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Techno Economic Analysis of ADVANCE Small Modular Reactor Technology

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Changing the World's Energy Future

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Idaho National Laboratory

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Content Note and Outline

Content Note:

The content of this presentation is taken from the lecture notes, publish articles and INL's internal reports. This presentation focused on the general overview of the techno economic analysis of small modular reactor system.

Presentation Outline

- Part-I: Objective, Motivation, Introduction, and Overview of SMR Technology
- Part-II: Method and Analysis
- Part-III: Representative Results, Discussion, and Summary

Objective and Motivation

Objective: To support experiment and modeling for reactor design, development, demonstration and deployment (4D).

Motivation: Most of the INL activities, especially the NS&T Directorate is dedicated to performing research, development, and demonstration (RD&D) of advanced nuclear energy generation and applications. Many of these RD&D efforts relates with the cost and scheduling. Therefore, a general techno economical analysis understanding would be supportive for these target challenges:

- **Goal: Strengthen the Techno economic analysis of ADVANCE reactor technology**
- **Goal: Enable U.S. Leadership in Global Nuclear Energy Markets (Advanced Reactors)**

Here, ADVANCE is for "Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy,"

  - as per the United States (U.S.) Department of Energy (DOE) ADVANCE act**,**
  - bipartisan legislation to provide a major boost to the future of nuclear energy in America.

Taken from: https://www.epw.senate.gov/public/index.cfm/2024/7/signed-bipartisan-advance-act-to-boost-nuclear-energy-now-law#:~:text=July%209%2C%202024&text=WASHINGTON%2C%20D.C.%20%E2%80%93%20Today%2C%20the,of%20nuclear%20energy%20in%20America.

Introduction: energy cost and nuclear perspectives

- *Energy cost involves various candidate fuels, materials, systems, and policies. These following items may impact the energy price including cost of electricity generation from nuclear reactors [1]:*
    - **Competition from Natural Gas and Renewables**
        - Cheap natural gas and subsidized renewables challenge nuclear energy
        - Continued competition for SMRs development and deployment
    - **Carbon Pricing and Clean Energy Incentives**
        - Carbon Pricing Worldwide
            - 53 nations with carbon pricing schemes (carbon tax or emissions trading systems)
        - U.S. Clean Energy Incentives
            - Zero-emission credits in New York, Illinois, and New Jersey
            - Offset advantages of production tax credits for renewables
        - Cost Reduction Pressures
            - Operating and Initial Cost Reduction
                - Significant pressure to reduce costs for SMRs
            - MIT Research on Decarbonizing Electricity Generation
                - Nominal cost: $5,500/kW
                - Low-cost scenario: $4,100/kW

SMR Technology: development options

- **Stages of SMR Technology Development [2]**
  - Near-Term vs. Long-Term Development
    - Near-Term Technology Development Can be achieved by adopting/buying existing technology
  - Long-Term Technology Development
    - Requires innovative designs with comprehensive development processes
  - As per IAEA's
    - Buying cases (Section 5.1)
    - Developing cases (Section 5.2)
    - Inventing cases (Section 6)

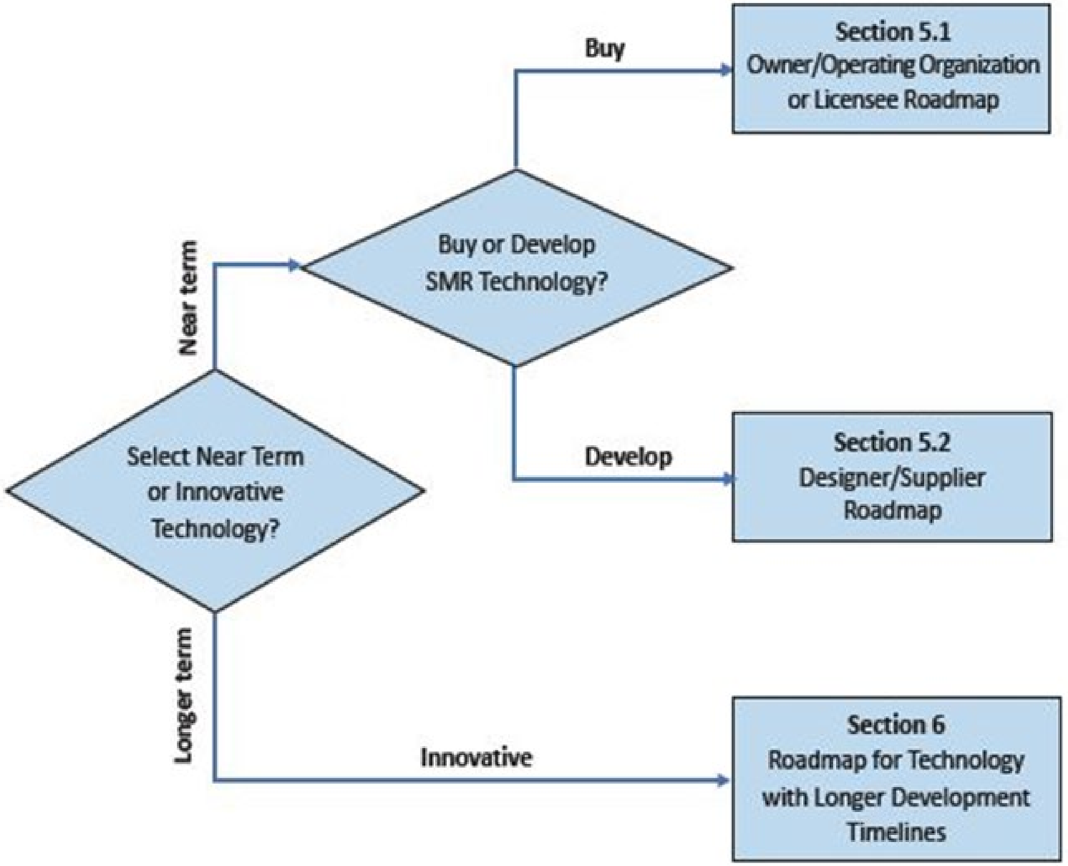


Fig. 1: SMR technology roadmaps flowchart, IAEA [2].

Thus, cases for buying, developing, and inventing require detailed techno-economic studies!

SMR Technology: cost reduction strategies

- **SMR Cost Mitigation Strategies**
  - Design Standardization and Modular Construction
    - Reduces need for design modifications
    - Faster construction times lower indirect and financing costs
  - Economic Case for SMRs
    - Stable and reliable baseload power
    - Complement renewables to decarbonize electricity generation
  - Impact of Carbon Pricing
    - Narrowing Cost Gap
      - Carbon pricing up to $25 per ton
      - Highlights low-emission character of nuclear energy
      - Promotes deployment of SMRs

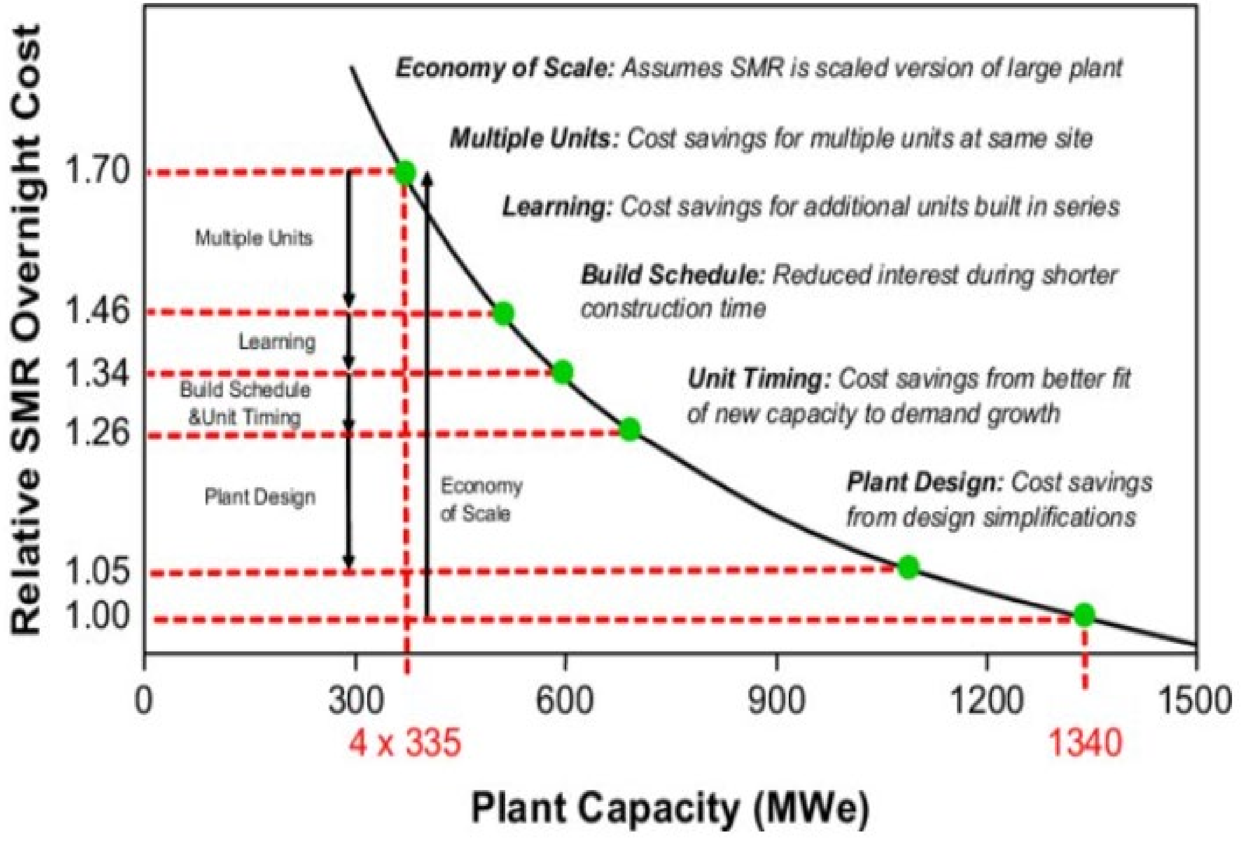


Fig. 2: Economic scaling factor for SMRs and a single large reactor plant [3].

SMR Technology: cost reduction strategies (cont’d)

- **Reducing Operational Costs**
  - Staffing Reductions
    - NuScale’s: 1 operator for 3 modules, 1 senior operator for 12 units
- **Regulatory and Training Adjustments**
  - Regulatory Changes: extensive human factors engineering, risk analysis, and number of operators needed.
  - Training Programs: to address multi-module control room challenges.
- **Reducing Downtime**
  - Unplanned Shutdowns and Refueling
    - Focus on reducing/eliminating unplanned shutdowns
    - Streamlining the refueling process
  - Modular Refueling Proposals
    - Factory construction and shipping new modules to sites
    - Feasibility and cost-effectiveness yet to be demonstrated

SMR technology: major deployment challenges

- **Supply Chain Development**
  - Rebuilding the Supply Chain
    - Loss of supply chain from 1980s-1990s nuclear construction hiatus
    - Recent efforts to rebuild, but more needed for reliability
  - First-of-a-Kind Challenges
    - Difficulty in establishing reliable, on-time procurement
    - Importance of key vendor partnerships to avoid delays and increased costs
- **Spent Fuel Management**
  - Challenges in
    - Spent fuel disposition challenges in countries with less infrastructure
  - Economic Costs
    - Need to consider costs associated with managing spent fuel
  - Design Mitigations
    - Some SMR designs offer longer fuel lifetimes to help mitigate spent fuel challenges

SMR technology: construction cost

- **Comparative Construction Costs [4-7]**
  - Nuclear Power Installations
    - Vogtle 3 and 4: $12,000/kW or more
    - South Korea: Approximately $2,500/kW
  - SMR Estimates
    - NuScale first plant: $5,100/kW, eventual reduction to $3,600/kW
    - General Electric BWRX-300: As low as $2,250/kW
  - Natural Gas Generation
    - New construction: About $1,000/kW, up to $2,300/kW with carbon capture
  - Wind and Solar
    - Wind: Approximately $1,800/kW
    - Solar: Approximately $2,600/kW
    - Battery storage: Additional $2,800/kW

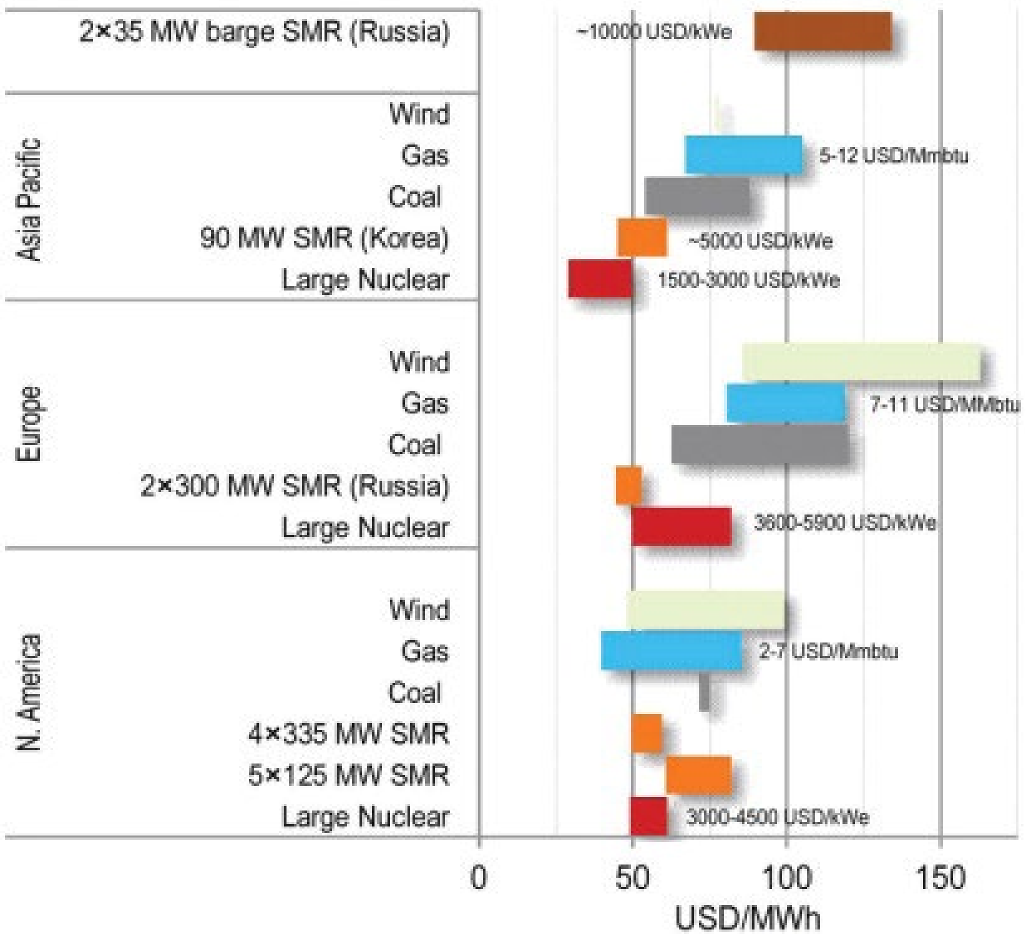


Fig. 3: OECD study on LCOE for SMRs and Some Alternative Sources, for Different Regions [8].

Method and Analysis: carbon capture design with SMR

- **System configuration and coupling [9]**
  - System design with possible design options
    - System optimization, example case, solvent-based direct air capture (L-DAC) process: with natural gas, and with SMRs

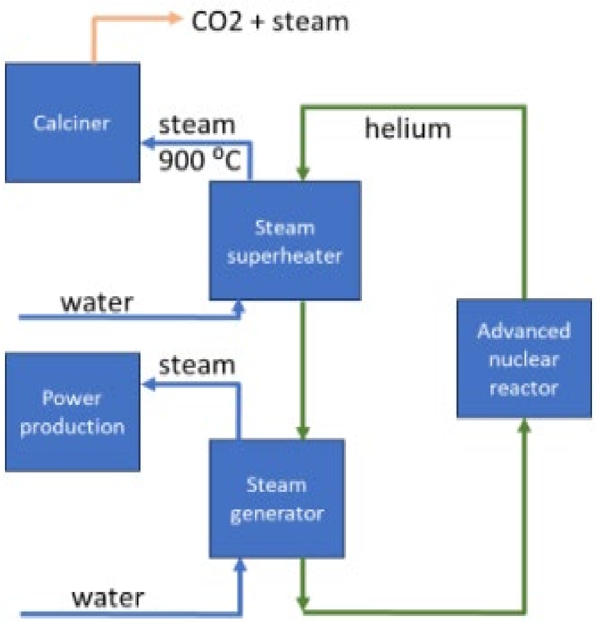


Fig. 4: Coupled L-DAC and SMR system [9].

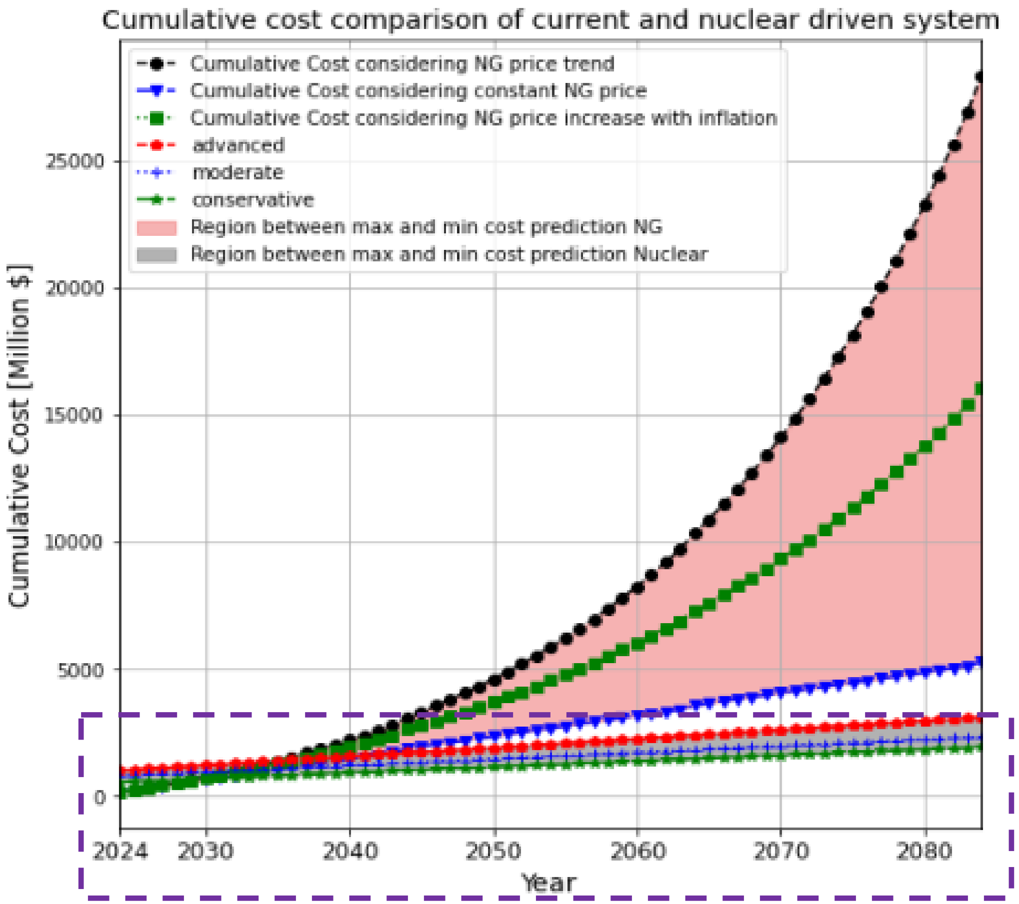
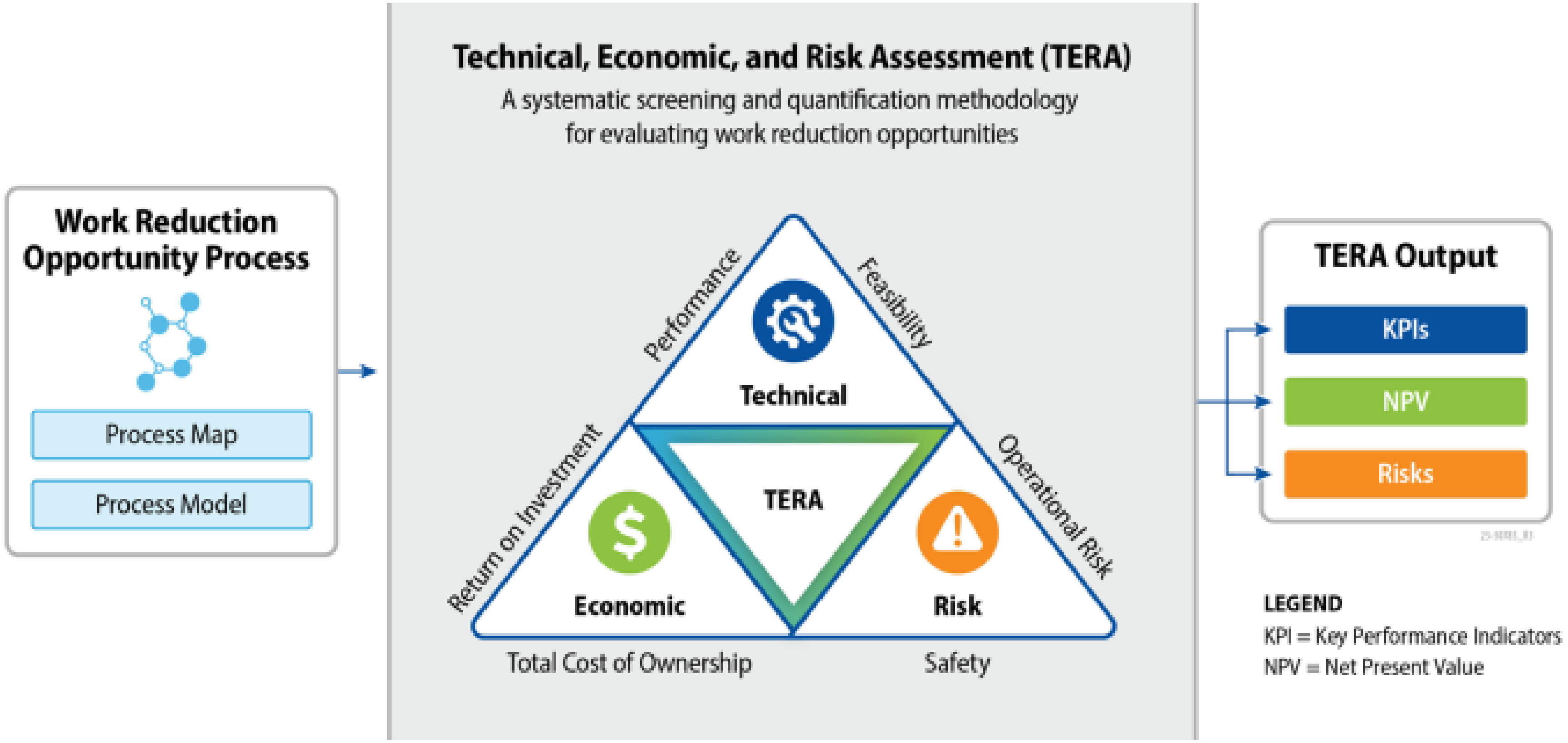


Fig. 5: Comparison of cumulative cost of energy using natural gas and advanced nuclear reactors over next 60 years [9].

Part-II:

Method and Analysis: INL initiatives/activities

- System design with possible design options
  - System optimization, for work reduction opportunities (WROs)



Taken from:
https://lwrs.inl.gov/Newsletter%20Images/Issue%2039/10-GA50624-39_R1-Article04.pdf

Fig. 6: The technical, economic, and risk assessment is used to evaluate WROs [10].

Method and Analysis: SMR cost elements

Table 1: Related equations and models related to technoeconomic analysis for reactor systems [11].

	Equations and Variables	Remarks
Estimation of various cost elements		
Overnight capital cost (OCC): cost of a plant if it were built right away, with current prices	$$OCC = \frac{DC + IC + O + G}{P}$$ where DC are the direct capital costs (\$), IC are the indirect capital costs (\$), O are the owner's costs (\$), G is the contingency costs (\$), and P is the maximum rated power of the plant (kW).	OCC provide options for comparative cost estimation among various reactor technologies, including SMRs, and non-nuclear energy technologies.
Direct capital costs (bottom-up assessment, top-down assessment, or set equal to a reference cost account)	SMRs must fight against economies of scale, so component costs do not scale linearly with a reduction in capacity. Therefore, top-down assessment needed, as follows: $$C = C_{ref}\left(\frac{X}{X_{ref}}\right)^{n}$$ where n is a scaling exponent determined from empirical data, C for cost and X for relevant parameters of the component to be estimated, and ref for reference component.	Bottom-up assessments create a cost estimate based upon the required factory fabrication, site labor, and material inputs of the component. Top-down assessments were used when bottom-up quantities were difficult to assess.

Method and Analysis: SMR cost elements (cont'd)

	Equations and Variables	Remarks
Estimation of various cost elements		
Indirect cost (IC): consist of construction, engineering, and field services, which depend on construction time	Relationship between nuclear plant construction time and indirect costs could be determined from historical data, as follows: $$IC = f508.5e^{.1523y}$$ where IC are the total indirect costs per kilowatt, f is a correction factor, and **y is the construction time in years**, was fit to the data.	IC varies over time. The mean IC of nuclear plants increased 17 % annually, from \$1,020/kW in 1978 to \$4,190/kW in 1987
Levelized cost of energy (LCOE): the average revenue per MW-hr of electricity that is required to recover the lifetime expenditures of the plant	LCOE estimates from capital costs, operation and maintenance (O&M) costs, fuel costs, and other financial and technological parameters into a discounted cash flow rate of return analysis, as follows: $$LCOE = \frac{\sum_{j=1}^{N}(C_t + OM_t + F_t + T_t)(1+r)^{-j}}{\sum_{j=1}^{N} E_t(1+r)^{-j}}$$ where Ct are the annual capital expenditures, OMt are the annual O&M expenditures, Ft are the annual fuel expenditures, Tt are the annual taxes and fees expenditures, Et is the annual electricity production, r is the discount rate, **N is the lifetime of the plant, and j is the given year**. Ct includes the cost of equity during the years of construction.	This calculation requires price of energy (MW-hr electric) for which the **net present value (NPV) was equal to zero based on a fixed internal rate of return over the life of the plant**. Since the LCOE considers the full lifetime of a plant, it is a useful benchmark to compare the economic viability of disparate systems.

Results and Discussion

OCCs is high for SMR compared to NG system

However, comparable to large reactor system

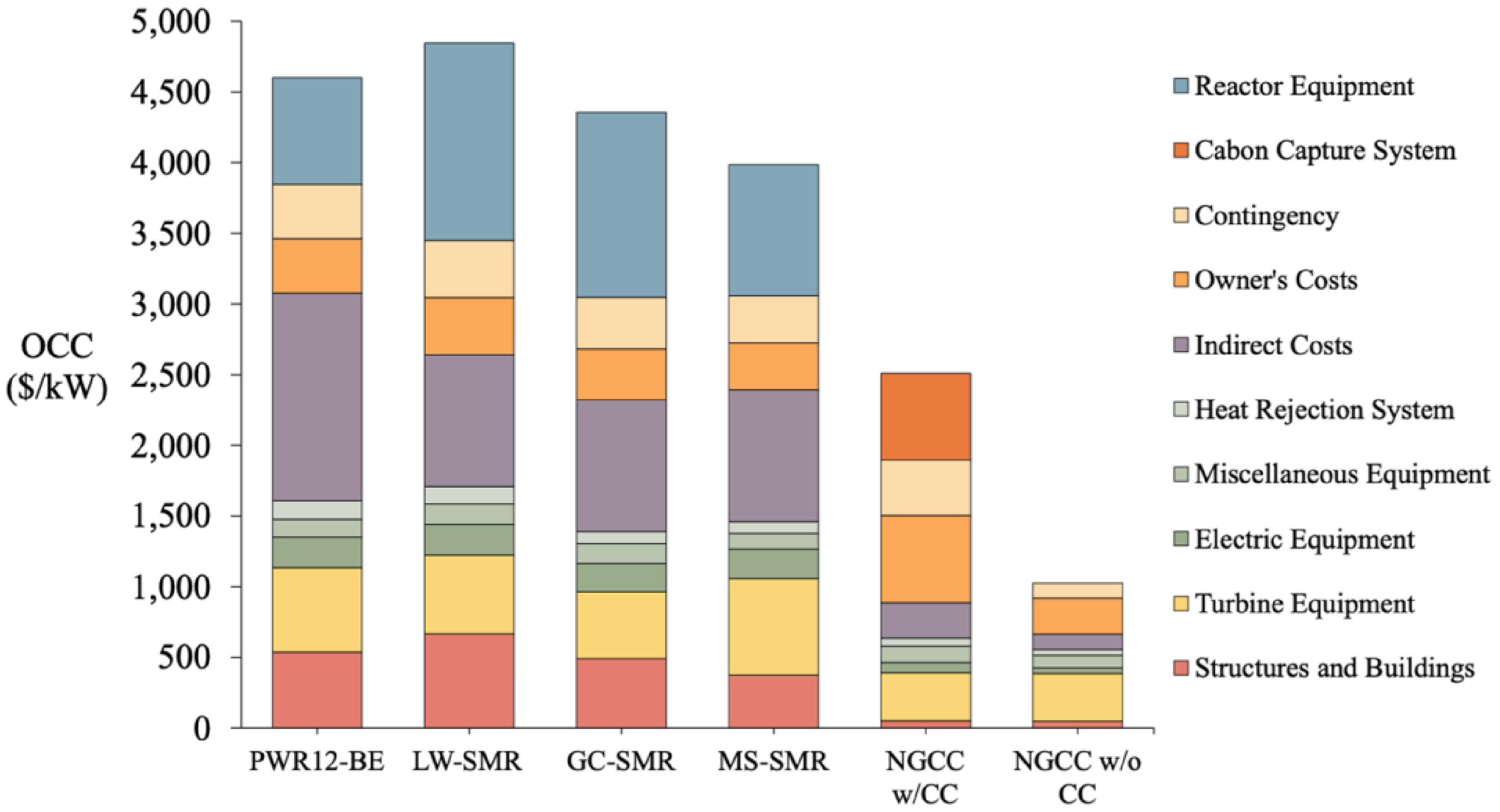
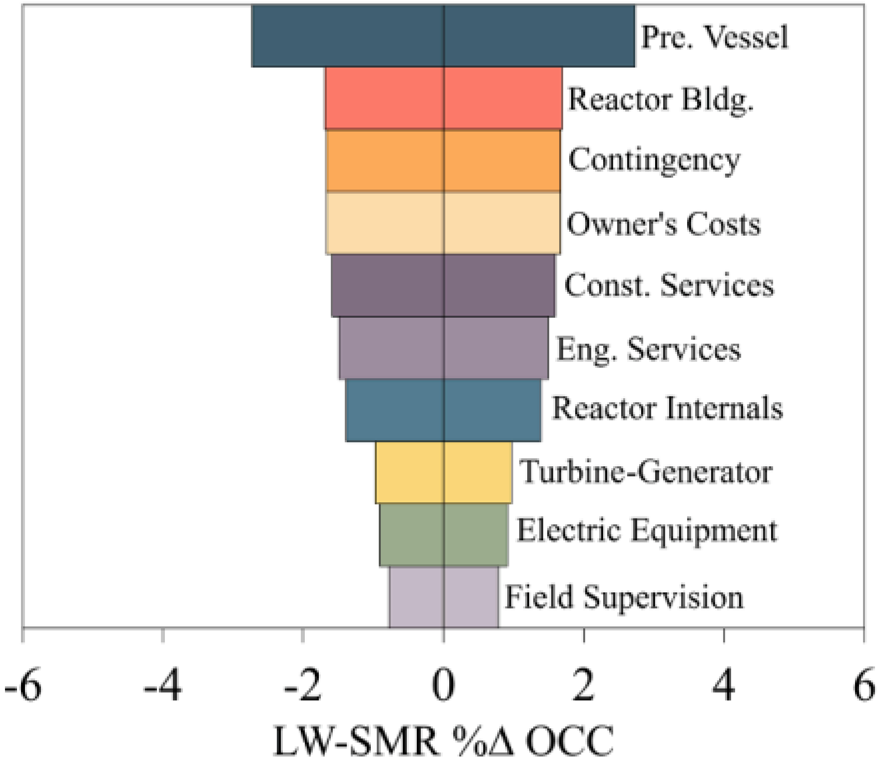


Fig. 7: Overnight capital costs (OCCs) of the PWR better experience (PWR12-BE), light-water SMR (LW-SMR), gas-cooled SMR (GC-SMR), molten salt SMR (MS-SMR), natural gas combined cycle plant with 90% carbon capture (NGCC w/CC), and natural gas combined cycle plant without carbon capture (NGCC w/o CC) [11].

Results and Discussion (cont'd)

For LW-SMR, cost of pressure vessel has the highest contribution to % change in OCC!

Net change from SMR to large reactors shows promise, which is still the motivation for ADVANCE SMR technology!



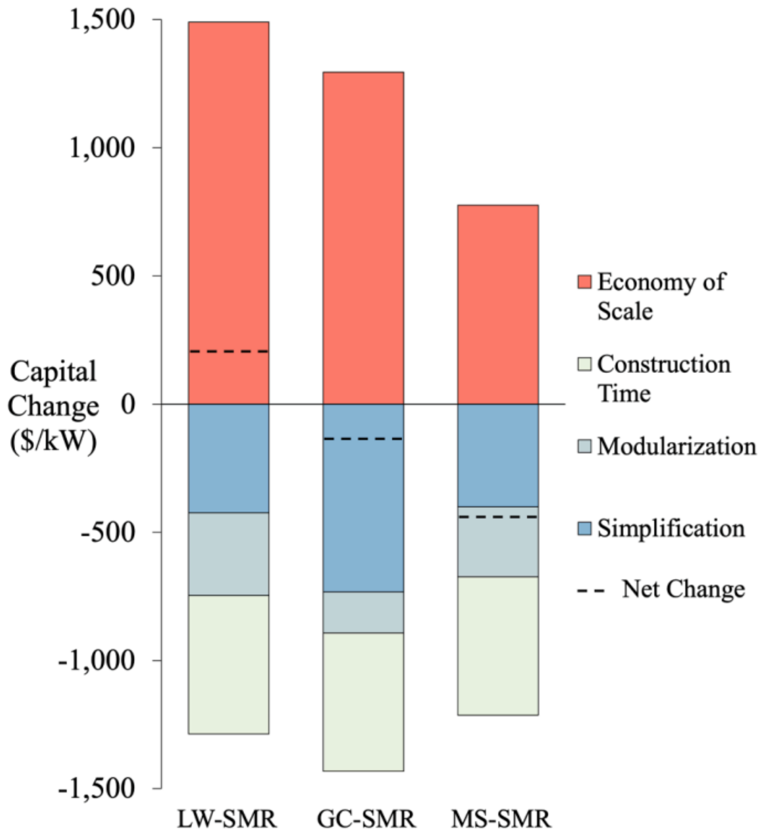


Fig. 8: Percent change in the OCCs of the LW-SMR by a 20% positive and negative change in the ten greatest cost drivers while holding all other components equal, (b) capital change due to economic of scale and simplification [11].

Results and Discussion (cont'd)

The original estimated cost increased in several times.

Under construction SMR project cost escalated due to increase of the material and labor cost!

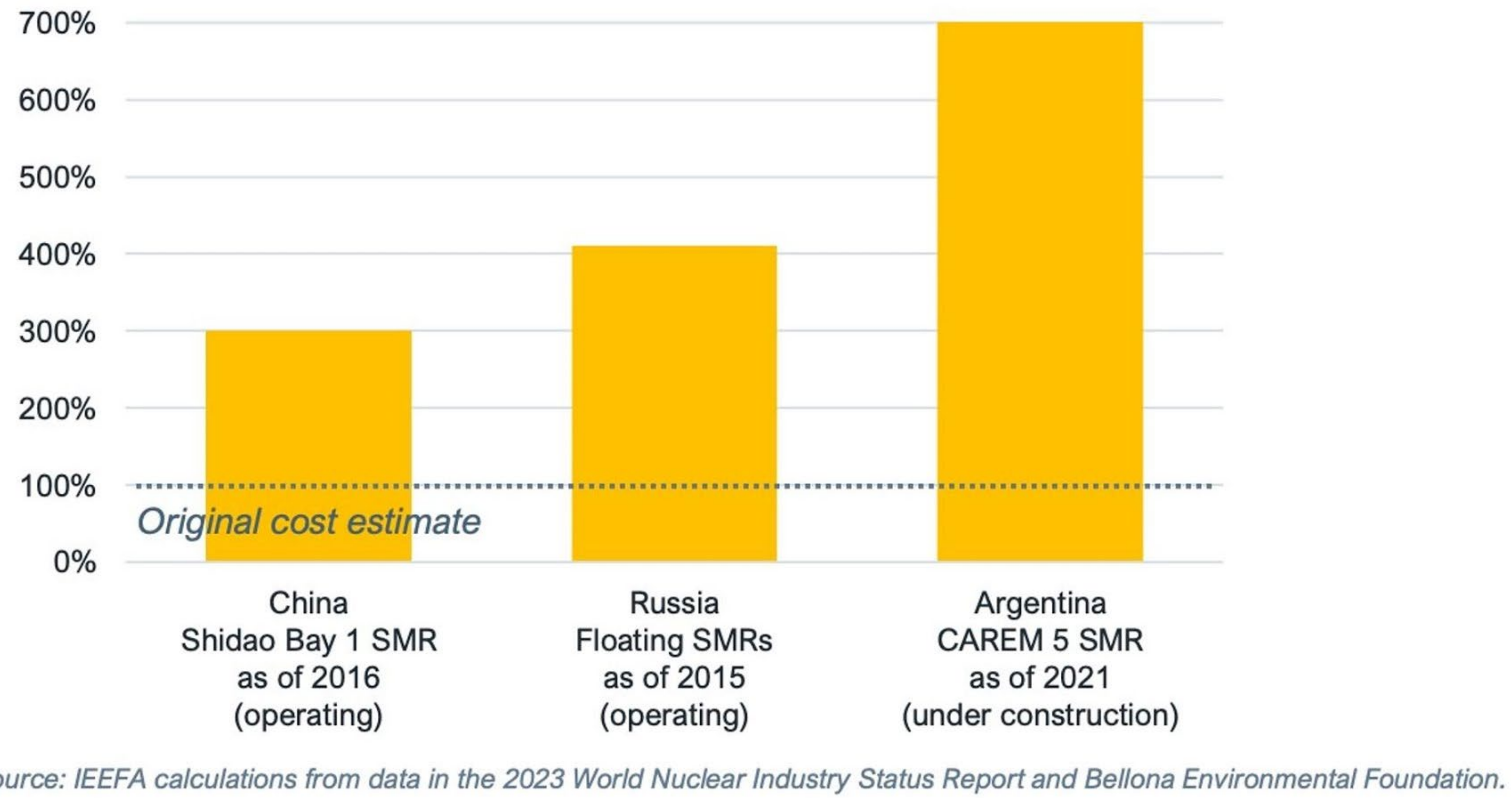


Fig. 9: Cost escalation experienced by SMRs in operation or under construction.

Taken from: Small modular nuclear reactors get a reality check in new report (ampproject.org)

Results and Discussion (cont'd)

Cost increased due to increase of the material and labor cost!

The first-of-a-kind (FOAK) reactor design extended construction and development years beyond what was expected and escalated expenses!!

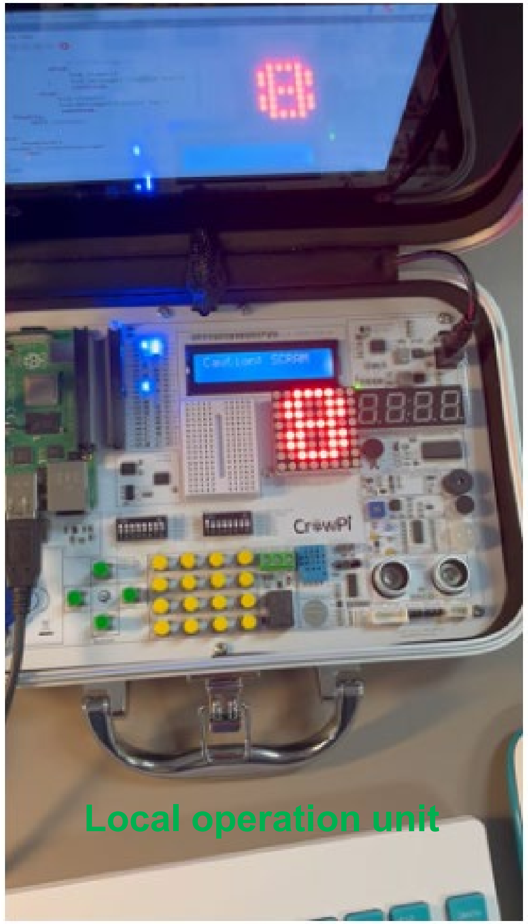
Source: IEEFA calculations based on public data for each of the projects converted to 2023-year U.S. dollars.

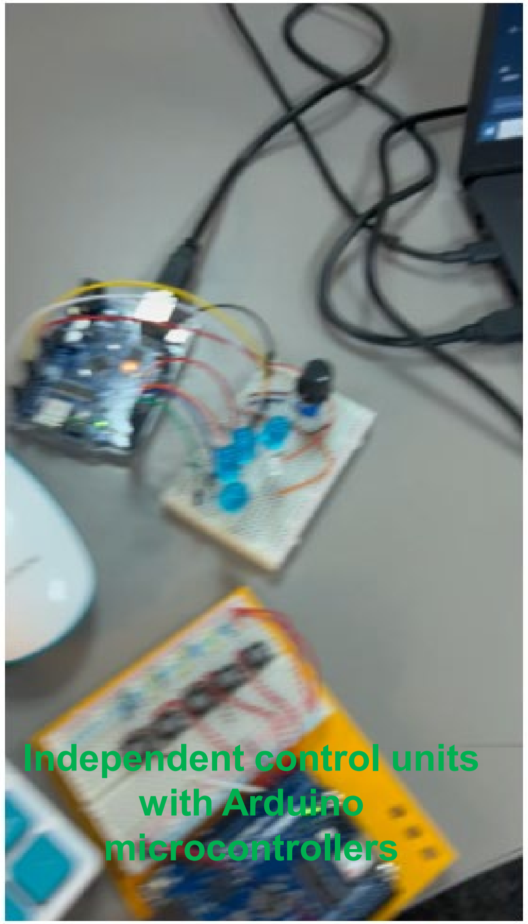
Fig. 10: Projected cost increase for proposed U.S. SMRs.

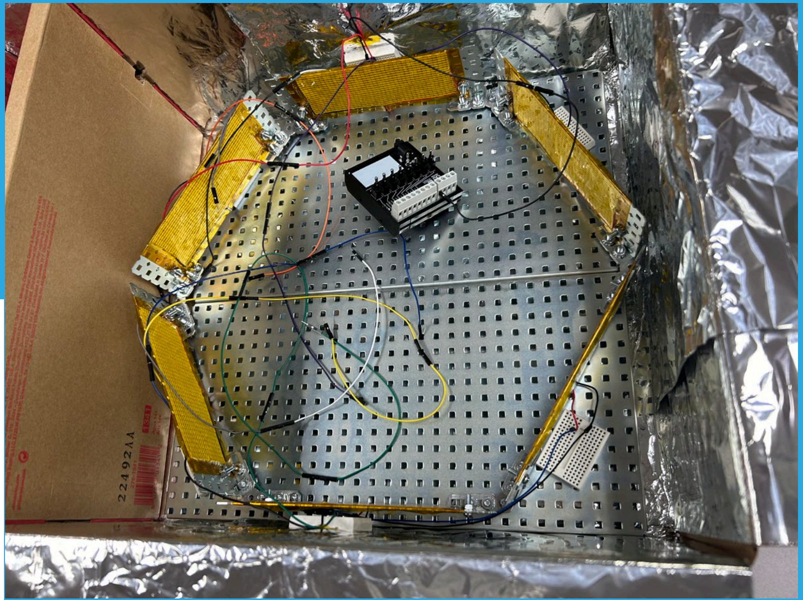
Taken from: Small modular nuclear reactors get a reality check in new report (ampproject.org)

Part-III:

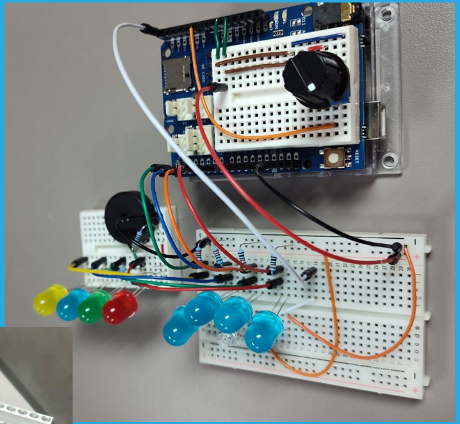
Example Case: Reactor system kits for high school interns with low budget

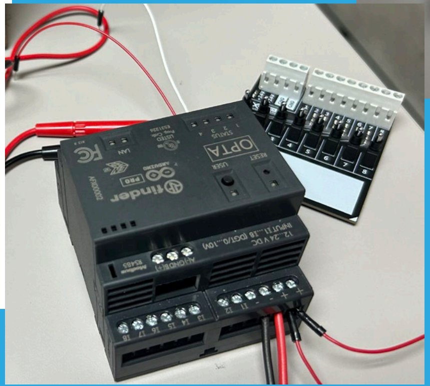






Independent temperature control units with Arduino microcontrollers





Independent logic control units Programable logic controller (PLC)

- Cost for this example case hardware demonstration is within $10,000!
- **However, hardware demonstration for SMR system would be millions to billions dollar!!**

Summary

- **Provided a general technoeconomic overview of SMR technology**
- **Revisited the energy cost and how it is impacted by energy policies**
- **Identified the SMR technology**
  - Development options (i.e., long-term and short-term plans) and cost relations
  - Strategies for reducing SMR cost, even losing economic scale benefit
    - Staffing, training and derisking, refueling and downtime
    - Supply chain, spent fuel issues, and construction cost
- Presented method and analysis with
  - Example design cases and INL studies
  - Relevant equations and correlations
- Discussion with representative results and findings.

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References

[1] Schlegel, J. P., and Bhowmik, P. K., “Small modular reactors,” In Wang, J., S. Talabi, and S. Bilbao y Leon (Eds.). Nuclear Power Reactor Designs, Elsevier, Inc., Philadelphia, PA, USA. pp. 283-308 (2024). https://doi.org/10.1016/B978-0-323-99880-2.00014-X.

[2] Armand, Y., Artisyuk, V. V., Banoori, S. M., Batra, C., Beville, T., Delmastro, D., ... & Zeliang, C. (2021). Technology Roadmap for Small Modular Reactor Deployment. IAEA Nuclear Energy Series, 1-108, 2021, Vienna:. INTERNATIONAL ATOMIC ENERGY AGENCY.

[3] Ingersoll, D. T. (2009). Deliberately small reactors and the second nuclear era. Progress in nuclear energy, 51(4-5), 589-603. https://doi.org/10.1016/j.pnucene.2009.01.003.

[4] Buongiorno, J., et al., Nuclear energy in a carbon-constrained world: Big challenges and big opportunities. IEEE Power and Energy Magazine, 2019. 17(2): p. 69-77.

[5] Gold, R., Tab swells to $25 billion for nuclear-power plant in georgia., in The Wall Street Journal. 2017.

[6] NuScale. NuScale Power. NuScale's Affordable SMR Technology for All, Accessed 12/9/2021. Available from: https://www.nuscalepower.com/newsletter/nucleus-spring-2020/featured-topic-cost-competitive

[7] US Energy Information Agency. Capital Cost Estimates for Utility Scale Electricity Generating Plants. 2016.

[8] Lokhov, A., Cameron, R., & Sozoniuk, V. (2013). OECD/NEA study on the economics and market of small reactors. Nuclear Engineering and Technology, 45(6), 701-706. https://doi.org/10.5516/NET.02.2013.517.

[9] Aziz, M. A. B., T. Grunloh, C. Brooks, “Coupling of Advanced Nuclear Reactors with Direct Air Capture Plant,” ANS, 2024.

[10] Asuega, A., Limb, B. J., & Quinn, J. C. (2023). Techno-economic analysis of advanced small modular nuclear reactors. Applied Energy, 334, 120669. https://doi.org/10.1016/j.apenergy.2023.120669.

[11] Spangler, R. M., Agarwal, V., Primer, C. A., Hansen, J. K., Lawrence, S., Howard, C., ... & Herb, R. (2023). Development of a Technical, Economic, and Risk Assessment Tool for the Evaluation of Work Reduction Opportunities (No. INL/RPT-23-74724-Rev000). Idaho National Laboratory (INL), Idaho Falls, ID (United States).

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