Status of Nuclear Power
Lecture to Course IF 401, IR 404, ES 504
Sabancı University

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Outline

• Nuclear Power Plant Developments
• Nuclear Power Plant Economics
• Nuclear Power Plant Safety
• Modular Reactors: Better Safety and Economics?
Nuclear Power Plant Developments
Status global nuclear power

Units in Operation: 446
390.4 GWe

- CIS 10.0%
- OECD-Pac 15.9%
- Europe 31.4%
- North America 29.4%
- Latin America 0.9%
- Non-OECD Asia 11.4%
- Middle East 0.2%
- Africa 0.5%

Units under construction: 61
61.5 GWe

- OECD-Pac 10.9%
- Latin America 2.1%
- North America 7.3%
- Europe 6.7%
- Non-OECD Asia 48.4%
- Middle East 8.7%
- CIS 17.9%

As per 13 August 2017
Source: Adapted from IAEA - PRIS
Figure 3: Breakdown of the number of reactors under construction worldwide (Aug 2016), the majority of which are Pressurised Light-Water-Moderated and Cooled Reactors (PWR).
Countries Expressing Interest, but Not Yet Building Nuclear Power Plants

Countries with contracts, plans or expressing interest:

• Algeria
• Bangladesh
• Egypt
• Indonesia
• Jordan
• Kenya
• Nigeria
• Poland
• Saudi Arabia
• Turkey
• Vietnam
Nuclear Power Plant (NPP) Growth Problems

• **OECD countries: Nuclear power continues to face problems on:**
  – **Knowledge depreciation**
    • Aging nuclear workforce and attrition
    • Nuclear science and engineering not popular topics among high school graduates
    • Potential shortage of competent (knowledgeable) regulators with obvious safety implications

• **Non-OECD Countries**
  – **Prospects for NPPs better in Asian and newcomer countries**
    • China, India, Pakistan
    • Russian Federation
    • United Arab Emirates
    • Latin America
    • Several African and Middle Eastern Countries
    • Nonetheless, public apprehension and signs of organized opposition is also becoming visible and rising in developing economies (with ongoing programs and new comers)
Nuclear Power Plant Economics
Importance of Power Plant Capital Cost (share of the levelized cost of electricity)

- 74% for nuclear
- 63% for coal
- 22% for natural gas
- 80% for wind
- 88% for solar PV

– Source, U.S. Energy Information Administration
**Capital Cost @ 3% Discount Rate**

3% LCOE = $27/MWh Investment Cost

- **Investment costs at stated rate (USD/MWh):** 26.99 USD/MWh (52.46%)
- **Refurbishment and decommissioning costs at stated rate (USD/MWh):**
- **Fuel and Waste Costs (USD/MWh):** 10.25 USD/MWh (19.9%)
- **LCOE at 3% Discount Rate – 51.45USD/MWh**

**Front end of nuclear fuel cycle:** USD 7.69/MWh (14.9% LCOE)

- **Uranium:** USD 3.84/MWh (7.5% LCOE)
- **Enrichment:** USD 2.69/MWh (5.2% LCOE)
- **Conversion and Fabrication:** USD 1.15/MWh (1.4% LCOE)

**Back end of nuclear fuel cycle:** USD 2.56/MWh (5.0% LCOE)

The Projected Cost of Producing Electricity

NEA-IEA, August 2015
Capital Cost @ 7% Discount Rate
7% LCOE = $55/MWh Investment Cost

Fuel and waste costs: 10.25 USD/MWh (12.7%)

Investment costs: 55.43 USD/MWh (68.83%)

Back end of nuclear fuel cycle:
- Uranium: 3.84 USD/MWh (4.8% LCOE)
- Enrichment: 2.69 USD/MWh (3.34% LCOE)
- Conversion and Fabrication: 1.15 USD/MWh (1.43% LCOE)

Front end of nuclear fuel cycle:
- USD 7.69/MWh (9.6% LCOE)

LCOE at 7% Discount Rate – $80.53/MWh

The Projected Cost of Producing Electricity
NEA-IEA, August 2015
Capital Cost @ 10% Discount Rate
10% LCOE = $84/MWh Investment Cost

The Projected Cost of Producing Electricity
NEA-IEA, August 2015
Nuclear Capital Cost Sensitive to Financing Costs and Construction Period

- Example: Darlington Nuclear Power Plant, Canada
  - construction began in 1981 at an estimated cost of $7.4 billion and finished in 1993 at a cost of $14.5 billion (1993 $)
  - 70% of the price increase was due to the increase in interest charges due to construction delays
  - source http://www.nuclearfaq.ca/cnf_sectionC.htm#darlington
Recent Important Construction Delays or Cancelations

• Santee Cooper announced in August, 2017 they were canceling the 2-unit Westinghouse-Toshiba AP1000 project in South Carolina.” [Sunk cost = $6 billion]

• In nearby Georgia, the cost of the similar 2-unit Vogtle NPP comes in around $25 billion. The initial estimated project cost was $14 billion. Georgia Power’s cancellation cost = $6.3 billion.

• The Georgia Vogtle plant received a DOE Loan Guarantee for most of the project thereby giving it less than market interest rates.

• Areva Gen III projects have had a similar history as the Westinghouse projects (e.g., the 1 unit Olkiluoto NPP is delayed by over 10 years at 3x the original estimate of 3 billion euro.)

• Areva now just manages the still uncompleted Olkiluoto Unit 3 and the rest of Areva’s assets have been dispersed. Westinghouse-Toshiba is working its way out of bankruptcy by selling its nuclear assets to Canada’s Brookfield Business Partners
Economic & Other Factors Hurting Nuclear in the OECD

- High upfront investments in mostly liberalized markets
- Poor track record regarding on time and on budget construction completion
- Massive reduction in cost of renewables and continued supporting policy incentives (subsidies)
- Costs of system integration of intermittent renewables externalized
- Cheap natural gas (LNG) & shale gas in North America
- Nuclear power dispatches 24/7: a problem in competitive power markets
- No economic benefits received for nuclear’s low GHG emissions
- Low growth or stagnating electricity demand
- Rising public opposition & politics in the aftermath of Fukushima
  - Safety concerns remain of high affecting the future prospects of nuclear power
  - Republic of Korea is the latest country to announce a nuclear phase-out following earlier steps undertaken by Germany, Switzerland and Belgium.
  - Other countries (e.g., France, Sweden) cap directly or indirectly the market share of nuclear power
  - Phase-out politics frustrate NPP staff and potentially affect nuclear operating safety

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Nuclear Power Plant Safety
Nuclear Power Plants Have Had a Good Safety Record But....

- **1979 3-Mile Island** (release of radioactive iodine caused by stuck valve and inattention by plant operators – subsequent studies showed no apparent effect on human health in & around the area)
- **1986 Chernobyl** (catastrophic radioactive release caused by operators’ incompetence & poor safety features)
- **2011 Fukushima** (significant radioactive release caused by inappropriate location of the backup power generators and tsunami – up to 1,000 cancers expected due to the radioactive release)
Accidents Adversely Affect Public Perception: Surveys before and after Fukushima

Effect of the accident on the risk perception of residents near a nuclear power plant in China

Q1: Nuclear power should be used in our country

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Q2: We should quickly increase the number of nuclear power stations in China

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Q3: If there is a vote for promotion of nuclear power, I will strongly vote for it

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Q4: I strongly welcome construction of a nuclear power station in my dwelling city such as Lianyungang

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Source: Adapted from Huang et al., 2013. Effect of the accident on the risk perception of residents near a nuclear power plant in China. Proc Natl Acad Sci U S A. 2013 December 3; 110(49): 19742–19747.
What’s Needed for Nuclear Power Plant (NPP) Safety?

• NPP must be well-designed and built, must meet all applicable standards

• NPP must be well operated:
  – well-trained operators
  – well-trained maintenance staff
  – Information about problems is shared widely (internationally)
  – a strong safety culture, top-to-bottom
  – a strong, independent regulatory agency
Factors that Would Cause Safety Issues in Newcomer Countries

- less rigorous operator training
- management is too “top-down & absence of a “questioning attitude” (a major factor behind the Fukushima melt-down)
- less ability to raise safety concerns without fear
- weak or unstable political and social structure
- a weak regulatory agency
- government corruption
Modular Reactors: Better Safety and Economics?
CAP 150 – Chinese PWR Design 150 MW
Estimated Cost = $90/MWh

Figure 1: Reactor System Configuration of CAP150
(Reproduced courtesy of SNERDI/SNPTC)
Typical SMR Safety Advantages
(all advantages do not apply to all SMR designs)

– Smaller core (much easier to cool)
– Less radioactivity available for release
– Simpler design, easier to operate/maintain
– Integrated systems design
– Vessel near atmospheric pressure
– Better separation of systems that in large LWRs have important dependencies
– No need for electric power
– Extended time to boil
– Smaller emergency planning zone
Potential SMR Economic Advantage

• SMRs built in factories and shipped as a turnkey reactor to be “plugged into” a power plant with steam turbines.
• On-site construction, the source of NPP cost overruns & delays, is minimized.
• Technological risk of the reactor is entirely with the manufacturer, not the customer.
• Significantly reduced financing costs.
• Smaller capacity (100-300 MW instead of 1 GW) requires less financial commitment & better scalability.
SMR Challenges

– Economics (can they compete?)
– Safeguards and Proliferation
– Regulation & Licensing?: Three possibilities:
  • (1) Licensed and regulated in host country?
  • (2) Licensed in country of origin, regulated in host country?
  • (3) Licensed and regulated in country of origin?
The Case for Small Modular Reactors: Reality or Hype?

Expected attractive benefits versus current commercially available NPPs

**Attractions**

- **Improved affordability**
  - Lower per unit capital costs
  - Much shorter periods between purchase and operation.
  - Easier to finance (lower capital exposure per unit and less risk)
  - Modularization and lower economic risk in the face of demand and market uncertainty (incremental capacity additions)
  - Manufacturing instead of construction
  - Lower staff requirements (if shared among multiple units)

**Issues**

- Economies of (single plant) scale effects greatly reduced
- Can factory build and reduced cost/expense/delay of onsite construction offset the reduced economics of scale?
- Competitive generating costs ($/MWh) would require large savings by manufacturing instead of construction.
# The Case for Small Modular Reactors: Reality or Hype?

## Attractions

- Suitable for low capacity or small grids (e.g., developing countries) and remote regions
- Longer refueling cycles
- Spent fuel take-back (possibly via entire core exchanges)
- Siting flexibility
  - SMR fleets vs stand-alone plants
  - Reduced emergency planning zones; allowing options of siting closer to demand & population centers
  - Industrial process heat and other energy services

## Issues

- Soft infrastructure
  - Independent and competent regulator
  - Low general safety culture, governance, etc.
  - Requested regulatory roll backs
  - Regulatory rigor
  - Public acceptance

- Hard infrastructure
  - Physical security of nuclear installations
  - Fuel cycle, spent fuel storage & transportation
  - Final disposal
Other Considerations

- Commercialization of SMRs will be a time-consuming process.

- Different challenges for evolutionary & revolutionary designs.

- Some evolutionary designs – essentially scaled down and repackaged standard PWRs have reached first-of-a-kind (FOAK) status.
  - Commercialization (proof of competitiveness) now requires the realization of economies of scope and obtaining regulatory approval (licensing).
  - Market entry: After 2025 ???
  - Manufacturing capacity versus market demand – Low demand = slow technology learning preventing the realization of economies of scope.

- Revolutionary designs have to pass pilot and demonstration plant stages, receive regulatory approval.
  - Market entry: Not before 2030.
  - SMR will only make it with revolutionary designs (economics & enhanced safety).
SMRs Under Construction Now

• **Argentina**
  – 27 MWe integral PWR

• **China**
  – 105 MWe pebble bed high temperature gas reactor

• **Russia**
  – 70 MWe integral PWR (ship)
  – 50 MWe integral PWR (icebreaker)
Further Reading


