



# International Workshop on Research, Development, and Demonstration to Enhance the Role of Nuclear Energy in Meeting Climate and Energy Challenges

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# INTERNATIONAL WORKSHOP ON RESEARCH, DEVELOPMENT, AND DEMONSTRATION TO ENHANCE THE ROLE OF NUCLEAR ENERGY IN MEETING CLIMATE AND ENERGY CHALLENGES

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# International Workshop on Research, Development, and Demonstration to Enhance the Role of Nuclear Energy in Meeting Climate and Energy Challenges

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ICARUS Project  
Fondazione Eni Enrico Mattei  
  
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Belfer Center for Science and International Affairs  
Harvard Kennedy School  
  
and  
the International Center for Climate Governance

*Cover Image:* Idaho National Laboratory's Advanced Test Reactor (ATR) core. Powered up, the fuel plates can be seen glowing bright blue, exhibiting what is known as Cherenkov Radiation. The core is submerged in water for cooling.

*Cover Source:* Argonne National Laboratory

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## Executive Summary

### **Key points**

- On safety: The Fukushima accident highlights the need for improved preparedness for events beyond the design basis for nuclear reactors, strengthened emergency response, and safer management of spent nuclear fuel. The accident has had an impact on public and investor confidence in nuclear energy, but nuclear power is likely to continue to grow in the most important nuclear markets.
- On RD&D: Major reductions in the cost of nuclear energy are not a major goal of current RD&D programs. Rather, current RD&D programs are targeted on offering new capabilities (such as high-temperature process heat) and improving features such as safety, waste management, sustainability of fuel resources, and proliferation-resistance, while maintaining or improving cost-competitiveness.
- On Gen IV: Gen IV systems will probably not be cheaper than Gen III/III+ (or light water reactor, LWR) designs. Instead, their value would come from the generation of by-products (i.e., hydrogen and process heat), the ability to extend uranium resources or minimize nuclear wastes, or from improved safety and proliferation-resistance.
- On small reactors: Small modular reactors (both LWR and Gen IV designs) may or may not be cost competitive with large Gen III/III+ designs, but could have other benefits, such as simpler financing, improved safety, or strengthened proliferation resistance. There was disagreement about their market potential.
- On barriers to large-scale deployment: For nuclear to play a major role in meeting the energy challenges of the 21st century, issues going well beyond RD&D need to be addressed, such as public acceptance, waste management, and government support for licensing and financing.

Dramatic growth in nuclear energy would be required for nuclear power to provide a significant part of the carbon-free energy the world is likely to need in the 21<sup>st</sup> century, or a major part in meeting other energy challenges. This would require increased support from governments, utilities, and publics around the world. Achieving that support is likely to require improved economics and major progress toward resolving issues of nuclear safety, proliferation-resistance, and nuclear waste management. This is likely to require both research, development, and demonstration (RD&D) of improved technologies and new policy approaches.

To gather information on the RD&D needs for the future of nuclear energy, the future cost and performance of nuclear technologies, and on the major barriers to large-scale deployment of nuclear energy, a team of researchers at Harvard University and the Fondazione Eni Enrico Mattei (FEEM) conducted two coordinated surveys of nuclear experts. The surveys asked experts how much they would recommend that their governments spend on nuclear energy RD&D; what progress in cost and performance might be expected by 2030 if those recommendations were followed; and what other factors might constrain or promote future nuclear energy growth. Leading experts from the United States (U.S.) and the European Union (E.U.) participated in this expert elicitation surveys during the summer and fall of 2010. In April 2011, the FEEM and Harvard teams held a workshop in Venice, Italy with a subset of the participating E.U. and U.S. experts to present and discuss the results of the elicitations, in an effort to

understand where there is consensus and where the most important disputes and uncertainties lie. Given the Fukushima nuclear accident in Japan, the meeting opened with a discussion of the significance of that event for the future of nuclear power, and of the main lessons learned.

The participating experts emphasized that the Fukushima accident was still unfolding, which made it difficult to understand its lessons in detail. However, the experts agreed that the accident highlighted the need to strengthen preparation for events that go beyond the design basis for individual nuclear plants, to have better emergency response plans in place, and to improve approaches to managing spent nuclear fuel, in particular to prevent fuel from melting or catching fire if a spent fuel pool loses its cooling mechanism.

In the elicitation survey (which took place before the accident), experts had already pointed to safety as one of the main issues that could set back the deployment of nuclear power, predicting that an accident or terrorist attack that led to a major release of radioactivity would result in 50-100% reductions in future construction of nuclear reactors in the United States and in the European Union. The experts participating in the workshop disagreed as to whether the releases from Fukushima represented the kind of major radioactive release they had envisioned in making this prediction. During the workshop, experts generally agreed that the accident would have different effects on nuclear construction in different countries, but would not be likely to greatly slow nuclear growth in China, India, and Russia, the largest current nuclear markets.

A key finding that emerged in the survey and was confirmed during the workshop discussion is that experts do not expect current public RD&D investments to lead to major reductions in the capital cost of nuclear power plants by 2030, although cost-competitiveness with other power generation technologies in the longer term is a goal of RD&D programs. Current RD&D is also targeted on other objectives, such as new abilities to produce hydrogen and high-temperature process heat, extension of uranium resources, improved waste management, and improved nuclear safety and proliferation-resistance. The reduction in the cost of Gen IV reactors in 2030 that the experts projected to arise from their recommended RD&D investments compared to a business-as-usual RD&D funding scenario was between 0-20%; the best guess of the cost of Gen IV reactors in 2030 ranges between 3,000 and 7,000 \$/kW in both the United States and the European Union (similar to that of Gen III/III+ reactors, see Figure ES-1). In addition, the workshop confirmed that under a business-as-usual and under an expanded nuclear RD&D funding scenario, over 50% of U.S. and E.U. experts thought that the cost of SMRs in 2030 would be greater than that of Gen III/III+ reactors. Under an enhanced nuclear RD&D funding scenario, 53% of E.U. experts thought that Gen IV reactors could be less expensive than Gen III/III+ reactors in 2030, while the majority of U.S. experts still thought that Gen IV reactors would be more expensive.

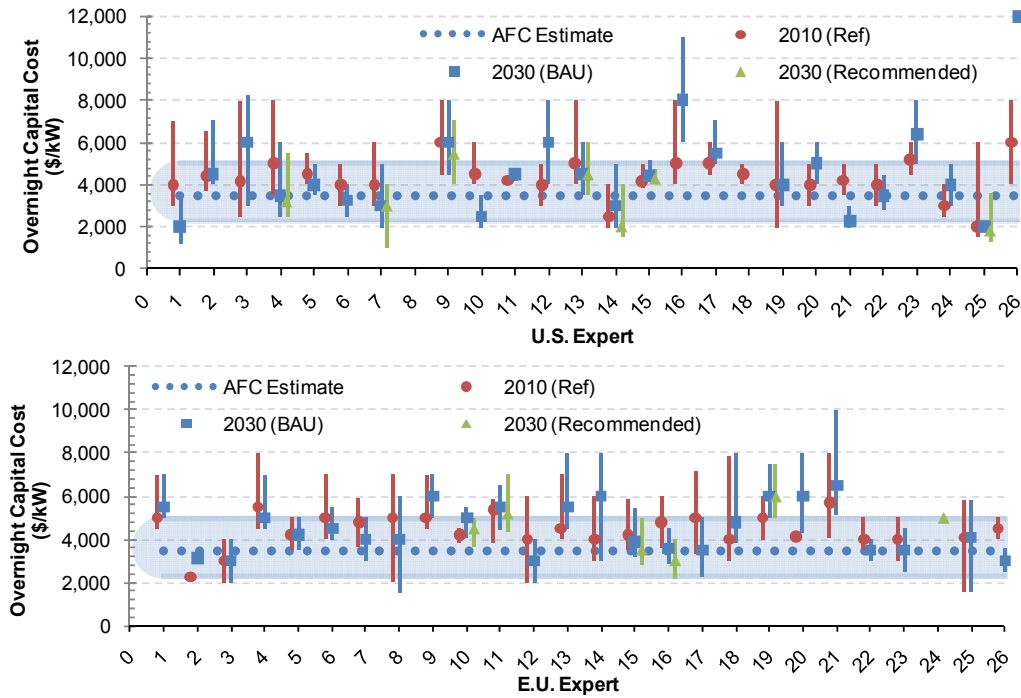
Experts from both sides of the Atlantic strongly agreed on the value of nuclear RD&D to achieve objectives other than cost reduction, and recommended annual RD&D funding between \$1 billion and \$2 billion in each geography (the U.S. budget in 2010 excluding funding for facilities was \$411 million, the average EU budget in the period 2005-2009 was \$730 million). Beyond financing RD&D and promoting solutions for long-term waste disposal, experts thought that governments should provide support for licensing

and siting novel reactor designs to help reduce the expected cost and the risks to the private sector.

During the workshop, U.S. and E.U. experts disagreed on the market for small modular factory built reactors (SMRs). While U.S. experts were split, E.U. experts did not foresee a large market. Consequently, U.S. experts placed more emphasis on public funding for SMR RD&D. Proponents of SMRs pointed to benefits that include: (a) less “lumpy” investments; (b) the possibility of achieving economies of scale in manufacturing to outweigh the smaller economies of scale in power generation; (c) the possibility of siting flexibility (arising from the potential for reduced water demands, potentially increased inherent safety, and possibly smaller areas for evacuation planning); (d) possible reductions in construction times (even shippability); (e) the possibility of recycling existing sites; and (f) avoiding the risk of having too much of a region’s electricity dependent on a single power plant.

Finally, the group of U.S. and E.U. experts agreed on the high uncertainty characterizing future nuclear deployment. Less than 20% of the experts, in both groups, considered likely (>66%) the medium scenario (defined as 286 GW of nuclear energy both in the United States and in the European Union by 2050), which is the one that had the largest probability after averaging across all experts. The other scenarios were a scenario that represented no growth of nuclear power in the two geographies by 2050, and a high-growth scenario that represented 400 and 477 GW installed in the European Union and in the United States, respectively, by 2050. When presented with results from integrated assessment models of climate change and potential responses that included scenarios in which nuclear power deployments might grow to 5-10 times their current level by 2050, the experts generally took the view that growth on that scale was technically feasible, but there was disagreement over whether it was realistic given political and regulatory barriers.

Some of the experts argued that sustaining a much larger nuclear enterprise for many decades would require recycling to extend uranium resources, while others argued that uranium supply would not be a major constraint for an extended period. Some experts argued recycling would also have waste management advantages, while others argued these were not large enough to be decisive. In addition, in the surveys, experts expressed their concern about the limited progress in working out long-term nuclear waste disposal options. A majority of U.S. and of E.U. experts thought that a successful repository siting in the United States would increase significantly the rate of construction of nuclear plants in their region. During the workshop, experts reemphasized the importance of progress in both near-term and long-term approaches to safe management of spent fuel and nuclear waste, particularly in the aftermath of the Fukushima accident.



**Figure ES-1: Gen III/III+ overnight capital costs estimates of U.S. (top panel) and E.U. (bottom panel) experts in 2030. The vertical line spans the 10<sup>th</sup> to the 90<sup>th</sup> percentile estimate. The red line with the circle indicates the range of Gen III/III+ costs in 2010. The blue line with the square indicates the costs under a business-as-usual level of government RD&D funding in 2030. The green line with the triangle indicates the range of SMR costs in 2030 under the recommended RD&D budget of the experts who thought public RD&D would affect Gen III/III+ costs in 2030. The Advanced Fuel Cycle (AFC) estimate (shown as the blue band) can be found in: Shropshire, D.E., Williams, K.A., Boore, W.B., Smith, J.D., Dixon, B.W., Duzik-Gougar, M., Adams, R.D., Gombert, D., Schneider, E. 2009. “Advanced Fuel Cycle Cost Basis.” Technical Report from the Idaho National Laboratory. Document INL/EXT-07-12107. Available at: [http://www.osti.gov/bridge/product.biblio.jsp?query\\_id=1&page=0&osti\\_id=983353](http://www.osti.gov/bridge/product.biblio.jsp?query_id=1&page=0&osti_id=983353).**



## **Background and Objectives**

The future role of nuclear energy is a key factor in determining a long-term energy strategy to cope with the challenges ahead: a growing planet with a growing thirst for energy; providing universal access to modern sources of energy; assuring energy security and availability at reasonable costs; the threat of climate change, which calls for a drastic shift from current energy generation technologies; and the myriad other local, regional, and global environmental impacts of energy use and production.

To play a major role in meeting these intertwined energy challenges, nuclear energy would have to grow dramatically, requiring strong support from governments, utilities, and publics around the world. Achieving that support is likely to require improved economics and major progress toward resolving issues of nuclear safety, nuclear security, proliferation-resistance, and nuclear waste management. To sustain a much larger nuclear enterprise for many decades may also raise the question of uranium availability and options for extending fuel resources.

The objective of the workshop was to present the main results of an expert elicitation survey that was conducted both in the United States and in the European Union during the summer/fall of 2010 to a set of worldwide known experts and to enable a discussion. In this workshop the Fondazione Eni Enrico Mattei (FEEM) and Harvard University teams presented and discussed the results of the U.S. and E.U. elicitations, with a particular focus on research, development, and demonstration (RD&D) needs, international cooperation, future costs and performance, and deployment scenarios in an effort to understand where there is consensus and where the most important disputes and uncertainties lie.

The workshop also included a discussion of the factors that are likely to shape the diffusion of nuclear energy technologies beyond RD&D. This topic was also covered by the survey and was the focus of the second day of the workshop.

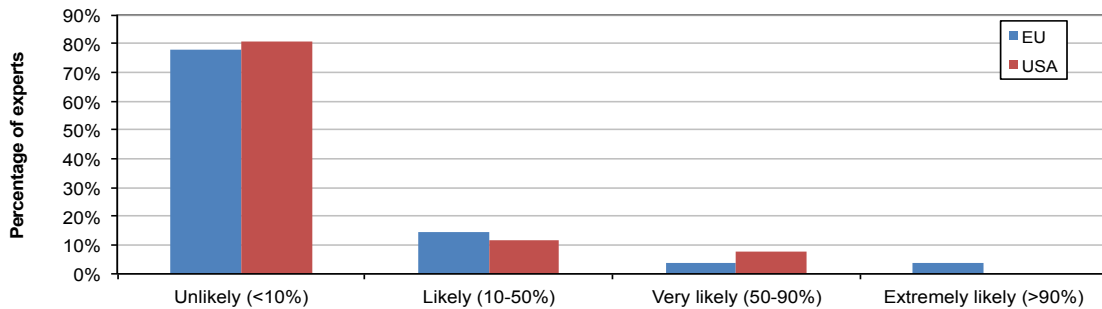
## 1. Impact of Fukushima

### *Highlights*

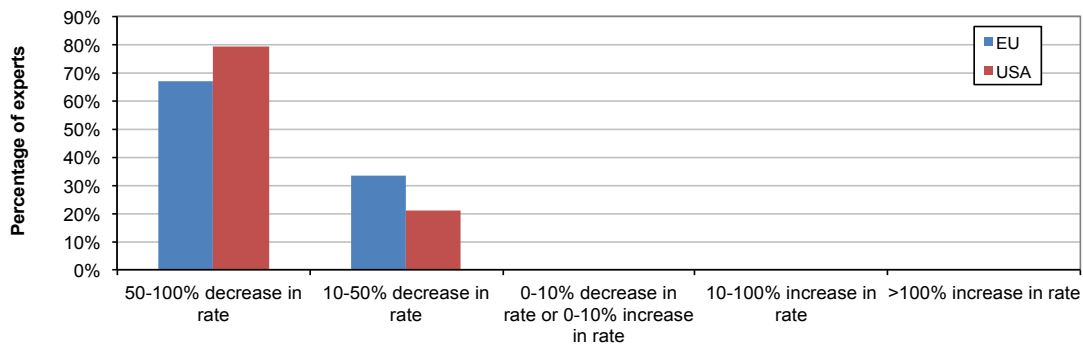
- Experts largely agreed that it was too early to fully understand what impact Fukushima would have and what lessons should be drawn.
- Prior to Fukushima, both U.S. and E.U. experts had predicted that an accident or terrorist attack leading to a “major radioactive release” would lead to 50-100% reductions in future construction of nuclear reactors in their regions.
- At the workshop, there was a split view about whether Fukushima counted as the sort of “major radioactive release” they had envisioned, with some experts arguing that the event was far less than a Chernobyl-scale release.
- Experts at the workshop expected the accident’s impact on future nuclear deployment would vary by country:
  - Possibly limited impact in India, China, and Russia
  - Diverse impact in Europe and in “newcomer” states
  - Projected construction in the United States is already modest
- Experts disagreed on the likely impact of the accident on relicensing of older reactors.
- Lessons learned:
  - Need for analysis of “beyond-design basis” events
  - Need for review of emergency plans
  - Need for approaches to management of spent fuel that will not lead to fuel melting or fires if spent fuel pools lose their cooling mechanism, and need for long-term management approaches to be put in place
  - Importance of understanding and addressing public concerns
  - Need to ensure robustness of electricity supply even when reactors are shut down for an extended period
  - Need to evaluate vulnerability of concentrated reactor siting
- Impact on recommended RD&D
  - Few experts revised their pre-Fukushima RD&D recommendations
  - Areas of increased future focus identified in the discussion included:
    - o Hydrogen management and control
    - o Risk assessment and management
    - o Responding to “beyond design basis” events
    - o Future systems that could survive the most severe accident scenarios without major releases
    - o Approaches to spent fuel management (short- and long-term)
- Several experts pointed out that an important difference between Gen III and Gen III+ designs was more passive safety measures in the Gen III+ systems, which can last for longer without power.
- But there was general agreement that none of the Gen III/III+ designs could withstand station blackout lasting for many days without operator action.
- The experts agreed that it was important to put nuclear risks in the context of risks from alternative energy technologies.

## 1.1 Survey Findings

This session began by posing a series of questions about the likely impact of the accident at Fukushima, and a presentation of E.U. and U.S. experts' pre-Fukushima survey responses on the likelihood and impact of major radioactive releases resulting from accidents or sabotage of nuclear plants (see Appendix A for a list of the workshop participants and Appendices B and C for a list of the survey participants). European and American responses to these questions in the survey were almost identical. Both groups of experts overwhelmingly thought that an accident or sabotage leading to a major radioactive release was very unlikely (<10%) between 2010 and 2030, and that if it did occur, it would reduce the rate of new construction of nuclear power plants in their region by 50-100% compared to what would have occurred without the accident. (The survey did not include a question on how much deployment outside the experts' own region would be reduced.) See Figure 1-1 and Figure 1-2.



**Figure 1-1: Probability of a major radioactive release due to an accident or sabotage between 2010 and 2030.**



**Figure 1-2: Impact of safety incident between 2010 and 2030 on the growth of nuclear power in the European Union and the United States.**

Part of the focus of this session of the workshop was on how, if at all, the Fukushima accident should change approaches to RD&D for the future of nuclear energy. As shown in Appendix D, before the accident, both E.U. and U.S. experts recommended dramatic increases in government RD&D spending on nuclear power. The mode recommendation for annual government funding for nuclear RD&D was around \$1.2 billion for U.S. experts, and \$2 billion for E.U. experts. E.U. experts allocated on average 9% of their total budget for risk and safety research, and U.S. experts allocated 7% of their total budget to this category. The experts participating in the workshop were given the opportunity to modify their previous RD&D recommendations based on the Fukushima accident and the discussion at the workshop; few chose to do so, though, as discussed below, in the discussion the participants identified several safety-related areas as deserving of additional work.

## **1.2 Summary of Workshop Discussion**

In the discussion, the experts disagreed as to whether Fukushima represented the kind of “major radioactive release” they were thinking of when they answered the survey. Some argued that given the large amounts of radioactive iodine and cesium that had been released, Fukushima should be considered a major radioactive release, and what they had considered unlikely to occur during 2010-2030 had in fact occurred. Others argued that the Fukushima release was much smaller than Chernobyl, and much smaller than the kind of release they had been thinking of when completing the survey. One expert went so far as to argue that the fact that such an extreme natural disaster, which killed more than 20,000 people, had led to such modest nuclear consequences might actually increase public confidence in nuclear energy in the long run.

While there was general agreement that it was too early to make detailed predictions of the impact of Fukushima, or to understand all of the lessons that should be learned, the participants nevertheless agreed that the impacts would be substantial, and drew a number of broad conclusions. First, they agreed that nuclear power was likely to continue to grow in some countries, but that other countries might cancel or reduce their plans. The experts generally expected that countries committed to large nuclear construction programs, such as China, India, and Russia, would likely continue those programs. In Europe, the impact in some countries (such as Germany) might be substantial, while other countries might proceed with only modest impacts on the scale and pace of planned construction. In the United States, little near-term reactor construction was expected even before the accident, for economic reasons (including low natural gas prices and the absence of a carbon price). The experts expected that the impact on “newcomer” countries building their first nuclear reactor would vary from one country to the next, with highly committed countries such as the UAE continuing and others possibly delaying or canceling plans.

One issue that will have as large an effect on how much nuclear energy is generated over the next few decades as the rate of new construction is relicensing beyond the originally licensed lifetimes of current reactors. (Ironically, Unit 1 at Fukushima had only recently received a license extension, and would have reached the end of its originally licensed 40-year life a few weeks after the earthquake.) One expert argued strongly that after Fukushima, it was time to take another look at whether relicensing of many older reactors lacking the most modern safety features made sense. Others argued that relicensing should go forward, and that regulators should not and would not allow unsafe reactors to operate, whether they were reaching the end of their licenses or not.

Second, beyond the impacts on future nuclear energy growth, the participants identified a few areas where the global nuclear industry should draw lessons and potentially modify approaches:

- Better analysis of potential “beyond design basis”<sup>1</sup> events, and strengthened abilities to respond to them.
- More effective emergency response plans (and more regulatory review of these plans).
- Safer management of spent fuel, and in particular avoiding approaches that allowed pools to become so filled with “hot” fuel that fuel could melt or catch fire if the pools lost their cooling mechanism.
- New steps to rebuild public confidence, including both steps to reduce the actual risks of nuclear energy and steps to better understand and address public fears and concerns.
- Improved analysis and approaches to ensure robust electricity supplies even when some reactors are shut down for an extended period.
- Improved analysis of the potential dangers of concentrating reactors very close together at a single site, as at Fukushima.

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<sup>1</sup> These are events are those that were not considered in the design of a reactor.

Third, the participants discussed how the Fukushima accident might affect the optimal size and focus of nuclear RD&D. Few experts modified their earlier RD&D recommendations. Nevertheless, in the discussion, the participants identified a number of areas for increased emphasis, including:

- Hydrogen management and control
- Risk assessment and management
- Responding to “beyond design basis” events
- Future systems that could survive the most severe accident scenarios without major releases
- Approaches to spent fuel management (short- and long-term)

The participants also discussed how the features of new reactor designs would affect their ability to cope with situations like those that arose at Fukushima. Several experts pointed out that an important difference between Gen III and Gen III+ designs was that the Gen III+ designs incorporate more passive safety measures, which can maintain cooling for a longer period without power. One participant pointed out that the Economic Simplified Boiling Water Reactor (ESBWR) design is intended to be able to rely entirely on passive cooling, without needing power, for up to 72 hours. But there was general agreement that none of the Gen III/III+ designs could withstand station blackout lasting for many days, as occurred at Fukushima, without operator action to maintain cooling.

Finally, given that the earthquake and tsunami in Japan killed more than 20,000 people, and the reactor accident has so far not led to any deaths, the participants agreed that it was important to put nuclear risks in the context of other risks society faces, and particularly the risks from alternative energy technologies, including:

- Hydropower dam vulnerabilities
- Coal mining and emissions
- Oil spills

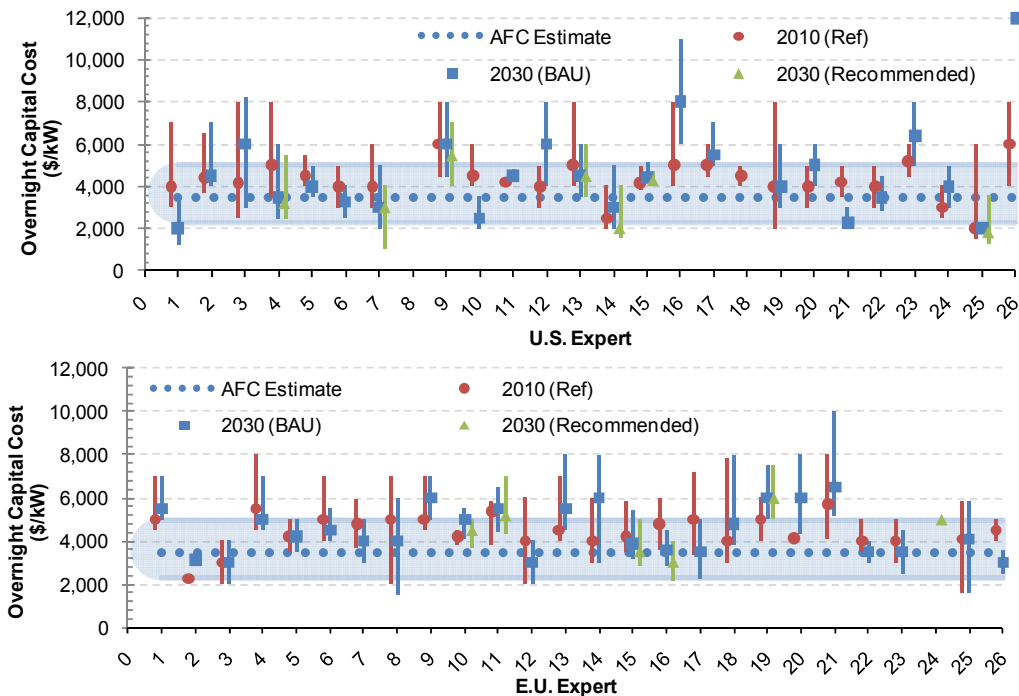
## **2. Generation III/III+ Power Plants**

### ***Highlights***

- Experts’ projected range of overnight capital costs of Gen III/III+ plants in both the European Union and the United States fall between \$2,000/kW and \$8,000/kW in 2030. Median projections for 2030 fall mainly in the \$3000/kW-\$6,000/kW range.
- At the workshop, experts provided several reasons for the overnight capital cost escalation in the United States and the European Union between 2003 and 2010:
  - Difference between “who is paying”/contract structure
  - Escalation of materials costs (a factor of two to five)
  - Increased safety requirements
  - Liberalization of electricity markets, which affects the cost of money
- Over half of the experts expected that Gen III/III+ costs in 2030 would be as high as or higher than they were in 2010.
- Since the Gen III/III+ plants are already developed, both U.S. and E.U. experts expect that additional RD&D will only lead to modest reductions, if any, in the costs of Gen III/III+ plants, although a number of experts projected some noticeable reduction from RD&D at their recommended budget levels.

## 2.1 Survey Findings

This session began with the presentation of E.U. and U.S. experts' projections of overnight capital costs for Generation III/III+ reactors in 2010, in 2030 under a business-as-usual (BAU) funding scenario, and in 2030 under experts' recommended funding scenario (Figure 2-1). The blue band in the figures represents the high, low, and best guess estimate of the "Advanced Fuel Cycle Cost Basis" report<sup>2</sup> (AFC), provided as a reference point. Experts' projected range of costs in both the European Union and the United States generally fall between \$2,000/kW and \$8,000/kW. 50<sup>th</sup> percentile projections for 2030 fall mainly in the \$3,000/kW-\$6,000/kW range. Numerous experts projected cost increases between 2010 and 2030 under a BAU funding scenario; however, two U.S. and two E.U. experts thought that their budget recommendation would reduce this price increase. Over 40% of E.U. experts thought costs would increase from 2010 to 2030 under BAU funding, and an equal percentage thought that costs would decrease. About 12% thought costs would stay the same. Half of U.S. experts thought costs would increase, while 33% thought costs would decrease, and 17% thought they would stay the same between 2010 and 2030 under BAU funding.



**Figure 2-1: Gen III/III+ overnight capital costs estimates of U.S. (top panel) and E.U. (bottom panel) experts in 2030. The vertical line spans the 10<sup>th</sup> to the 90<sup>th</sup> percentile estimate. The red line with the circle indicates the range of Gen III/III+ costs in 2010. The blue line with the square indicates the costs under a business-as-usual level of government RD&D funding in 2030. The green line with the triangle indicates the range of SMR costs in 2030 under the recommended RD&D budget of the experts who thought public RD&D would affect Gen III/III+ costs in 2030. The blue band marks the AFC estimate.**

In Figure 2-1, the absence of a 2030 estimate under recommended funding levels means that experts did not think government spending on nuclear energy RD&D would change Gen III/III+

<sup>2</sup> Shropshire, D.E., Williams, K.A., Boore, W.B., Smith, J.D., Dixon, B.W., Dunzik-Gougar, M., Adams, R.D., Gombert, D., Schneider, E. 2009. "Advanced Fuel Cycle Cost Basis." Technical Report from the Idaho National Laboratory. Document INL/EXT-07-12107. Available at: [http://www.osti.gov/bridge/product.biblio.jsp?query\\_id=1&page=0&osti\\_id=983353](http://www.osti.gov/bridge/product.biblio.jsp?query_id=1&page=0&osti_id=983353).

costs in 2030. Seven experts from the European Union and six experts from the United States did include estimates for Gen III/III+ costs under an enhanced RD&D budget.

## **2.2 Summary of Workshop Discussion**

The discussion following the presentation of the above results centered on the reasons for the cost escalation between 2010 and 2030 (as well as the cost escalations that had already occurred by 2010). Experts cited as possible reasons: (1) the dependence on “who is paying,” or the contract structure; (2) the escalation of materials costs by a factor of between two and five; (3) the increased safety requirements associated with earlier cost increases; and (4) the liberalization of electricity markets affecting the cost of capital. Experts noted that China is an exception where costs are moderate and made the observation that nth-of-a-kind plant overnight capital costs may be lower than first-of-a-kind plant costs. When given the chance to revise their GenIII/III+ overnight capital cost projections, one U.S. expert and one E.U. expert revised theirs upwards, while one E.U. expert revised his downwards.

## **3. Generation IV Nuclear Plants**

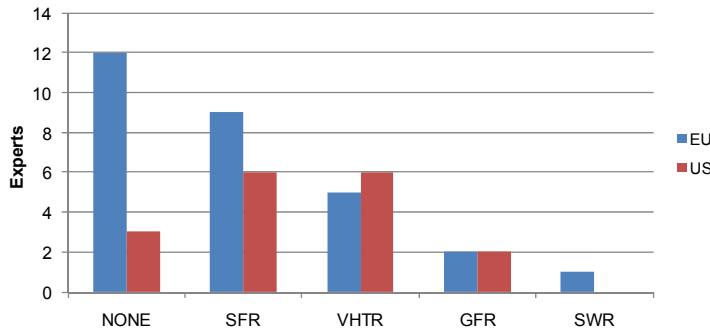
### **Highlights**

- E.U. experts appear in general less optimistic about the costs of Gen IV designs in 2030 and about when Gen IV plants will be commercially available.
- U.S. experts diversified their recommended RD&D budget across a wider range of Gen IV reactors, while E.U. experts emphasized sodium-cooled fast reactors (SFRs).
- U.S. experts tend to focus on demonstration, while E.U. experts still see a large need for further basic and applied R&D.
- Among U.S. experts, consensus is less clear that more RD&D spending would lower the cost of Gen IV reactors.
- In general the biggest projected effect of expanded RD&D is in cutting the tail of very high costs, and U.S. experts are less optimistic about that.

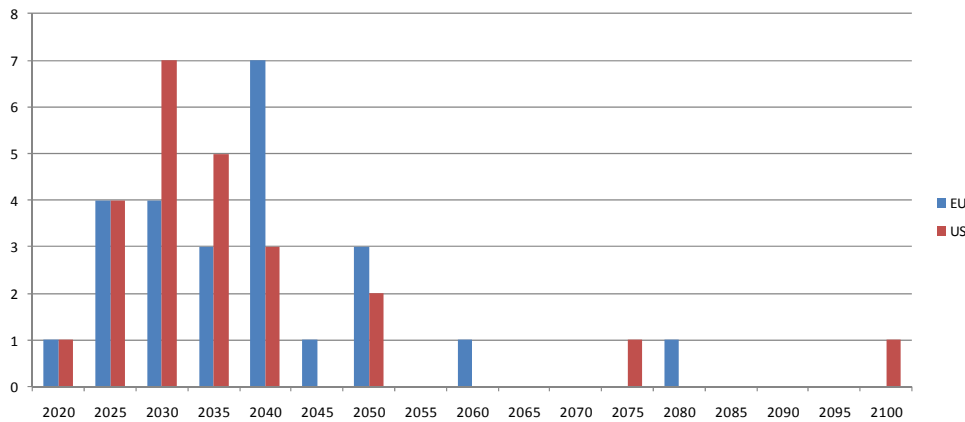
### **3.1 Survey Findings**

In the survey conducted ahead of the workshop, experts were asked to project the cost and performance of Generation IV systems under several RD&D funding scenarios. Results of the survey indicate that, given current public and private RD&D funding, most E.U. experts are pessimistic regarding the commercial viability of Gen IV nuclear facilities in 2030, while U.S. experts are slightly more optimistic. For both groups, sodium-cooled fast reactors (SFRs) and very-high-temperature reactors (VHTRs) are the Gen IV systems mostly likely to be commercially available by 2030.

When assessing the time frame when the 1 GWe Gen IV power plant or system will first become commercially available under the RD&D scenario each expert proposed in the survey, U.S. experts are in general slightly more optimistic about timing, while E.U. experts appear to converge around the year 2040 (see Figure 3-2). At the workshop experts agreed that E.U. experts may have converged around 2040 as a commercialization date because that is when projects in the E.U. plan for the SFR to be commercialized. A small number of experts thought that none of the Gen IV reactors would be commercially viable for many decades.



**Figure 3-1: Generation IV nuclear facilities that will be commercially viable by 2030 while addressing the Generation IV goals. Sodium-cooled fast reactor (SFR); Very-high-temperature reactor (VHTR); Gas-cooled fast reactor (GFR); Supercritical-water-cooled reactor (SCWR).**



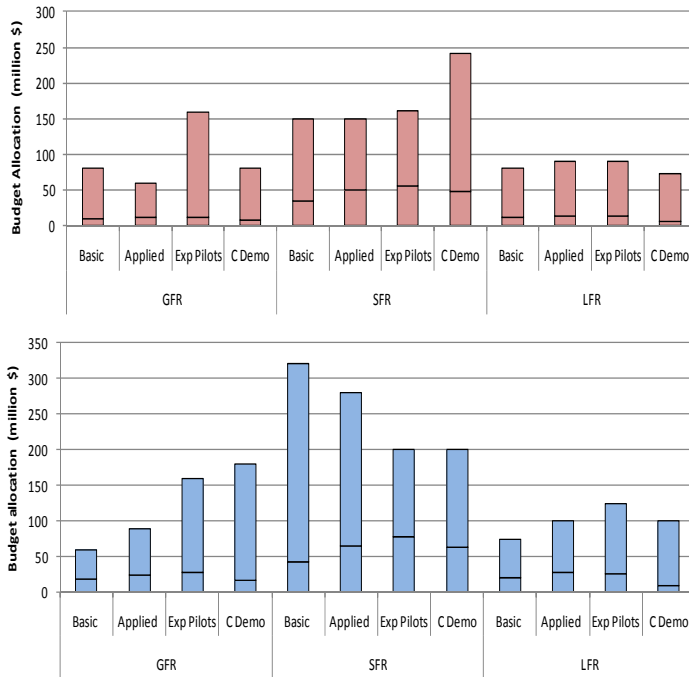
**Figure 3-2: Time when Generation IV nuclear plant or system will first become commercially available under the R&D scenario proposed by expert.**

If we look at the allocation of the recommended budget, it is noticeable how E.U. experts (on the top in Figure 3-3) focus more on a single design (SFR), while the distribution across designs is less skewed in the case of U.S. experts. The two categories also differ in the type of RD&D recommended, as pilots and demonstration take the largest share in the U.S. case, while basic and applied R&D, at least in the case of SFR designs, is prevalent according to E.U. experts.

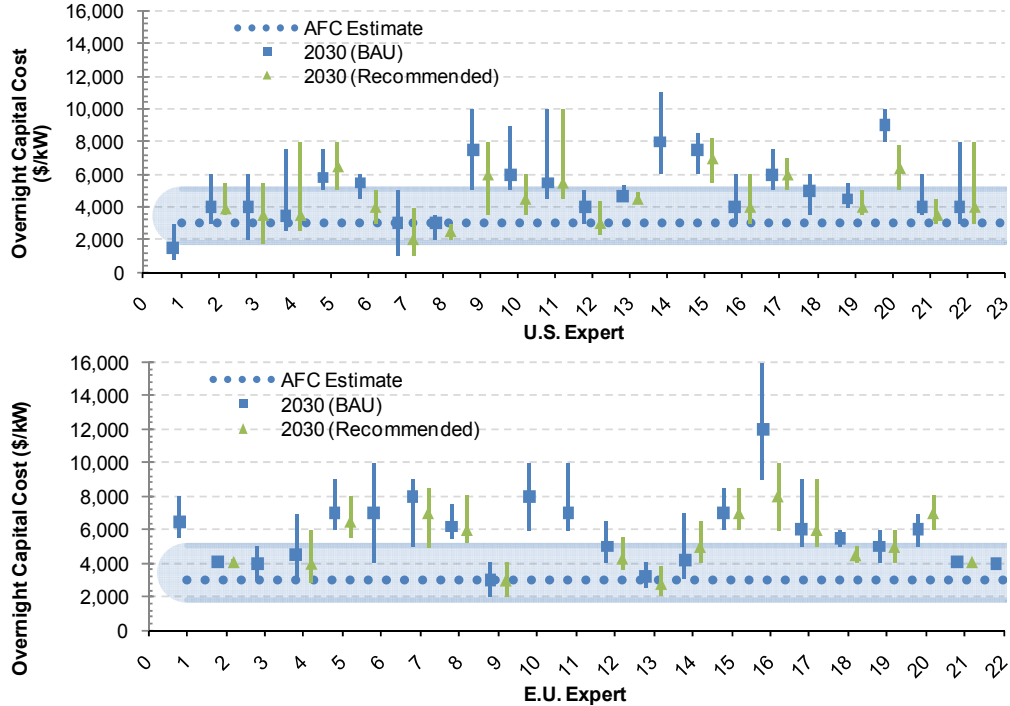
Figure 3-4 reports 2030 Gen IV cost projections for both groups. It shows that there are 10 out of 23 U.S. experts and 4 out of 22 E.U. experts that have a median cost expectation in 2030 at or under \$4,000 kW under the BAU RD&D scenario. Uncertainty ranges are generally large. On average, the differences between the 10<sup>th</sup> and the 50<sup>th</sup> percentiles and the 10<sup>th</sup> and the 90<sup>th</sup> percentiles are 30% and 44% of the 50<sup>th</sup> percentile for the E.U. and U.S. cases, respectively.

On the effectiveness of RD&D funding of Gen IV designs, there is again a divide in U.S. and E.U. perspectives. E.U. experts see a key role of RD&D in cutting the right tail of the cost distribution and U.S. experts can be clustered in two subgroups: one subgroup includes those that are skeptical of any role for RD&D, and the other subgroup is fairly optimistic about the role of RD&D in lowering the cost of Gen IV, even below those of Gen III/III+.





**Figure 3-3: Minimum (always zero) Average and maximum recommended RD&D budget allocation on Fast Reactor systems over the next 10 years (top panel for U.S. experts, bottom panel for E.U. experts). Basic: basic research; Applied: applied research; Exp Pilots: experiments and pilots; and C Demo: commercial demonstration.**



**Figure 3-4: Gen IV overnight capital costs estimates of U.S. (top panel) and E.U. (bottom panel) experts in 2030. The vertical line spans the 10<sup>th</sup> to the 90<sup>th</sup> percentile estimate. The blue line with the square indicates the expected cost in 2030 under the BAU RD&D funding scenario. The green line with the triangle indicates the expected cost under the recommended RD&D funding scenario. The blue band marks the AFC estimate.**

### **3.2 Summary of Workshop Discussion**

Experts agreed that Gen IV reactors face a challenging target in competing with Gen III/III+ LWRs in terms of cost and that it is extremely important to clarify that some Gen IV reactors are not only for electricity production but also for hydrogen and/or process heat production, and that others are able to dramatically extend uranium resources through recycling. In addition, experts see part of the benefit of RD&D investments in Gen IV reactors in improving the technology along important criteria other than cost, for example safety, proliferation resistance and by simply providing a new technology for diversification of options. Experts also thought it necessary to clarify the main reasons for pursuing particular Gen IV designs before setting RD&D priorities. There was a wide agreement across experts on the role of government in providing options for the future by funding demonstrations that the private sector will not invest in. Previous studies of SFRs found irreducible cost overheads due to the intermediary secondary cooling system. Some experts argued that lead-cooled reactors could, in principle, overcome this extra cost.

## **4. Small Modular Factory-built Reactors (SMRs)**

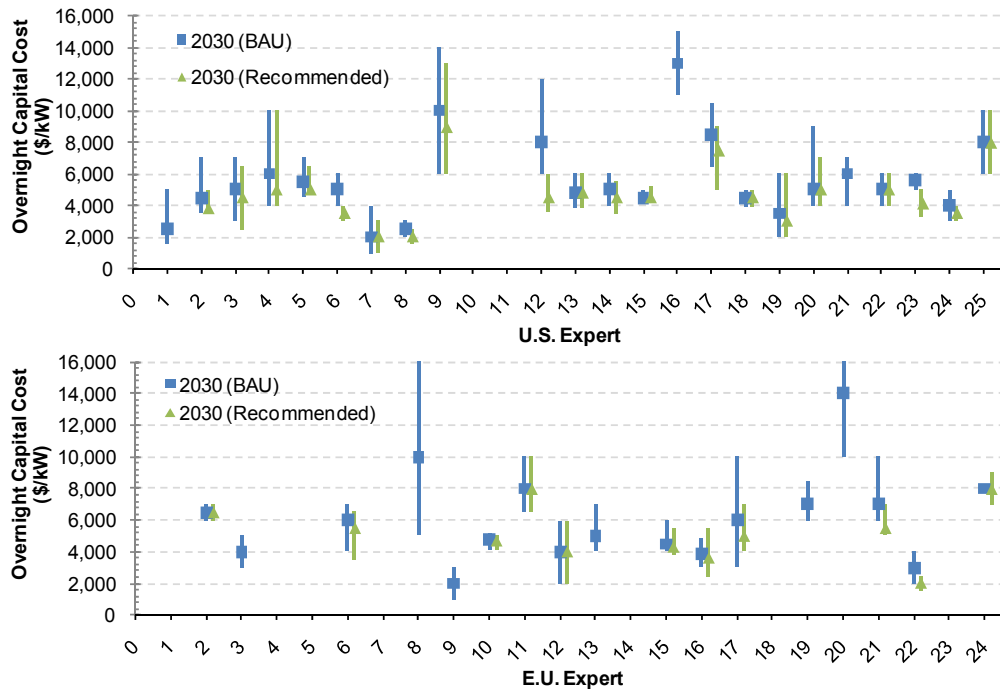
### **Highlights**

- It is important to differentiate between different types of SMRs and the need for government support. While the fundamental R&D on LWR-based SMRs is done, there is value in providing support towards licensing. Non-LWR-based SMRs need more RD&D support.
- U.S. and E.U. experts differed somewhat on the commercial market for SMRs. While U.S. experts were split, E.U. experts did not foresee a large market. Consequently, U.S. experts placed more emphasis on public funding for SMR RD&D.
- The majority of U.S. and E.U. experts expected SMR overnight capital costs ranging from \$2,000 to \$7,000/kW, although some experts expected costs above the \$8,000/kW range.
- The majority of E.U. and U.S. experts expect SMRs to be more expensive than Gen III/III+ reactors in 2030, although public RD&D increases the fraction of experts that think that SMRs will be less expensive.
- Cost is not the only metric that should be used to evaluate SMRs. They have other potential advantages over larger nuclear units:
  - They require less “lumpy” capital investments
  - It may be possible to achieve economies of scale in manufacturing to outweigh the smaller economies of scale in power generation
  - They provide siting flexibility (e.g., they require less water)
  - They could reduce construction times (even be shippable)
  - They would enable the possibility of recycling existing sites
  - They could contribute to avoiding the “single-shaft risk”
  - In the discussion there was little focus on possible safety and nonproliferation benefits
- U.S. experts placed more emphasis on the need for the government to support SMR demonstrations and licensing than E.U. experts.
- Government support is expected to decrease SMR costs in 2030 by between 5 and 20%

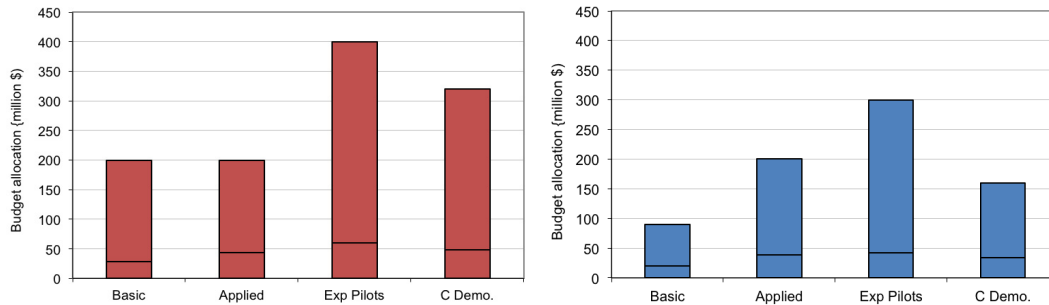
### 4.1 Survey Findings

In the survey conducted ahead of the workshop, experts were asked to evaluate the overnight capital cost of small modular factory-built reactors (with capacities up to 300 MWe) in 2030 under current federal nuclear RD&D funding and increased levels of funding. The results shown in Figure 4-1 indicate that, while there is a concentration of answers of U.S. and E.U. experts between \$2,000-\$7,000/kW, there are wide variations across experts. An E.U. and a U.S. expert estimated a 10<sup>th</sup> percentile estimate as low as \$1,000/kW. In terms of 90<sup>th</sup> percentile estimates, the two most pessimistic E.U. experts estimated 90<sup>th</sup> percentiles as high as \$16,000/kW, while the two most pessimistic 90<sup>th</sup> percentile estimates from U.S. experts were \$14,000/kW and \$15,000/kW.

Both on average, and also in terms of maximum recommended RD&D funding levels by an individual expert, U.S. experts recommended greater amounts of federal nuclear RD&D investment for SMRs than E.U. experts (Figure 4-2). Indeed, while over half of U.S. experts recommended SMRs as one of their top four areas to invest (sixteen out of 30 experts), only 27% of E.U. experts (or eight out of 29) had SMRs as one of the top four areas to invest RD&D. The emphasis of U.S. experts on basic research on SMRs compared to E.U. experts is due to their focus on Gen IV (not LWR) SMR designs. Just as in the funding allocations for Gen IV reactor research, U.S. experts also allocated relatively more funds for experiments and pilots, and commercial demonstration of SMRs than E.U. experts. U.S. experts also allocated (on average) significantly larger funds for basic research on SMRs.



**Figure 4-1: Overnight capital costs estimates of U.S. (top panel) and E.U. (bottom panel) experts in 2030 for SMRs. The vertical line spans the 10<sup>th</sup> to the 90<sup>th</sup> percentile estimate. The blue line with the square indicates the range of SMR costs under a business-as-usual level of government RD&D funding. The green line with the triangle indicates the range of SMR costs under each expert’s recommended nuclear RD&D funding.**



**Figure 4-2: Minimum (always zero), average and maximum recommended RD&D budget allocation on SMRs over the next 10 years (left panel for U.S. experts, right panel for E.U. experts). Basic: basic research; Applied: applied research; Exp Pilots: experiments and pilots; and C Demo: commercial demonstration.**

Over three-quarters of both U.S. and E.U. experts thought that SMRs would be more expensive than Gen III/III+ reactors in 2030 under a BAU RD&D funding. Under the recommended RD&D scenario, about 40% of U.S. experts expect SMRs to become competitive with Gen III/III+ reactors. However, it is worth emphasizing that there are several other possible advantages of SMRs when compared to Gen III/III+ reactors besides overnight capital cost. This comparison is only made for reference purposes.

Overall, the experts' recommended RD&D investments (which ranged from \$1 to \$3 billion per year for nuclear RD&D), were expected to result in 5% to 20% reductions in the capital cost of SMRs in 2030 over the costs under a BAU RD&D funding scenario.

**Table 4-1: Experts opinions on the RD&D thrusts of public support programs for SMRs. The number of experts holding each opinion is noted in parenthesis.**

U.S. experts	E.U. experts
<ul style="list-style-type: none"> <li>▪ Demonstration of the economic viability of such designs (10)</li> <li>▪ Safety testing (including computer codes used in the regulatory process) (10)</li> <li>▪ NRC design certification and licensing process (9)</li> <li>▪ Factory fabrication methods (6)</li> <li>▪ Demonstration reactor (3)</li> <li>▪ Fuels and materials testing (3)</li> <li>▪ Spent fuel transport (2)</li> <li>▪ Proliferation resistance (2)</li> <li>▪ Reducing operating and maintenance costs</li> <li>▪ Integral PWR in-service-inspection and -testing capabilities</li> <li>▪ Multimodule advance control room design with reduced operator staffing</li> <li>▪ Generic SMR cost model</li> <li>▪ Passive safety</li> <li>▪ Early site licenses for process heat applications</li> </ul>	<ul style="list-style-type: none"> <li>▪ Fuel, materials, and core behavior in long-term refueling (20 year) cycles (4)</li> <li>▪ Confirmation of claims related to economy of SMR (e.g., construction time, factory fabrication) (4)</li> <li>▪ Proliferation resistance (3)</li> <li>▪ Compact steam generators, internal control rod drive mechanisms (3)</li> <li>▪ Demonstration reactor and proof of operability (2)</li> <li>▪ Decreasing O&amp;M costs</li> <li>▪ Integral testing, system and component qualification</li> <li>▪ Impact of modularity on fuel-cycle economics</li> <li>▪ Internationalization of regulatory process</li> <li>▪ Innovative designs (designs very close to conventional PWR technology do not require much RD&amp;D)</li> <li>▪ Safety and management issues associated with locations close to public conurbations</li> </ul>

E.U. experts are more pessimistic about reductions under their recommended budget, clustering around reductions of 0-10% over the BAU RD&D estimates. In contrast, most U.S. experts expect SMR cost reductions ranging from 0-30% under their recommended budget. E.U. and U.S.

experts both expect that a RD&D budget ten times greater than what they had recommended would lead to significant SMR cost reductions.

As expected by their greater RD&D allocation on demonstrations of SMRs, most U.S. experts recommending significant support for SMRs recommended carrying out demonstrations to evaluate the economic viability of SMR designs. U.S. experts also placed a greater emphasis on the need for the U.S. government to support the licensing and certification process (Table 4-1). Both E.U. and U.S. experts emphasized the need to support factory fabrication methods to evaluate whether the decreased economies of scale on the reactor could be compensated with increased economies of scale in manufacturing. Non-proliferation and safety were other important areas of focus for RD&D support.

#### **4.2 Summary of Workshop Discussion**

U.S. and E.U. experts differed somewhat on the commercial market for SMRs. While U.S. experts were split, between those who thought that there were significant markets (in some cases niche markets) for SMRs, and others who thought the reductions in economies of scale in the reactor would lead to costs that are too high. By and large, E.U. experts did not foresee a large market for SMRs.

Experts also emphasized the fact that cost is not the only metric that should be used to evaluate SMRs. SMRs have other potential advantages over larger nuclear units. First, SMRs require less “lumpy” capital investments than 1 GWe or 700 MWe units. Given the perceived risks in siting a nuclear plant, partly due to negative public perceptions and to long construction and siting processes, putting a significantly lower amount of capital “at risk” could be a significant advantage for investors. Second, modularization and improvements in the fabrication process could result in significant economies of scale in manufacturing. Third, SMRs is that they could increase siting flexibility, since some sites may not have sufficient water (or other) resources to support a full-scale nuclear plant but may be able to host a smaller one. Fourth, factory fabrication could also reduce construction times, which is an important factor contributing to high nuclear costs. In addition, SMRs may even be shippable, which would also reduce construction costs. Fifth, some experts pointed out that in the United States there are several relatively small old coal plants with very low efficiency that may be replaceable with small (but not large) nuclear reactors. This could create the possibility of recycling existing sites. And the sixth and final possible advantage of SMRs discussed was that they could avoid the “single-shaft risk.” Today, nuclear capacity factors are very high, but when a 1 GWe plant is down, the grid has to deal with a very large capacity loss (essentially this means that there has to be extra generation capacity able to compensate for this scenario). Having several small units could decrease the probability that the grid will have to deal with very large imbalances.

In spite of efforts to bring the topic to the table, there was little discussion on possible safety and nonproliferation benefits of SMRs.

Experts also noted that it is important to differentiate between different types of SMRs and the need for government support. While the fundamental R&D on LWR-based SMRs is done, there is value in providing support towards licensing. Non-LWR-based SMRs need more RD&D support.

## 5. The Nuclear Fuel Cycle

### Highlights

- U.S. experts placed more emphasis on fuel cycle R&D and on economics than E.U. experts.
- Some U.S. experts highlighted the lack of a clear strategy for U.S. fuel cycle RD&D.
- There was disagreement on uranium availability and the value of reprocessing for sustainability.
- There were different views on whether non-aqueous recycling technologies count as “reprocessing” and their risks.
- There was disagreement on the value of reprocessing for waste management and its impact on public acceptance.
- There was agreement on the need to focus increased attention on establishing viable pathways for long-term disposal.

### 5.1 Survey Findings

In the survey conducted ahead of the workshop, experts were asked to allocate their recommended nuclear RD&D budget across a range of areas, including the fuel cycle. A greater fraction of U.S. experts, 70% (21 out of 30 experts), when compared to 62% of E.U. experts (18 out of 29) had fuel cycle as one of the top four areas for allocating nuclear RD&D funding.

As shown in Figure 5-1, U.S. experts were more likely to have fuel cycle as one of their top areas for investment. Those E.U. experts that recommended RD&D on fuel cycle only recommended between 7% and 15% of their budget to that topic, while those U.S. experts that recommended funding on fuel cycle recommended between 9% and 32% (the distribution of U.S. answers is highly skewed to high fractions of total investments).

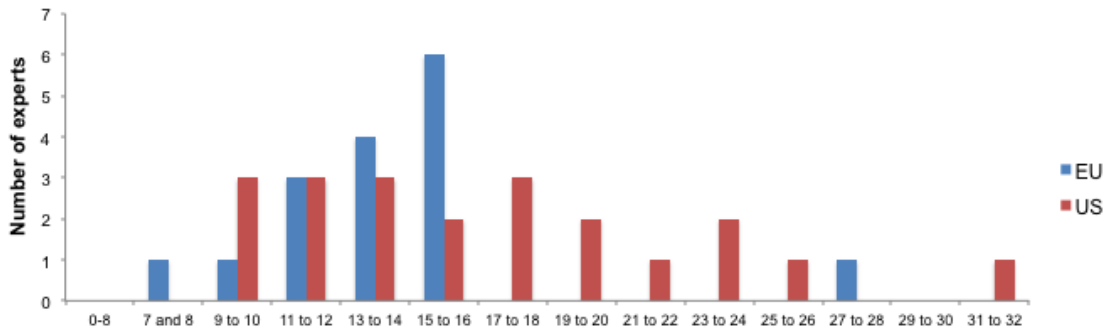


Figure 5-1: Percentage of recommended nuclear RD&D budget devoted to fuel cycle [%].

U.S. and E.U. experts also differed in the RD&D thrusts of fuel cycle research. While the most common thrust mentioned by U.S. experts was improving the economics, E.U. experts emphasized waste minimization and recycling—an area that U.S. experts also focused on. The separation of minor actinides was also an RD&D thrust with a lot of support from both E.U. and U.S. experts. Waste disposal was another research area perceived to be important by the experts.

**Table 5-1: Experts’ opinions on the RD&D thrusts of public support programs for fuel cycle. The number of experts holding each opinion is noted in parenthesis.**

<b>U.S. experts</b>	<b>E.U. experts</b>
<ul style="list-style-type: none"> <li>▪ Improving economics (6)</li> <li>▪ Separation chemistry of minor actinides (5)</li> <li>▪ Waste minimization, spent fuel recycling (4)</li> <li>▪ Improving proliferation resistance (2)</li> <li>▪ Interim storage and geologic disposal (2)</li> <li>▪ Pyroprocessing</li> <li>▪ Transuranic burnup in fast reactors</li> <li>▪ Blanket process for breeders</li> </ul>	<ul style="list-style-type: none"> <li>▪ Waste minimization, spent fuel recycling (6)</li> <li>▪ Partitioning technologies to separate, recycle, and burn minor actinides (4)</li> <li>▪ HLW repositories, spent fuel geologic disposal (2)</li> <li>▪ Pyroprocessing</li> <li>▪ Carbide and nitride fuels</li> <li>▪ Electrochemical refining of metal fuel</li> <li>▪ Proliferation and safety</li> <li>▪ Optimization of radioactive waste</li> </ul>

## **5.2 Summary of Workshop Discussion**

As already discussed, U.S. experts placed more emphasis on fuel cycle research than E.U. experts. They also placed more emphasis on research that would demonstrate or disprove that the economics of particular fuel cycle approaches are favorable.

In the discussion of the future direction of fuel cycle research, some U.S. experts highlighted the lack of a clear strategy for U.S. fuel cycle RD&D. They indicated that this was a real problem that could lead to an inefficient use of funds.

The value of reprocessing to increase the sustainability of the uranium resource (to make sure the world does not run out of economically viable uranium) was an area of debate. Experts disagreed about whether it would be necessary to recover plutonium and uranium from spent fuel within the next half-century to ensure that nuclear power has enough uranium fuel globally.

Experts also disagreed about whether non-aqueous recycling technologies count as “reprocessing” and their risks. One participant argued that since non-aqueous technologies such as pyroprocessing would not separate pure plutonium from which nuclear weapons could be made, it posed significantly lower proliferation risks and should not be considered reprocessing. Another participant noted that studies in the United States had concluded that there was little difference in proliferation risk between pyroprocessing and traditional aqueous reprocessing technologies, and that the U.S. government had determined that pyroprocessing should be considered “reprocessing” as that term is used in limiting exports under U.S. law.

The last area of disagreement was whether reprocessing had advantages from a waste management perspective. In particular, some experts felt that reprocessing did not result in significantly smaller requirements for geologic disposal, while others asserted that there were benefits to be gained. Several experts expressed the view that the public does not see reprocessing as a way to solve the waste management question, which implies that public acceptance would not necessarily increase from a push for reprocessing.

There was one area in which all experts agreed, however, this was the need to focus attention on long-term disposal. Achieving success in siting, licensing, and operating long-term disposal sites would be a very important step forward for nuclear energy.

## 6. International Cooperation

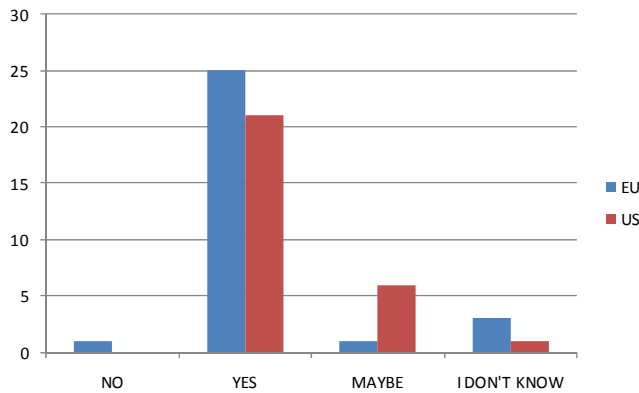
### Highlights

- Most experts agree that to pursue innovation in an efficient manner it will be necessary to select a subset of technologies that are judged to be ahead of others and to reorganize internationally harmonized efforts and investments on applied research, pilots, and demonstrations.
- E.U. experts tend to see greater advantages in collaborative projects on basic and applied research, establishing an E.U. governance to foster the dynamics of knowledge and technology transfer.
- U.S. experts are more concerned with international collaboration on demonstration for Generation IV technologies, sharing costs and results with countries like China, Japan, and South Korea.

### 6.1 Survey Findings

Interrogated on the usefulness of international cooperation, both E.U. and U.S. experts agree on the importance of establishing active partnerships with other countries (Figure 6-1).

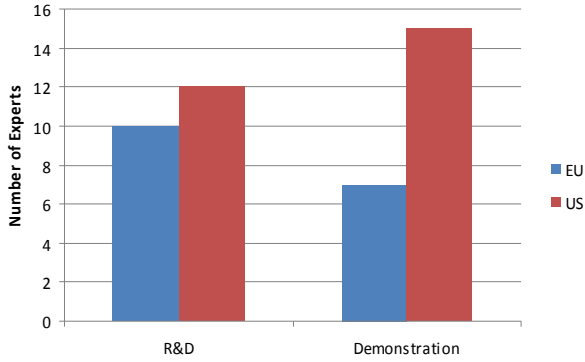
The Fukushima accident revived the international debate on the importance of defining common cross-boundary regulation systems and standards on nuclear plants. Although the main purpose of an effective international cooperation remains the design and enforcement of safety rules related to the global effects of a nuclear accident, several other crucial advantages from cooperation, mainly linked with cost sharing and knowledge transfer, arose from the surveys of both E.U. and U.S. experts.



**Figure 6-1: Experts willing to spend some of the RD&D funds they recommended in collaborative projects with other countries.**

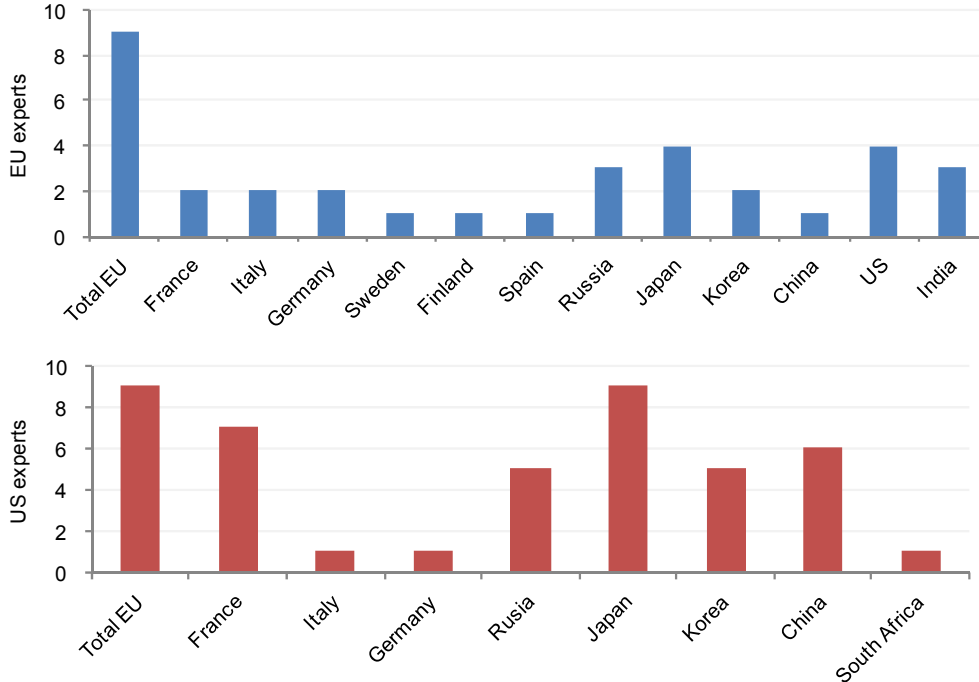
Most experts agree that to pursue innovation in an efficient manner, it will be necessary, sometime between 2020 and 2030, to select a subset of technologies that are judged to be ahead of others and to reorganize internationally harmonized efforts and investments on applied research, pilots, and demonstrations. Pursuing RD&D on all types of reactors does not seem to be feasible, given time and resource constraints. Most experts suggested focusing on relatively mature Generation IV technologies, particularly SFR and VHTR systems.





**Figure 6-2: Main areas of cooperation selected by the E.U. and U.S. experts (each expert could select more than one area).**

Regarding RD&D expenditures, E.U. experts tend to see higher advantages in collaborative projects on basic and applied research (Figure 6-2). They suggest that all E.U. countries with active nuclear programs should aim at establishing an E.U. governance to foster the dynamics of knowledge and technology transfer. R&D should mainly focus on Gen IV technologies, to share the research advancements on innovative materials and nuclear fuel, and on safety and waste management technologies. E.U. experts recommend establishing international consortia on basic and applied research with technologically advanced countries like the United States and Japan. They stressed the necessity of exploiting bilateral or multilateral partnerships with Korea, Japan, Russia, China, and India on joint construction and operation of large experimental facilities, and on new design features for demonstrators (Figure 6-3).



**Figure 6-3: Country partners for nuclear RD&D recommended by the E.U. experts (top) and the U.S. experts (bottom).**

There are several reasons why experts thought international cooperation in nuclear RD&D should be supported. U.S. experts recognized the need of a joint research effort on Gen IV reactors, especially with France and Japan. They are particularly supportive of international collaboration on demonstration of Gen IV technologies (Figure 6-2). One of the main reasons for this is the lack or scarcity of experimental facilities in the United States. According to the experts, much of U.S. experimental infrastructures in the nuclear area have been lost. The new systems will require irradiation facilities and other means of testing, and other countries, especially China, Japan and South Korea, have been very active in building new capabilities (Figure 6-3).

All experts pointed to the fact that international demonstrations are useful to share the results and the high costs. U.S. experts also felt that collaboration with other countries is critical because nuclear power is becoming more global in nature, and the United States should be an active part of new international arrangements. Experts from the United States and the European Union thought that multilateral cooperation could contribute to more transparent non-proliferation verification.

Finally, both E.U. and U.S. experts are aware of the existing hurdles to effective international cooperation, which are generally a lack of common commitments and objectives, and could therefore be overcome through the definition of a single international authority.

## **6.2 Summary of Workshop Discussion**

E.U. and U.S. experts underlined the importance of establishing common programs and objectives at the international level. During the workshop session they mainly emphasized the difficulty in creating productive collaborative efforts, mainly because most international cooperation is currently driven by the need to support national objectives.

The experts described a few positive examples of international cooperation: the Superphénix project (run by the NERSA consortium, a joint company of EdF, France, ENEL, Italy and SBK, Germany), the collaboration between CEA and Slovenia, and the international cooperative effort on safety in LWRs in the 1970s and 1980s. According to the experts, establishing a country lead ensured the success of the above cited cases.

The experts did not acknowledge a sufficient effort toward international cooperation on Gen IV reactors. They considered the Generation IV International Forum (GIF) mostly as an information exchange platform, and they recognized that France and Japan are still split on leading SFRs. Since few E.U. experts had recommended collaborating with the U.S. on demonstration activities, U.S. experts considered the possible barriers to cooperation due to difficulties in licensing.

## 7. Financial Barriers and Other Factors Affecting the Growth of Nuclear Power

### **Highlights**

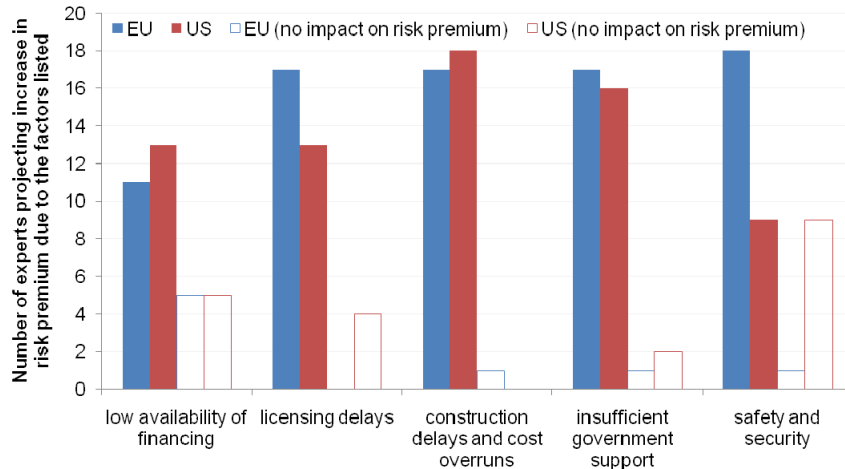
- U.S. and E.U. experts largely agree that licensing and construction delays, costs overruns, and insufficient government support result in an increased risk premium for nuclear power facilities over natural gas.
- Most E.U. and U.S. experts are convinced that in the short term the risk premium on nuclear investments will remain higher than the natural gas plant discount rate, but in the long term there will be a progressive decrease in the importance of non-technical factors on the risk premium for nuclear investments.
- Global events like nuclear accidents, major costs overruns, and proliferation from the civilian nuclear energy system could cause a significant decrease in the rate of construction of new nuclear power plants in the E.U. and in the U.S.
- Successful siting and demonstration projects, and failures in the use of fossil fuel and renewable energy technologies would have a positive effect on the deployment of nuclear power.

### **7.1 Survey Findings**

E.U. and U.S. experts were asked to assess the role of non-technical non-cost factors, which are not likely to be affected by RD&D programs, in constraining the deployment of nuclear power in the European Union and in the United States by 2030. Five specific conditions were selected which could contribute to a risk premium for nuclear power facilities greater than for natural gas power plants. The natural gas power plant discount rate assumed was 10%. Risk premium is the financial return in excess of the risk-free rate that a riskier investment is expected to yield. It is also known as the weighted average cost of capital. It is expressed as a certain percentage point, B%, rate increase over the risk-free rate (A%).

U.S. and E.U. experts largely agree that delays, overruns, and insufficient government support result in an increased risk premium over natural gas. U.S. and E.U. experts are split about whether “low availability of financing” results in a risk premium over natural gas plants. Most E.U. experts think that “safety and security” affects the risk premium, while U.S. experts are split (Figure 7-1).

Most E.U. and U.S. experts are convinced that in the short term (around 2010 or the present time), there is a large element written into investment risk evaluation for non-technical factors (i.e., public perception) (Figure 7-2). As time goes on, governments could be forced, for practical purposes, to expand nuclear generation, and the majority of the public would become more or less indifferent to the issues currently surrounding nuclear power. According to most experts, this element will contribute to a partial, but progressive, decrease in the importance of non-technical factors on risk premium for nuclear investments. The process will not be linear, but faster in the early years, mainly between 2020 and 2030.



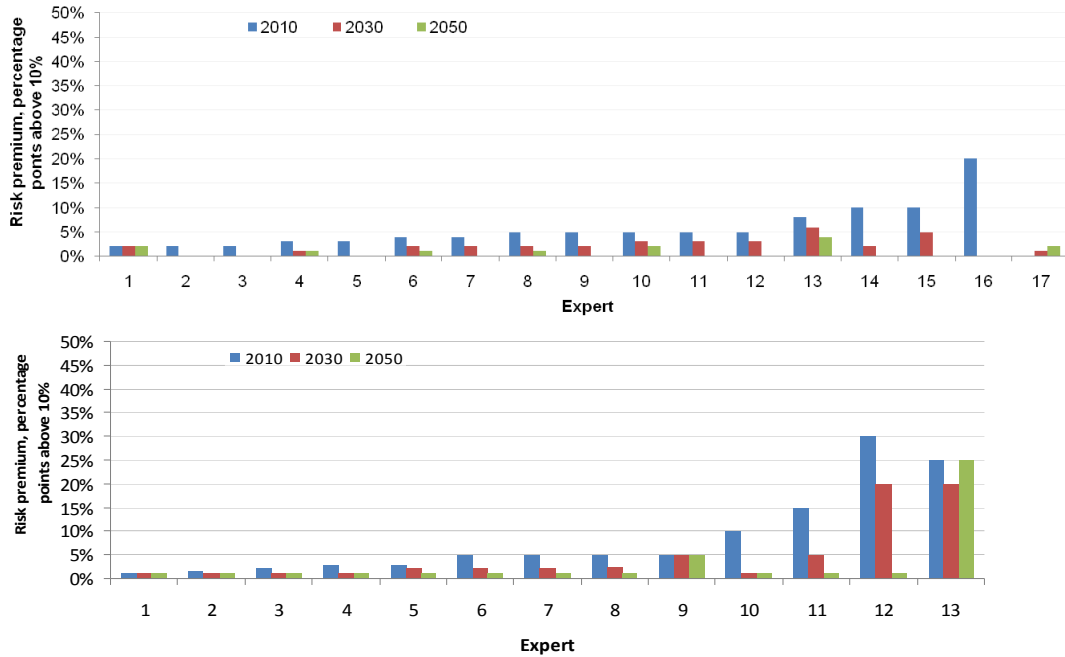
**Figure 7-1: Impact on risk premium due to the selected non-technical factors.**

Both E.U. and U.S. experts agreed that major radioactivity releases caused by an accident or sabotage could decrease by 50-100% the rate of construction of new nuclear power plants in the European Union and in the United States, in the 20 years after the event takes place (Table 7-1), although they consider these events very unlikely to happen before 2030 (Table 7-2). Both E.U. and U.S. experts recognize the serious impact of major costs overruns, which could lead to a reduction of 10-50% in the development of nuclear plants. The experts are split concerning the likelihood of such an event. Proliferation from the civilian nuclear energy system, although unlikely to take place (especially according to U.S. experts) is the third crucial factor of risk, which could decrease by 10-50% the rate of nuclear plant construction.

While U.S. experts highlighted the positive effects of a successful repository siting in the United States, which would lead to an increase in the deployment of nuclear plants by 10-100%, E.U. experts also recognized the important role of an international repository siting, which would also increase the deployment of nuclear plants in the next 20 years (Tables 7-1 and 7-2).

The experts indicated a few other events that would positively affect the rate of nuclear power plant construction by 2030 (Table 7-3). Both E.U. and U.S. experts considered the effects of major problems in the electricity grid possible due to the use of alternative energy sources. According to most experts, the deployment of nuclear power plants would benefit from the successful operation of new nuclear plants. The inclusion of nuclear energy into long-term national policy, and the enforcement of a carbon policy would also push the development and diffusion of nuclear.

Successful demonstration projects on a large scale would highlight the benefits of nuclear deployment, and this process would receive positive feedback effects in the event of large coal slurry or oil spills. On the other hand, E.U. experts recognised the crucial role of public perception and opinion in leading to the institutional acceptance of nuclear power as a key solution for future energy production.



**Figure 7-2: Risk premium for nuclear investment above natural gas power plant discount rate according to U.S. experts (above) and E.U. experts (below) E.U. experts 12 and 13 are probably referring to the total risk premium.**

**Table 7-1: Impact of global developments or events on nuclear power plant construction.**

	50-100% decrease	10-50% decrease	0-10% increase/decrease	10-100% increase	>100% increase	No response
<b>US</b>						
Major cost overruns	5	16	4	1	0	4
Major radioactivity release due to accident or sabotage	19	5	0	1	0	5
Successful U.S. repository siting	1	2	5	18	0	4
Successful international repository siting	0	1	19	5	0	5
Proliferation from civilian nuclear energy system	5	17	4	0	0	4
Other	1	1	0	12	0	
<b>EU</b>						
Major cost overruns	6	19	3	0	0	1
Major radioactivity release due to accident or sabotage	18	9	0	1	0	1
Successful U.S. repository siting	2	1	9	14	1	2
Successful international repository siting	0	2	6	19	1	1
Proliferation from civilian nuclear energy system	5	16	6	0	0	2
Other	0	2	0	9	0	

**Table 7-2: Likelihood of global developments or events.**

	<10%	10-50%	50-90%	>90%
Major Cost overruns	1	13	7	5
Major radioactivity release due to accident or sabotage	21	3	2	0
<b>US</b> Successful U.S. repository siting	6	10	10	0
Successful international repository siting	0	3	14	9
Proliferation from civilian nuclear energy system	14	12	0	0
Major Cost overruns	1	12	12	3
Major radioactivity release due to accident or sabotage	22	4	1	1
<b>EU</b> Successful U.S. repository siting	2	13	11	2
Successful international repository siting	0	4	10	14
Proliferation from civilian nuclear energy system	17	8	3	0

**Table 7-3: “Other” events that would affect nuclear power plant construction rates over the next 20 years. All events but the last row (in grey) would have a positive impact on construction.**

E.U. experts	U.S. experts
<ul style="list-style-type: none"> <li>Repeated blackouts/brownouts</li> <li>Major electricity grid failure due to incoherent grid loading by alternative energy sources</li> </ul>	<ul style="list-style-type: none"> <li>Recurring power shortages/outages</li> </ul>
<ul style="list-style-type: none"> <li>New plant in operation within planned budget</li> </ul>	<ul style="list-style-type: none"> <li>Successful construction, operation of several plants (U.S., outside U.S., Gen IV)</li> </ul>
<ul style="list-style-type: none"> <li>Strong government policy support that nuclear is part of the long-term energy mix</li> </ul>	<ul style="list-style-type: none"> <li>Widespread adoption of a carbon tax (U.S. &gt;\$10/ton CO<sub>2</sub>)</li> <li>Increase of fossil fuel price</li> <li>Major increase in competition for oil with other countries (like China)</li> <li>Demonstration of nuclear deployment benefit to economy</li> </ul>
<ul style="list-style-type: none"> <li>Materialization of total nuclear disarmament (Obama’s speech, Prague, 6 April, 2009)</li> <li>Successful partitioning and transmutation demonstration on a large scale</li> </ul>	<ul style="list-style-type: none"> <li>Largest coal slurry spill or oil spill in history</li> </ul>
<ul style="list-style-type: none"> <li>Stronger anti-nuclear movements</li> </ul>	

**7.2 Summary of Workshop Discussion**

The workshop discussion confirmed the survey finding that licensing and construction delays, cost overruns, and insufficient government support contribute to an increased risk premium for nuclear power facilities over natural gas. Over time, experts expect that, as more facilities get off the ground, the risk premium for nuclear investments will decrease.

Beyond the financial risk premium, experts raised several factors that could contribute to an acceleration or deceleration of the construction of nuclear power plants in the United States and the European Union. Experts highlighted that nuclear accidents (such as the one in Fukushima or larger) or proliferation from the civilian nuclear energy system could lead to significant decreases in the rate of construction of nuclear power plants. In contrast, accidents or cost overruns in the development and use of fossil sources and renewables could accelerate nuclear plans. Similarly, the siting of long term waste repositories and the successful on-budget completion of nuclear demonstration projects could improve the prospects for nuclear power.

## 8. Diffusion of Nuclear Power

### **Highlights**

- 17% of E.U. and 13% of U.S. experts considered “likely” (>66%) the medium scenario of nuclear growth to 2050. U.S. (E.U.) experts attach greater (smaller) weight to the tails, as 7% (3%) and 3% (0%) of them consider “likely” the low and high scenarios, respectively.
- Most of the participating experts believed that scaling up nuclear deployment to very high levels would be feasible over the long term. Others argued that a variety of political and regulatory constraints made such huge growth highly unlikely.
- The experts generally agreed that improved reactor and fuel-cycle technologies could help achieve such high levels of nuclear growth while minimizing safety, security, and proliferation risks and waste management challenges.
- Some experts argued that fueling such high levels of nuclear growth would require recycling to extend uranium resources, while others argued that sufficient uranium would be available to fuel a once-through cycle for many decades to come.
- For many experts the diffusion of nuclear technology factors beyond technology will be critical (e.g., public acceptance, government support for licensing and financing, etc.).

### **8.1 Survey Findings**

Experts were asked to estimate the probability of three scenarios (low, medium, and high) for the growth of nuclear power in 2050 in both the United States and the European Union.<sup>3</sup> The low scenario is defined as the current E.U./ U.S. nuclear power capacity maintained to 2050; in the medium scenario an expansion of up to 286 GW in both E.U. and U.S. nuclear capacity is assumed; in the high scenario the expansion of EU/U.S. nuclear capacity in 2050 will reach 400/477 GW, respectively.

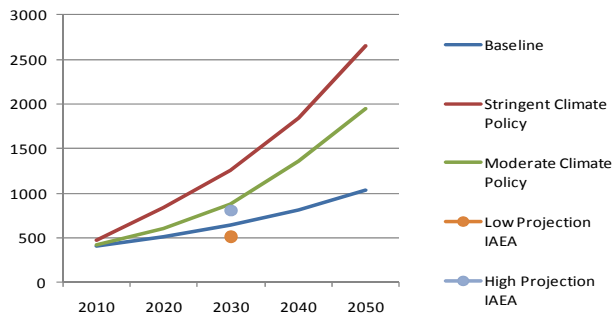
### **8.2 Summary of Workshop Discussion**

During the workshop experts were shown nuclear deployment numbers taken from the Energy Modeling Forum 22 (EMF 22) study database (Figure 8-1)<sup>4</sup>. Published in late 2009, it includes modeling results from a large number of different groups around the world. The study examined a wide range of cases. CO<sub>2</sub> constraints were varied from business-as-usual (no constraint) to atmospheric concentration as low as 550 ppm CO<sub>2</sub> equivalent (moderate climate policy) and 450 ppm CO<sub>2</sub> equivalent (stringent climate policy) (Figure 8-2).

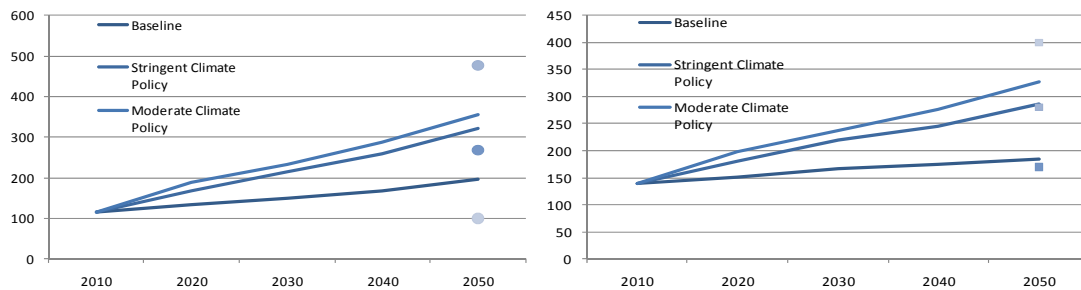
Projected nuclear penetration dramatically depends on what policies are assumed to be in place. In particular, climate policies could trigger larger rates of nuclear deployment throughout the world. The deployment of nuclear in a fast growing country under a stringent climate policy could be critical in determining its cost, hence the importance of country participation to an international climate agreement. Integrated assessment models produce very divergent projections for these fast-growing countries, primarily because they have different assumptions about the extent to which governments in different fast growing economies (mainly China) will rely on nuclear power to meet their growing electricity demand.

<sup>3</sup> At least two experts claimed they had in mind climate change when assessing the likelihood of diffusion scenarios

<sup>4</sup> Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., Tavoni, M., “International climate policy architectures: Overview of the EMF 22 International Scenarios”, *Energy Economics* 31 (2009) S64.



**Figure 8-1: Nuclear Projections EMF 22 Study: Global Capacity Installed.** The units are GW. The continuous projections represent the average across ten EU/U.S. models under different policy scenarios. The two dots represent IAEA projections for 2030.<sup>5</sup> Installed capacity in 2010 is not exactly the same in different models because for some of the models the data for 2010 is simulated, and not historic.



**Figure 8-2: Nuclear Projections EMF 22 Study: Capacity Installed.** The units are GW. The continuous projections represent the average across ten EU/U.S. models under different policy scenarios in the United States (on the left panel), and in the European Union (on the right panel). Markers represent the low, medium, and high scenarios evaluated by experts.

In discussing these figures:

- Most of the participating experts believed that scaling up nuclear deployment to such levels would be feasible over the long term. Others argued that a variety of political and regulatory constraints made such huge growth highly unlikely.
- The experts generally agreed that improved reactor and fuel-cycle technologies could help achieve such high levels of nuclear growth while minimizing safety, security, and proliferation risks and waste management challenges.
- Some experts argued that fueling such high levels of nuclear growth would require recycling to extend uranium resources, while others argued that sufficient uranium would be available to fuel a once-through cycle for many decades to come.
- For many experts the diffusion of nuclear technology factors beyond technology will be critical (e.g., public acceptance, government support for licensing and financing, etc.).

<sup>5</sup> IAEA. 2009. "Energy, Electricity and Nuclear Power Estimates for the Period up to 2030." 2009 Edition. International Atomic Energy Agency. Vienna, Austria. Available at: [http://www-pub.iaea.org/MTCD/publications/PDF/RDS1-29\\_web.pdf](http://www-pub.iaea.org/MTCD/publications/PDF/RDS1-29_web.pdf)



## Nomenclature

<b>Acronym</b>	<b>Description</b>
BAU	Business-as-usual
CEA	Commissariat à l'énergie atomique (Atomic Energy Commission)
EdF	Électricité de France
ENEL	Ente Nazionale per l'Energia eLettrica
EMF	Energy Modeling Forum
Gen IV	Generation IV reactors are innovative reactors that will enable nuclear energy to meet the energy needs of the future while also complying with the concept of sustainable development, in particular relating to more efficient use of uranium and optimized management of nuclear waste
GFR	Gas-cooled fast reactor (Gen IV)
HLW	High level waste
IAEA	International Atomic Energy Agency
LFR	Lead-cooled fast reactor
LWR	Light water reactor
NERSA	Nuclear European Reactor SA
PWR	Pressurized water reactor
RD&D	Research, development & demonstration
SBK	Schnell-Brüter-Kernkraftwerksgesellschaft mbH
SCWR	Supercritical-water-cooled reactor (Gen IV)
SFR	Sodium-cooled fast reactor (Gen IV)
SMR	Small modular factory-built reactors (<300 MWe, or MW electric)
VHTR	Very-high-temperature reactor (Gen IV)

## Appendix

### *A. List of E.U. and U.S. nuclear experts participating in the Workshop*

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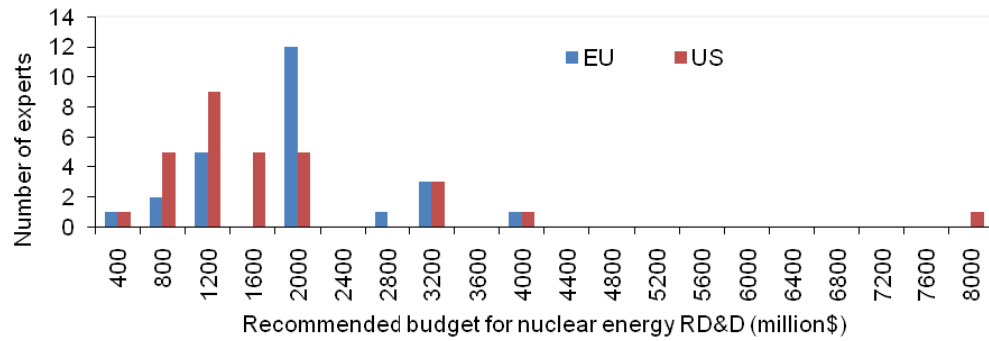
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Any errors that remain are the responsibility of the authors.

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