be relatively small, and inconsequential compared with overall national/regional emissions

Analytical Approach, and Key Results

Energy Security Attributes of Regional Nuclear Fuel Cycle Cooperation Options: Summary Results

- **Social-Cultural Security**
  - Given growing civil-society movements in some countries with concerns regarding nuclear facilities power in general, reprocessing in particular, and local siting of nuclear fuel-cycle facilities, Scenario 4 arguably offers the highest level of social-cultural security
    - In some cases current laws—in Japan, for example—would have to be changed to allow long-term at-reactor storage; changing those laws has its own risks.
- **Military Security**
  - Safeguarding in-country enrichment and reprocessing facilities in Scenario 1, including stocks of enriched U and of Pu, puts largest strain on military and/or other security resources
  - Security responsibilities are shifted largely to the regional level in Scenario 2, to the international level in Scenario 3
    - More stress on the strength of regional and international agreements
  - Level of military security (guards and safeguard protocols) required in Scenario 4 is likely considerably less than in other scenarios.

Conclusions and Next Steps

- **Conclusions**
  - Consistent with other studies, analysis shows that cooperation scenario without reprocessing yields lower costs
  - Overall cost differences are probably less important than considerations of proliferation resistance, social-cultural security, and military security, for which scenario 4 (dry-cask storage, no reprocessing) has advantages
  - Options using mostly regional or international facilities (scenarios 2 and 3) provide some non-proliferation benefits over scenario 1 (national enrichment/reprocessing) at cost differences that are likely insignificant, but will require considerable effort to arrange
  - Issues related to DPRK “denuclearization” may play a role in shaping regional nuclear fuel cycle cooperation strategies

Conclusions and Next Steps

- **Next Steps in EASS Project**
  - Evaluate generation costs to compare three nuclear capacity paths
  - Investigate implications of climate change mitigation/adaptation for nuclear power, and for regional spent fuel management/enrichment proposals in Asia
  - Investigate implications of new reactor and other nuclear technologies for regional spent fuel management/enrichment proposals in Asia
  - Explore possible safeguards implications of various nuclear fuel cycles and related cooperation scenarios

THANK YOU!

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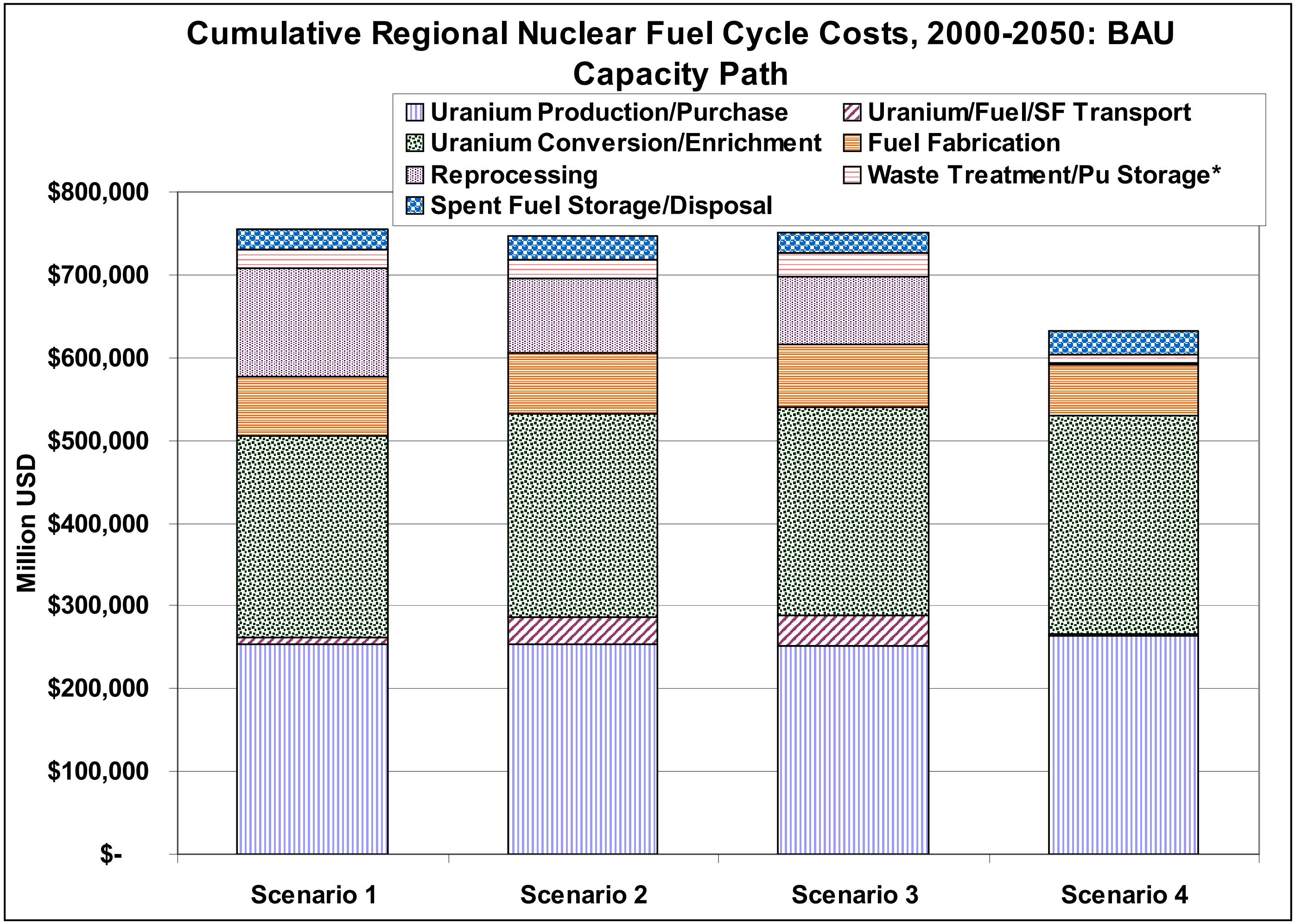
EXTRA AND REFERENCE SLIDES

Analytical Approach, and Key Results

- Cumulative fuel cycle costs, 2000-2050, not including generation costs



Analytical Approach: Additional Key Assumptions

- Uranium Cost/Price: $120/kg in 2009, escalating at 1%/yr
- Average Uranium concentration in ore: 0.1%
- International enrichment 30% gaseous diffusion in 2007, declining to 0% by 2030
- Enrichment costs $160/kg SWU—no escalation
- Raw Uranium transport costs at roughly container freight rates
- Cost of U_3O_8 conversion to UF_6: $6.2/kg U
- Cost of UOx fuel fabrication: $270/kg heavy metal (HM)
- Cost of MOx fuel blending/fabrication: $1800/kg HM
- Fraction of Pu in MOx fuel: 7%

Analytical Approach: Additional Key Assumptions

- Spent fuel transport costs (ship): ~$40/tHM-km
- Cost of reprocessing: $1200/kg HM (except in Japan, $3400/kg HM)
- Effective average lag between placement of fuel in-service and removal from spent fuel pool: 8 years
- Cost of treatment and disposal of high-level wastes: $150/kg HM reprocessed
- Mass of Pu separated during reprocessing: 11 kg/t HM
- Cost of storage/safeguarding Pu: $3000/kg Pu-yr
- Capital cost of dry casks (UOx or MOx): $0.8 million/cask
- Operating cost of dry cask storage: $10,000/cask-yr
- Cost of interim spent fuel storage (total): $360/kg HM
- Cost of permanent storage of spent fuel: $1000/kg HM (but not implemented or charged to any scenario by 2050)