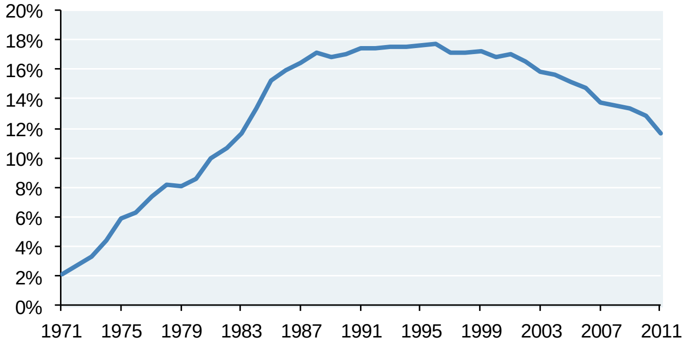
## 2: The rising cost of nuclear power

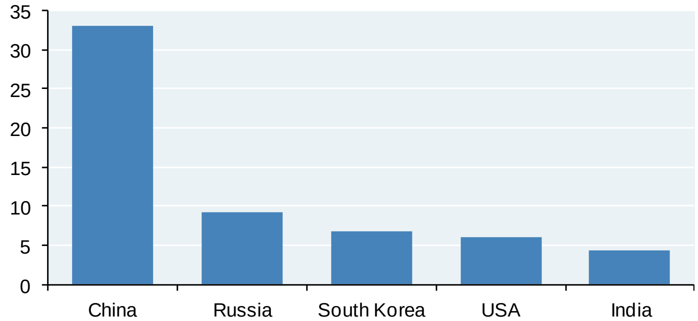
In 1945, physicists predicted that nuclear breeders would be man's ultimate energy source. A decade later, the chairman of the US Atomic Energy Commission predicted that it would be "too cheap to meter". Then things got complicated. Fast forward to today; while some countries have adopted a more cautious stance (Japan, Germany), nuclear power is still with us. Asia leads in the number of reactors under construction (China 29, India 6 and South Korea 5), and the US has 5 under construction as well (6 GW of capacity).

**The rise, plateau and fall of nuclear energy's share of global electricity generation,** percent of total generation




Source: 2014 OECD Factbook. Data through 2011.

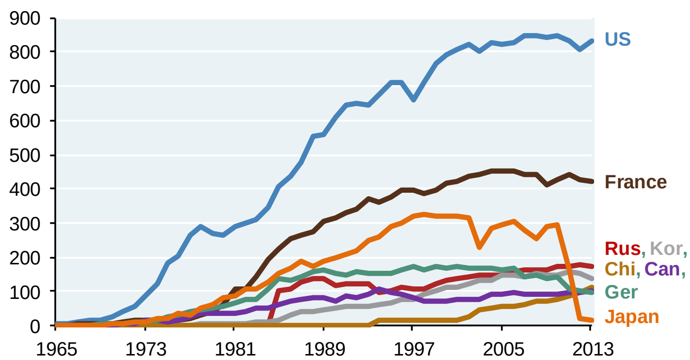
**Asia leads the way in nuclear plant capacity currently under construction,** Gigawatts of capacity




Source: World Nuclear Association. June 2014. Under construction: first concrete for reactor poured, or major refurbishment of a plant under way.

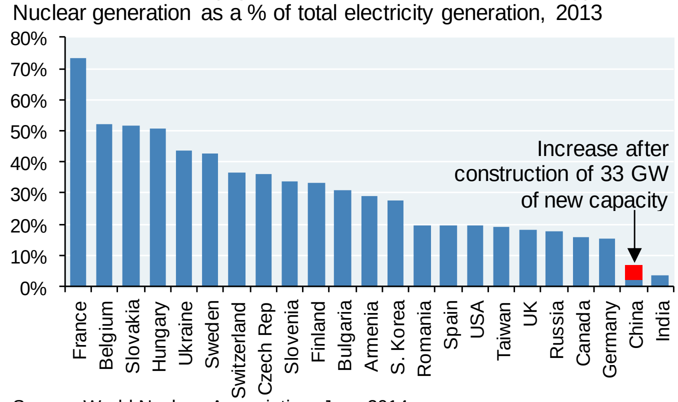
The appeal of nuclear power: capacity factors [see box on page 10] of 80%-95% for US nuclear vs. 55-70% for coal[10] and 30-40% for wind and hydro-electric power, and no $CO_2$ emissions from ongoing operations, though they can be high during construction. **The problem: it is getting a lot more expensive to build and operate.** One place to examine these trends is France, #2 in terms of nuclear terawatt-hours generated and #1 in terms of nuclear power as a share of electricity generation.

**World's biggest nuclear electricity generating countries**
Terawatt-hours of nuclear electricity generation




Source: BP Statistical Review of World Energy. 2013.

**Share of electricity generation from nuclear energy**
Nuclear generation as a % of total electricity generation, 2013



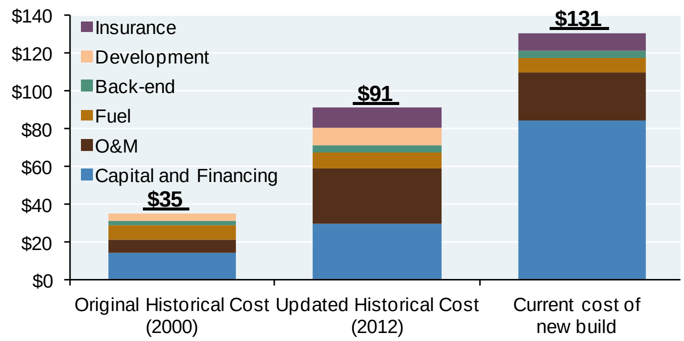

Source: World Nuclear Association. June 2014

[10] **Any comparison of electricity generation sources should incorporate the fully-loaded costs of coal.** In last year's energy note, we walked through the fact that coal powered electricity as a % of global primary energy consumption is at its highest level since 1970, and discussed the various consequences for $CO_2$, smog, acid rain, heavy metals emissions (sulfur dioxide and nitrous oxide) and mercury, and the associated creation of polluted streams, waste heaps, slurry and fly ash ponds, underground fires, etc.

***Nuclear power in France***. After Fukushima, French Prime Minister Fillon ordered an audit of its nuclear facilities to assess their safety, security and cost. As a result, we now have a more accurate assessment of the fully-loaded levelized costs for French nuclear power. Levelized cost is an important concept in energy analysis: it incorporates upfront capital costs, financing costs, operating & maintenance and fuel costs, capacity factors (actual vs. potential output), and any insurance or fuel de-commissioning costs.

A prior assessment using data from the year 2000 estimated levelized costs at $35 per MWh. The French audit report then set out in 2012 to reassess historical costs of the fleet. **The updated audit costs per MWh are 2.5x the original number**, as shown by the middle bar in the chart. The primary reasons for the upward revisions: a higher cost of capital (the original assessment used a heavily subsidized 4.5% instead of a market-based 10%); a 4-fold increase in operating and maintenance costs which were underestimated in the original study; and insurance costs which the French Court of Audit described as necessary to insure up to 100 billion Euros in case of accident. In a June 2014 update from the Court of Audit, O&M costs increased again, by another 20%.

**The rising cost of nuclear power in France**
Levelized cost measured in 2010 $/MWh

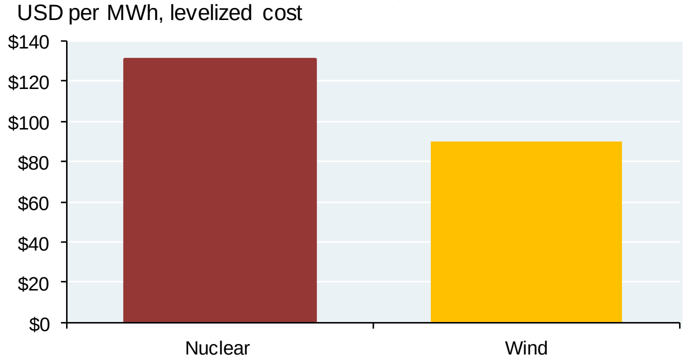



Source: N. Boccard, *"The cost of nuclear electricity: France after Fukushima"*, Energy Policy Journal, December 2013.

**Subsequent analyses set out to assess the cost of *future* nuclear power in France.** Based on data from a 1.6 GW facility under construction in Flamanville, costs have risen *again* (third bar in the chart). The main reason: higher capital costs for the new facility. Construction delays have compounded the project's cost, in part a consequence of greater security measures mandated after Fukushima. It's possible that future plant costs won't be as high if the industry gains more experience with the new type of pressurized water reactor being built in Flamanville. Nevertheless, the picture is clear: **the days of nuclear energy being a cheap way to add baseload power are a thing of the past.**

Due to rising costs, France aims to reduce nuclear from 70% to 50% by 2025 and replace it with renewable energy. On paper, wind is cheaper than nuclear in France, but replacing nuclear with wind/solar will require spending on grid integration and/or storage (as things stand now, other than hydro, France only gets 5% of electricity from renewable energy). The electricity issue is particularly important in France, as it has the most electrified heating system in Europe. The path of least resistance: extend the life of existing nuclear reactors to 50-60 years instead of building new ones, and phase in renewable energy over a longer period of time.

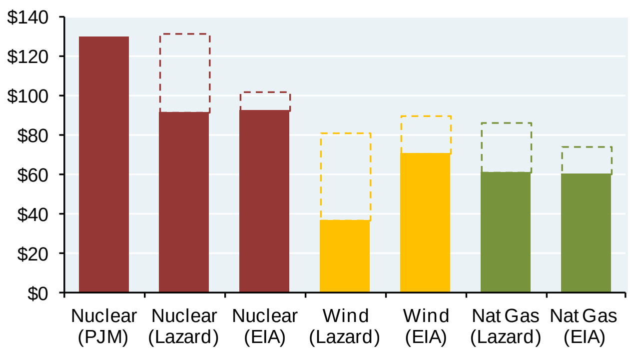
**In France, nuclear looks more expensive than wind**
USD per MWh, levelized cost




Source: N. Boccard, *"The cost of nuclear electricity: France after Fukushima"*, Energy Policy Journal, December 2013.

Escalating costs are not just an issue in France: in the US, real costs per MWh for nuclear power have been rising at 19% annually since the early 1970's. The highest nuclear cost bar in the chart below comes from PJM, the US East Coast interconnection grid operator which oversees the world's largest competitive wholesale electricity market. Another confirming observation: in a 2010 analysis, Exelon's assumed costs per metric ton of displaced $CO_2$ from nuclear are double the same estimates from 2008. One final example of rising costs: the UK agreed to purchase power from EDF Energy at $158 per MWh (in today's dollars), sourced from a 3.2 GW nuclear plant to be completed by 2023. Bottom line: expect the contribution of nuclear power to global electricity generation, shown in the first chart on page 7, to keep declining.

**Nuclear all-in costs are high in the US as well**
USD per MWh, levelized cost




Source: PJM, EIA, Lazard (as of 2014). Subsidies not included.

***What about the future for nuclear?*** Academics, scientists and private sector companies are exploring ways of lowering costs, increasing productivity and reducing radioactive by-products (e.g. travelling wave reactors). However, commercial deployment of these reactors is many years (if not decades) away, while our report is about the most important developments of the year. The 2014 update from France is more relevant as we consider near-term prospects for nuclear power in the OECD and its impact on electricity prices. We do not have comparable data for nuclear costs in Asia, or insight into whether post-Fukushima construction and operational standards have changed there. Given fewer domestic energy alternatives, countries like China, Korea and India may be willing to pay a higher price for the certainty and lower carbon footprint of nuclear power.

**Understanding capacity factors**

A capacity factor measures the ratio of electricity produced during a certain period of time relative to the electricity that *could* have been produced if the generator had run continuously at full-power during the same period. Reasons why capacity factors are less than 100%: intermittency of naturally occurring resources (the degree of wind speeds and solar irradiation levels; availability of water for hydroelectric dams); plant downtime for maintenance and repairs and inefficiencies resulting from plants being ramped on and off; voluntary curtailment of power (e.g., when wind or solar energy cannot be absorbed by the grid); or when looking at power plants that are not designed for continuous use, such as natural gas peaker facilities which are only drawn upon when electricity demand spikes. As noted on page 11, capacity factors for the US wind fleet have been stable over the last few years in the mid 30's, while solar capacity factors have been rising towards these levels in the sunniest US locations and when axis tracking systems are used (otherwise, they are in the teens). Nuclear plants tend to have the highest capacity factors (80%-90% in most countries), followed by coal and natural gas. Capacity factors are an important input in the computation of levelized cost of electricity, since fully loaded costs measure *actual* electricity output, rather than theoretical output.

## 1f. Is there a cheaper way to do it? A balanced system, with nuclear power

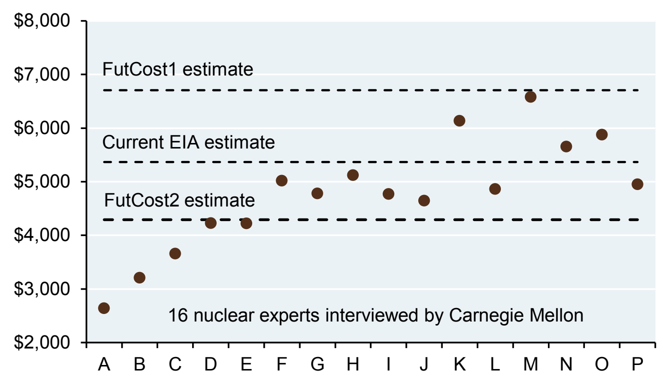
*Nuclear Power*. For some, the discussion stops here, since they have scientific, financial, environmental or geopolitical objections. That said, we analyze a **balanced** system as well: Germany maintains the wind, solar, hydro and biomass it now has; relies on nuclear to meet 35% of demand by turning back on some of its idle plants; and uses a 50/50 natural gas/coal mix for the remainder. Balanced results are shown in the last row, along with no-storage and storage scenarios for *Energiewende,* and the current system.

| | Installed capacity (GW) | | | | | | | Generation | | Cost | | $CO_2$ emissions | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total | Wind | PV | Storage | Hydro & Bio | Therm | Nuclear | Therm gen. (TWh) | Therm gener. reduc. | $/MWh cons. | $/MWh gen. | $CO_2$ (MMT) | $CO_2$ reduc. | $/MT of $CO_2$ reduc. |
| Current; No Stor; Curr cost | 120 | 24 | 25 | 0 | 7 | 58 | 7 | 223 | | $108 | $108 | 188 | | |
| Energiewende; No Stor; Curr cost | 278 | 118 | 86 | 0 | 14 | 60 | 0 | 107 | 52% | $203 | $180 | 70 | 63% | $300 |
| Energiewende; Hydr Stor - 2; Curr cost | 278 | 118 | 86 | 9 | 14 | 60 | 0 | 100 | 55% | $212 | $191 | 65 | 66% | $316 |
| Energiewende; Pump Stor - 2; Curr cost | 278 | 118 | 86 | 23 | 14 | 60 | 0 | 95 | 57% | $211 | $193 | 62 | 67% | $306 |
| Energiewende; Batt Stor - 2; Curr cost | 278 | 118 | 86 | 17 | 14 | 60 | 0 | 99 | 56% | $209 | $190 | 64 | 66% | $308 |
| Balanced; No Stor; Curr cost | 149 | 36 | 38 | 0 | 14 | 46 | 16 | 95 | 57% | $136 | $134 | 62 | 67% | $84 |

Source: Germany grid operators, JPMAM. 2015.

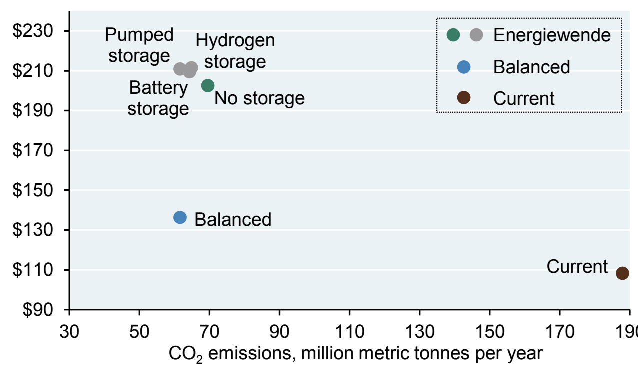
The balanced system we analyzed achieves cost and $CO_2$ reductions at a *much* lower cost per metric ton than *Energiewende* …**but only if** EIA nuclear cost projections are accurate. In support of EIA data, Carnegie Mellon published a 2013 survey of 16 nuclear power industry practitioners in the *Proceedings of the National Academy of Sciences*. Their median cost estimates for nuclear plants developed in the Southeast US were **pretty close** to the most recent EIA projections.

**Median cost estimates of large nuclear plants in line with EIA estimates,** Capital cost, USD per kW




Source: EIA, Carnegie Mellon, JPMAM. 2015. Experts interviewed in 2013.

**Balanced system at current cost: better cost/emission outcome…if you believe EIA nuclear power costs**
System cost, USD per MWh consumed




Source: Germany grid operators, JPMAM. 2015.

**However, EIA and Carnegie Mellon cost estimates may not reflect reality.** The rising trend in OECD nuclear capital and operating costs is a topic we addressed last year. In the US, real costs per MWh for nuclear have risen by 19% annually since the 1970's[5]. Even in France, the country with the greatest reliance on nuclear power as a share of generation and whose centralized decision-making and regulatory structure are geared toward nuclear power, costs have been rising and priorities are shifting to renewable energy[6]. Globally, nuclear power peaked as a share of electricity generation in 1995 at 18% and is now at 11%, primarily a reflection of slower development in the OECD.

[5] Even when nuclear power plants are not completed, as with the cancelled Levy County plant in Florida, they can become huge political and economic liabilities.

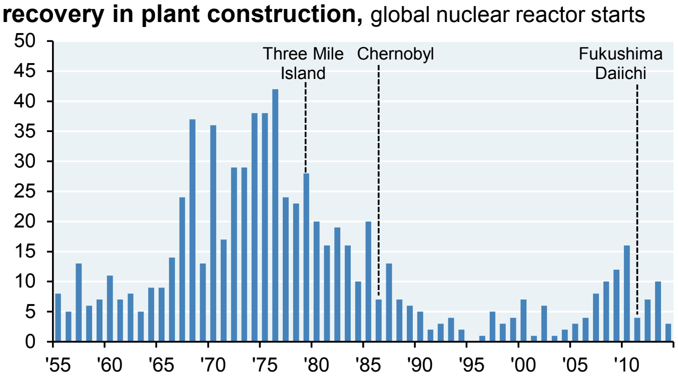
[6] There are huge cost over-runs at Flammanville France and Olkiluoto (Finland), the first plants built in Europe in 20 years. In Finland, 50% cost over-runs and delivery delays of nine years resulted in the utility abandoning its option to apply for a second French Evolutionary Power Reactor (EPR). In February 2015, Areva asked the US Nuclear Regulatory Commission to suspend work on EPR design certification until further notice. The **coup de grace**: France now aims to reduce nuclear from 70% to 50% of its electricity mix and increase renewable energy.

**In contrast to stagnation in the US and Europe, nuclear power is alive and well in Asia where 50 GW are under construction and where plant costs are lower.** The World Nuclear Association cites nuclear construction costs in China and Korea that are 20%-30% below US and EU levels. KEPCO (S Kor.) is building 5.6 GW of nuclear in the UAE, scheduled for delivery in 2017 at $3,600 per kW, which is 35% below EIA cost assumptions for the US. Asian cost differentials vs. the US and Europe are apparently related to shorter lead times, shorter construction times and lower labor costs. The differences do not appear to reflect different nuclear technology, since almost all plants under construction worldwide are either boiling water reactors or pressurized water reactors.

Some of the cost difference, in our view, reflects a greater degree of collectivism in government energy policy in Asia relative to the US and Europe. Whatever the reasons, there are intense debates as to whether the nuclear standardization and cost structure in Asia could be replicated in the US or Europe without compromising regulatory and legal protocols. It may be possible, but we have little to base this on without more evidence of *exactly* why costs are so much lower in Asia.

The chart below shows nuclear plant construction starts worldwide since 1955. Over 80% of plants now under construction are in emerging economies. **While balanced systems may offer cost and $CO_2$ emissions advantages vs. high-renewable systems, a grid with 35% of demand met by nuclear power appears to run counter to current government and voter preferences in the OECD**.

**Emerging economies account for most of the recent recovery in plant construction,** global nuclear reactor starts



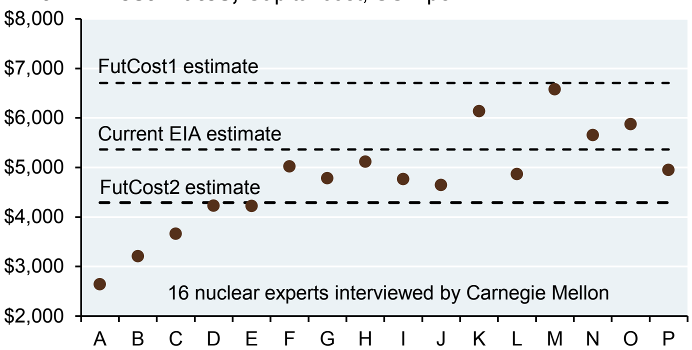

Source: IEA, IAEA Power Reactor Information System. 2014.

**Appendix V: Nuclear power cost and future technology alternatives**

Carnegie Mellon surveyed 16 nuclear industry participants regarding capital costs of large nuclear plants using existing technology, and of prototype small modular reactors. Note how wide the range of estimates is in the first chart; and these are just *median* estimates (the full range of the high and low estimates was even wider). These cost projections reflect the technology, regulatory, legal, environmental and political framework in which nuclear power is developed in the Southeastern United States. In other words, they are not a universal measure of nuclear power costs, since many of these items differ by jurisdiction. As explained earlier, nuclear power costs are 25%-30% lower in Asia.

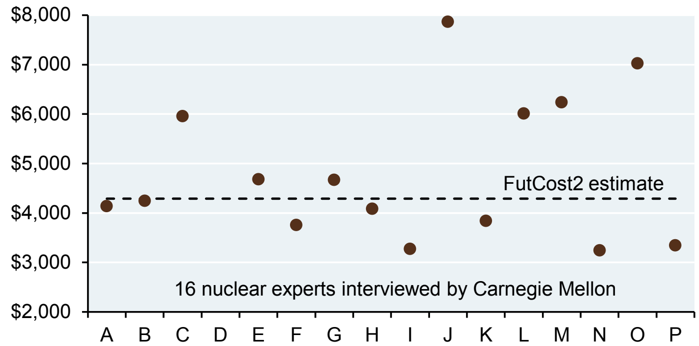
Our FutCost1 estimate is meant to reflect possible cost **increases** in cost based on safety, spent fuel and containment issues raised by the accident in Fukushima. Our FutCost2 reflects **decreases** in cost due to possible standardization and streamlining of existing technology (along the lines of Asian costs), and/or an optimistic assessment of small modular reactors of the future (see below).

**Median cost estimates of large nuclear plants in line with EIA estimates,** Capital cost, USD per kW




Source: EIA, Carnegie Mellon, JPMAM. 2015. Experts interviewed in 2013.

**Median cost estimates of small modular reactors**
Capital cost, USD per kW




Source: Carnegie Mellon, JPMAM. 2015. Experts interviewed in 2013.

***The future of nuclear power.*** The list of those who see nuclear power as a critical component of future grids is a long one. It includes the Clean Air Task Force, International Energy Agency, the Breakthrough Institute, climatologist/activist James Hansen of Columbia University, David Mackay of Cambridge, Robert Hargraves from Dartmouth, Ralph Moir from Lawrence Livermore National Laboratory, British environmentalist Mark Lynas, etc.). The industry itself is scrambling to find a better and cheaper way forward; the box shows nuclear technologies under development. But even if an economic and acceptable alternative emerges soon, how fast it could be scaled up to become more than a marginal contributor?

- molten salt reactors
- fluoride salt-cooled high temperature reactors
- liquid metal-cooled fast reactors
- high temperature gas reactors
- pebble bed reactors
- nuclear battery reactors
- small modular reactors
- thorium reactors
- fusion reactors
- floating offshore nuclear plant
- super-critical $CO_2$ reactors

There's enthusiasm in some circles for small modular reactors (SMRs). The idea: smaller design (10 MW to 100 MW capacity), factory-produced with higher levels of quality control, shipped to site by rail or barge. More than 20 companies are developing SMRs worldwide, with 3 in the US focused on "light water" SMRs. The problem: smaller units tend to have lower economies of scale, so it is not a foregone conclusion that SMRs would be cheaper than today's plants. The same *National Academy of Sciences* paper cited earlier also looked at possible SMR costs; the low end of median projections for 45-225 MW SMRs ranged from $3,500 to $4,000 per kW, which is ~25% below EIA cost estimates for larger plants using current designs. **To be clear however, the upper end of the median cost range was considerably higher, and even more tellingly, none of these units is under construction.** It may be decades before we know just how much new nuclear power designs really cost.