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Economics and advanced reactor technology development

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Advanced reactor* technology development

- Situation – Advanced reactors seen as solution for large light water reactor issues / problems
- Complication – Limits to advanced reactor technology; may not be solution to all problems
- Question – What issues can advanced reactor technology resolve?
- Answer – Economics can help focus advanced reactor technology development

* In this presentation, the term Advanced Reactors refers to advanced reactor designs (e.g., Gen IV) and small modular reactor (SMR) designs – all are different from existing large light water reactor designs (e.g., Gen II, Gen III, and Gen III+).

Advanced reactor objectives linked to issues with large LWR

Large Light Water Reactors	Advanced Reactors?
High LCOE	Lower initial capital cost
	Lower generating cost
Large size	Smaller size
Base load operation	Flexible operation
Electricity generation only product	Multiple products
Potential reactor safety issues	Higher safety levels

Fits with public view of new technology

- Products will have smaller size, more capability, lower cost, frequent upgrades, etc.
- Based on electronics industry
  - Moore's Law is dominant technology paradigm
  - Larger number of transistors on silicon chips
  - More capability in smaller & cheaper devices
- Non-electronics consumer products and motor vehicles have similar product attributes

Complication – limits to advanced reactor technology

- Nuclear power different from consumer electronics
- Nuclear power
  - Difficult, expensive, needs highly specialized knowledge
  - Long lived power plants limit product updates
- Trade-offs between objectives
  - Smaller ≠ cheaper ≠ faster to build ≠ safer
- Advanced reactors may not be able to
  - Solve all real / perceived LWR problems
  - Meet public expectations

Question: What problems can advanced reactor technology development solve?

- Important to understand the interactions between objectives and focus on larger goal
- Can advanced reactors can take the place of large LWR?
- How can economic concepts help guide advanced reactor technology development?

Economics can help focus advanced reactor development

- Economic perspectives on
  - Initial capital cost
  - Generating cost
  - Smaller size
  - Flexible operation
  - Multiple products (i.e., not just electricity)
  - Higher reactor safety

Initial capital cost ($/kWe)

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Initial Capital cost

- High *total* capital cost at large light water reactors leads to desire for lower capital cost
- Lowering initial capital cost for any reactor
  - Standard designs and sequential build program
  - Capture gains from learning
  - Increase size & power output to lower capital cost/kWe
    - Some project costs (e.g., design, site, safety analysis, and licensing) may not vary with reactor size or output
    - Equipment costs may not be linked to size (i.e., a small valve may cost as much as a large valve)

Advanced reactor capital costs

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Initial Capital cost

Gen II / III large LWR capital costs

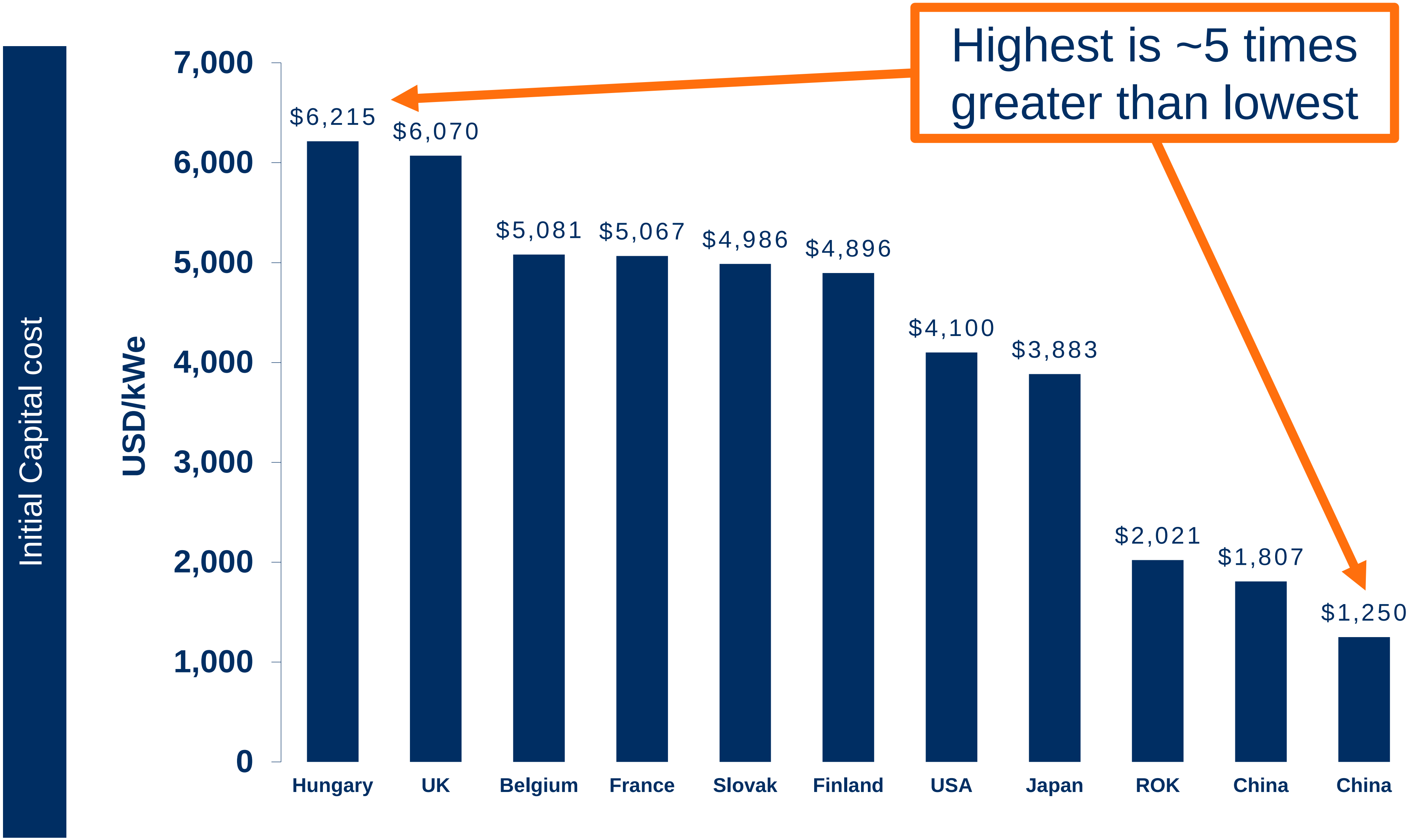
Advanced reactor costs higher
- initial licensing and safety analyses for new reactor designs
- loss of scale economies
- FOAK project issues

Advanced reactor cost reduction potential
- Shorter build time
- Multiple modules & learning
- Factory build
- Less safety equipment

Increased value
- Higher safety
- Easier to site
- Other

Advanced reactor capital costs

Which large LWR benchmark?



Source: OECD 2015, Projected Cost of Generating Electricity, Table 3.4, overnight capital costs in USD/kWe

Project learning important, but global ***industry*** learning also important

Initial Capital cost

- Large LWR nuclear designs have decades of operating experience across multiple countries
  - Operating & regulatory approach evolved over time
  - Lessons from experience / incidents / accidents
  - Sharing (Regulators / INPO / WANO / IAEA / etc.)
  - Design improvements based on experience
    - Better materials of construction (e.g., steam generator tubes)
    - Fuel design and manufacture
    - Man-machine interface / I&C
    - Safety concepts, systems, and equipment
- Advanced reactors will have similar evolution

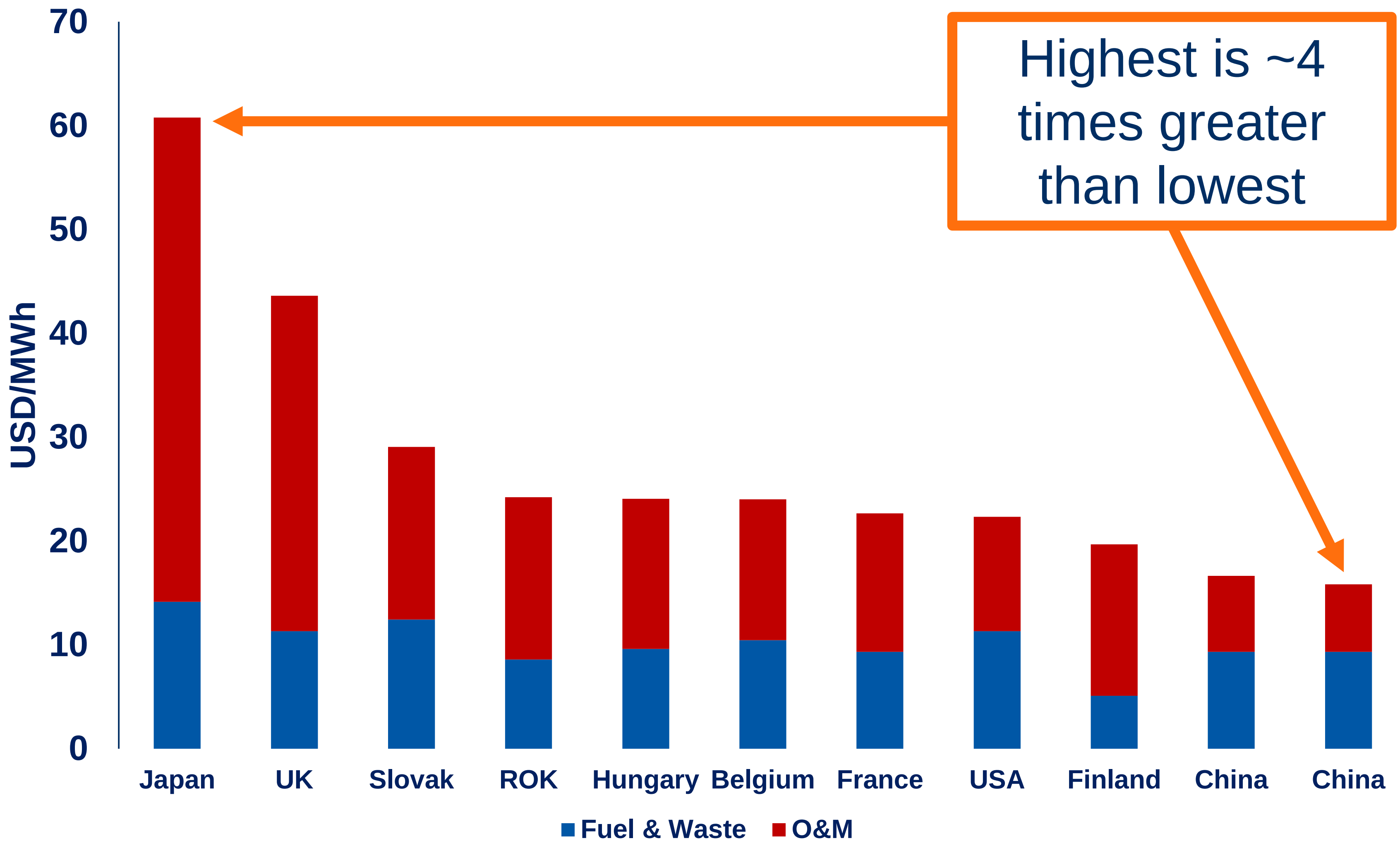
Generating cost

Generating Cost

- LWR generating costs (i.e., $/MWh for fuel, O&M, & on-going capital costs) higher than some electricity market prices
- Economies of scale apply to generating costs
  - Larger nuclear power plant does not need more operators, security, engineers, etc.
  - Smaller size for advanced reactors may mean higher generating costs due to higher non-fuel O&M
- Fuel costs depend on reactor type

Large LWR fuel and operating cost benchmark?

Generating Cost



Source: OECD 2015, Projected Cost of Generating Electricity, Table 3.18, overnight capital costs in USD/kWe

Smaller size

- Smaller size can add value
  - In small electricity systems, where a large LWR would require added reserves due to large single contingency
  - System planning may show higher value for small reactor compared to large reactor, depending on costs
  - Multiple units maximize learning and lower capital at risk in each project
- But smaller size may not have value in some situations (e.g., large utilities with existing large nuclear power plants to replace)

Smaller size (continued)

Smaller size

- Can smaller nuclear power plant find enough gains in other areas to offset lost scale economies?
- If smaller size has value, why not make small LWRs (e.g., GEH BWRX-300)
- If smaller size has low value, why not large advanced reactors?
  - Are small advanced reactors prototypes for larger ones?
  - Can small advanced reactor designs be scaled up?

Flexible operation*

Flexible Operation

- Baseload operation of LWR nuclear power plants
  - Not a design flaw, but economic dispatch of units with zero marginal cost
  - Large LWR plants capable of flexible operation
- Flexible operation may not be economic
- Flexible operation / load following valuable if
  - Large amount of nuclear (France)
  - Large amount of renewables (US, Europe)
  - Electricity market prices < zero

**See discussion of flexible operation at https://nuclear-economics.com/12-nuclear-flexibility/ ;*
Nuclear Base Load at https://nuclear-economics.com/nuclear-base-load/; and
Short-Run Marginal Cost at https://nuclear-economics.com/nuclear-power-short-run-marginal-cost/

Flexible operation (continued)

Flexible Operation

- “Adding” flexible operation to advanced reactor designs may not improve economics of projects
- Some advanced reactors may have operation modes and fuel cycles that make flexible operation even more difficult than in LWRs
  - Lock in marginal costs of zero (or < zero)
  - Limit or preclude start/stop cycles
  - Require a fairly high minimum generation level
- Having a positive marginal cost would help with this

Products other than electricity

Alternate Products

- Interest in advanced reactors that can produce electricity AND hydrogen, desalinated water, etc.
  - Multiple product streams requires additional systems, adding cost, operation issues, and safety issues
  - Example – electricity-only nuclear + RO desalination
- Electricity may be highest-value product – unless other products become more valuable
- Switching to other products when electricity output is curtailed or dispatched off/down may facilitate / mitigate operating flexibility

Higher reactor safety

- Public perception seem to be driver
  - LWR reactor safety high, but concerns remain
  - Public visibility of past advanced reactor accidents low (e.g., Windscale, Fermi 1, KNK, THTR, Monju, etc.)
- Conceptual issue
  - Different reactor design = different accident scenarios
  - Advanced reactor designs may preclude LWR accidents, but do not preclude ***any*** accidents
  - Lower cost depends on nuclear safety regulator licensing requirements for advanced reactor designs

Higher reactor safety (continued)

Higher Reactor Safety

- Higher safety is fundamentally good, but may be hard to capture economic value
- Higher safety adds value to a project if:
  - Siting and licensing is easier and lower cost
  - Nuclear safety regulators allow advanced reactors to avoid safety features of large light water reactors (e.g., containment, emergency planning zones, operators, emergency power systems, etc.)
  - Project licensing will require more analysis and support to justify different regulatory requirements

Summary

- R&D on advanced reactors is a good thing, but
  - R&D is different from technology deployment
  - Dry hole risk (mPower, PBMR, Hyperion, etc.)
  - Technology dominance by LWR difficult to overcome
- Focus on total project features and economics
- Rather than define new markets (e.g., hydrogen), for advanced reactors, focus on designs that can replace large LWR in existing markets & systems

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