Economics of Nuclear Power

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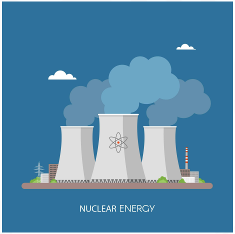


Environmental and Natural Resource Economics - **December 7, 2024**

Presentation Outline

1. Nuclear Energy Basics
2. Basic Costs of Nuclear Power
3. Conclusion

Basics of Nuclear Physics in Power Plants

- **Nuclear Fission:**
  - Splitting of heavy nuclei (e.g., Uranium-235) into smaller nuclei.
  - Releases a large amount of energy as heat.
  - Initiated by neutron absorption.
- **Chain Reaction:**
  - Released neutrons cause further fission events.
  - Controlled in reactors to maintain steady energy output.
- **Key Components in Power Plants:**
  - *Reactor Core:* Contains fuel rods where fission occurs.
  - *Control Rods:* Absorb neutrons to regulate the chain reaction.
  - *Coolant:* Transfers heat to generate steam for turbines.
  - *Moderator:* Slows neutrons to sustain the fission process.
- **Energy Conversion:**
  - Heat from fission converts water to steam.
  - Steam drives turbines connected to electricity generators.

Economic Considerations of Nuclear Power

- **Fuel Efficiency and Costs:**
  - High energy density of nuclear fuel reduces transportation costs.
  - Uranium enrichment and waste disposal increase upfront costs.
- **Capital and Operational Costs:**
  - Initial reactor construction is capital-intensive.
  - Long operational lifespan offsets high initial costs.
- **Regulation and Safety:**
  - Extensive safety measures required to control chain reactions.
  - Compliance with regulations adds to ongoing operational costs.
- **Impact of Waste Management:**
  - Long-lived radioactive waste requires secure storage.
  - Adds long-term liabilities to economic planning.
- **Economies of Scale:**
  - Larger reactors lower per-unit electricity costs.
  - Innovations like small modular reactors (SMRs) may change cost dynamics.

Early History of Nuclear Power and Nuclear Physics

- **1896: Discovery of Radioactivity**
  Henri Becquerel discovers radioactivity, revealing the potential energy within atoms.
- **1905: Einstein's Mass-Energy Equivalence**
  Albert Einstein formulates $E = mc^2$, establishing a theoretical basis for atomic energy.
- **1932: Discovery of the Neutron**
  James Chadwick discovers the neutron, a key component in nuclear reactions.

Early History of Nuclear Power and Nuclear Physics

- **1938: Nuclear Fission**
  Otto Hahn and Fritz Strassmann achieve nuclear fission in uranium, explaining how atoms can release vast amounts of energy.
- **1942-1947: Manhattan Project**
  Oppenheimer leads a team of 130,000 people focused on the development of the atomic bomb

Development of the Nuclear Power Industry

- **1942: The First Nuclear Reactor (Chicago Pile-1)**
  Enrico Fermi and team build the first nuclear reactor, proving a controlled chain reaction is possible.
- **1951: First Electricity from Nuclear Power**
  Experimental Breeder Reactor I (EBR-I) in Idaho generates the first usable electricity from nuclear energy.
- **1954: First Commercial Nuclear Power Plant**
  Obninsk, USSR, becomes the world's first nuclear power plant for electricity production.
- **1957: Commercial Reactors in the United States**
  Shippingport Atomic Power Station in Pennsylvania begins operation, marking the start of commercial nuclear power in the U.S.

History of Nuclear Power industry

- **1979: Three Mile Island Incident**
  Partial meltdown in Pennsylvania causes safety concerns, affecting nuclear power policies worldwide.
- **1986: Chernobyl Disaster**
  Explosion at Chernobyl, USSR, raises international awareness about nuclear safety risks.
- **2000s-2020s: Revival and Debate**
  Renewed interest in nuclear as a low-carbon energy source alongside concerns over safety and waste management.

Price of Uranium over Time

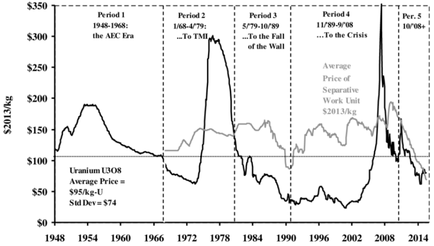


Figure 1: Events Shaping Uranium Market

Where Uranium is Mined

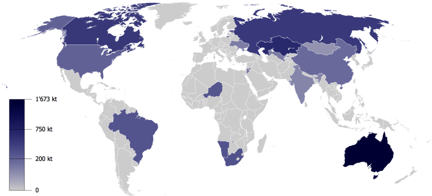


Figure 2: Good ole Siberia...

National Security Implications

- **Energy Independence:**
  - Domestic nuclear energy reduces reliance on foreign energy sources.
  - Enhances national resilience to global energy market disruptions.
- **Nuclear Proliferation:**
  - Enriched uranium and plutonium from reactors can potentially be diverted for weapons.
  - International safeguards (e.g., IAEA) are essential to prevent misuse.
- **Cybersecurity Risks:**
  - Advanced reactors are increasingly reliant on digital systems.
  - Vulnerability to cyberattacks poses threats to critical infrastructure.
- **Nuclear Waste Management:**
  - Long-lived radioactive waste requires secure storage.
  - Improper handling could lead to environmental and security risks.
- **Terrorism Concerns:**
  - Nuclear facilities could be targeted for sabotage.
  - Transport of nuclear materials requires stringent security protocols.

National Security Implications

- **Strategic Stability:**
    - Nations with advanced nuclear programs gain strategic influence.
    - Balancing peaceful energy use with global non-proliferation efforts is critical.
- **Geopolitical Impacts:**
    - Exporting nuclear technology strengthens alliances.
    - Dependence on uranium supply chains can create geopolitical vulnerabilities.

Comparison of Uranium and Thorium for Nuclear Power

Characteristic	**Uranium**	**Thorium**
Abundance	Less abundant in Earth's crust	More abundant in Earth's crust
Fissile Isotope	^{235}U (requires enrichment)	^{233}U (produced from ^{232}Th)
Energy Density	High	Comparable to Uranium
Reactor Type	Mostly Light Water Reactors (LWRs)	Molten Salt Reactors (MSRs), others
Waste Generation	Long-lived, highly radioactive waste	Lower volume and shorter-lived waste
Proliferation Risk	High (potential for weapons use)	Lower (harder to weaponize ^{233}U)
Operational Experience	Well-established	Emerging technologies
Natural Fissile Content	^{235}U ($\sim$0.7% naturally fissile)	None (requires breeding to ^{233}U)

Uranium vs. Thorium

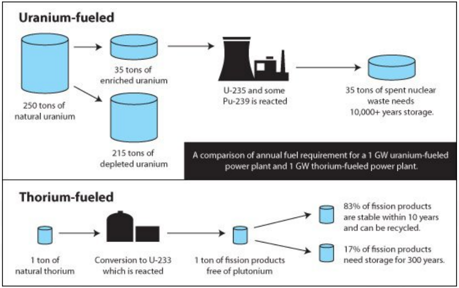


Figure 3: Is Thorium the Future?

Elements of a Nuclear Reactor

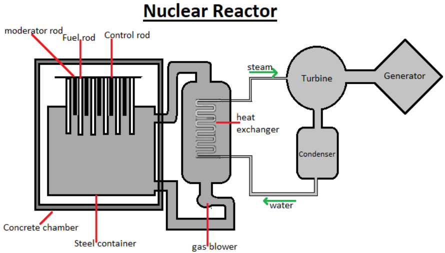


Figure 4: Don't let this fail!

Nuclear Power Plant Diagram

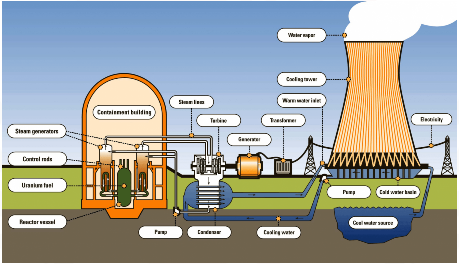


Figure 5: Hot rocks!

How Nuclear Interacts with Costs

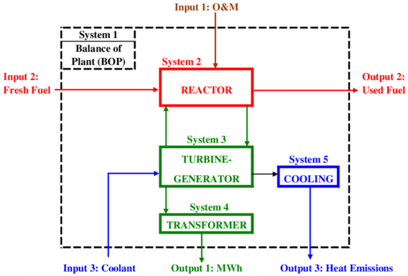


Figure 6: Money and the pain of nuclear engineers goes in... Eventually megawatts come out

Types of Nuclear Reactors

- Pressurized water reactors
- Boiling water reactors
- Molten salt and small modular reactors

Pressurized Water Reactors (PWRs)

- **Key Features:**
    - Uses pressurized water as both coolant and moderator.
    - Water in the primary loop does not boil due to high pressure.
- **Advantages:**
    - High safety due to separate primary and secondary loops.
    - Stable and well-established technology.
- **Challenges:**
    - Complex design and high capital costs.
    - Requires enriched uranium as fuel.
- **Applications:**
    - Widely used for civilian and naval reactors worldwide.

Boiling Water Reactors (BWRs)

- **Key Features:**
  - Uses water as both coolant and moderator.
  - Water in the reactor core boils to generate steam directly for turbines.
- **Advantages:**
  - Simpler design compared to PWRs.
  - Lower construction and operational costs.
- **Challenges:**
  - Higher risk of radioactive contamination in turbines.
  - Requires stringent operational controls.
- **Applications:**
  - Commonly used in civilian nuclear power plants.

Molten Salt Reactors (MSRs)

- **Key Features:**
  - Uses liquid salt as coolant and sometimes as fuel.
  - Operates at high temperatures with low pressure.
- **Advantages:**
  - High thermal efficiency and inherent safety features.
  - Can use thorium as fuel, reducing waste and proliferation risk.
- **Challenges:**
  - Still in experimental stages; not widely deployed.
  - Requires new infrastructure and regulatory frameworks.
- **Applications:**
  - Promising for next-generation nuclear reactors.

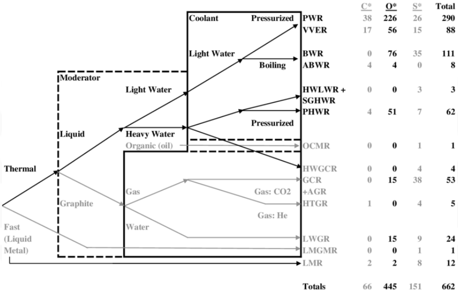
Small Modular Reactors (SMRs)

- **Key Features:**
  - Compact nuclear reactors with output typically below 300 MW.
  - Designed for factory fabrication and modular deployment.
- **Advantages:**
  - Lower upfront capital costs and shorter construction times.
  - Flexible deployment for remote or small-grid applications.
- **Challenges:**
  - Higher cost per MW compared to large reactors.
  - Requires regulatory approval and market adoption.
- **Applications:**
  - Suitable for distributed power generation and industrial applications.

Economic Comparison of Reactor Types

Factor	**PWRs**	**BWRs**	**MSRs**	**SMRs**
Capital Costs	High	Moderate	Moderate	Low
Operational Costs	High	Moderate	Low	Low
Waste Management	High	High	Low	Moderate
Fuel Utilization	Moderate	Moderate	High	High
Deployment Speed	Slow	Slow	Emerging	Fast
Market Readiness	Established	Established	Experimental	Emerging

Types of Reactors



	C*	O*	S*	Total
PWR	38	226	26	290
VVER	17	56	15	88
BWR	0	76	35	111
ABWR	4	4	0	8
HWLWR + SGHWR	0	0	3	3
PHWR	4	51	7	62
OCMR	0	0	1	1
HWGCR	0	0	4	4
GCR +AGR	0	15	38	53
HTGR	1	0	4	5
LWGR	0	15	9	24
LMGMR	0	0	1	1
LMR	2	2	8	12
Totals	66	445	151	662

Figure 7: Nuclear Power Flow Chart

Nuclear Industry: United States

- **Reactor Technology:** Predominantly PWRs and BWRs.
- **Policy and Regulation:** Stringent; NRC oversees safety.
- **Deployment Pace:** Slowing; aging fleet, limited new builds.
- **Waste Management:** Long-term storage challenges.
- **Economic Focus:** Cost reduction in existing fleet.
- **Nuclear Power Share:** 20% of electricity generation.
- **Public Perception:** Mixed; support tied to climate goals.
- **RD Focus:** SMRs, advanced reactors, fusion research.

Nuclear Industry: Commonwealth of Nations

- **Reactor Technology:** Advanced CANDU reactors (Canada).
- **Policy and Regulation:** Varies; robust in Canada, evolving elsewhere.
- **Deployment Pace:** Slow; Canada leads, others lag.
- **Waste Management:** Progress in deep geological storage (Canada).
- **Economic Focus:** Small Modular Reactors (SMRs) development.
- **Nuclear Power Share:** 15% in Canada; low elsewhere.
- **Public Perception:** Positive in Canada; skeptical elsewhere.
- **RD Focus:** SMRs, CANDU optimization.

Nuclear Industry: Western Europe

- **Reactor Technology:** Mix of PWRs, BWRs, and experimental tech.
- **Policy and Regulation:** Strong EU frameworks.
- **Deployment Pace:** Slow; transitioning due to renewables.
- **Waste Management:** Advanced strategies in Scandinavia.
- **Economic Focus:** Efficiency and decommissioning.
- **Nuclear Power Share:** 25-30% in France, lower elsewhere.
- **Public Perception:** Divided; strong anti-nuclear movements.
- **RD Focus:** Fusion and waste reduction.

Nuclear Industry: East Asia

- **Reactor Technology:** Focus on PWRs and fast reactors.
- **Policy and Regulation:** Strict regulations, rapid approvals.
- **Deployment Pace:** Rapid; major new construction.
- **Waste Management:** Progressing; mixed long-term solutions.
- **Economic Focus:** Export markets and domestic expansion.
- **Nuclear Power Share:** 25% (Japan recovering, China growing).
- **Public Perception:** Broad acceptance, especially in China.
- **RD Focus:** Advanced reactors, thorium exploration.

Key Reactor Factors

- Cost-effectiveness
- Safety
- Security and nonproliferation
- Grid Appropriateness
- Fuel Cycle:

Generations of Nuclear Reactors

- Generation 1 (1950-1970): Early prototypes of different designs
- Generation 2 (1970-1995): Commercial power plants designed to be economical and reliable, mostly light water reactors
- Generation 3 (1995-2030): Generation 2 nuclear reactors with improvements in fuel technology, thermal efficiency, modularized construction, safety systems, and standardized design. 60 year operational life. Mostly pressurized water reactors and advanced boiling water reactors
  - No Gen 3 reactors in the US
  - Gen 3+ is evolutionary improvement on Gen 3: Votgle
- Generation 4 (2030+): small modular reactors designed for efficiencies

Generations of Nuclear Reactors

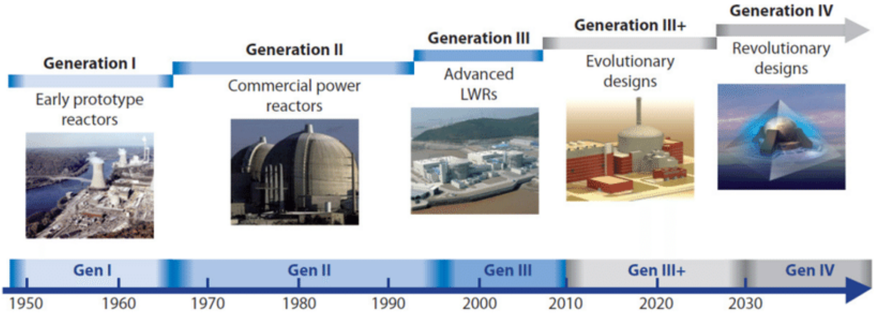


Figure 8: Nuclear Power Plants over Time

Why Nuclear Fell out of Favor

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- Just a reminder that both Chernobyl and 3 Mile Island had active generators as recently as 2019 and will soon again...

Why Nuclear Fell out of Favor

- Most people think nuclear went away because of security concerns
- These people are wrong or maybe Japanese
- Just a reminder that both Chernobyl and 3 Mile Island had active generators as recently as 2019 and will soon again...
- So why did nuclear fall out of style in the United States?

Why Nuclear Fell out of Favor

- Nuclear is expensive and had difficulty competing in the competitive marketplace
- Nuclear cost overruns caused utility bankruptcies leading to high cost of capital
- Nuclear is remarkably labor and capital intensive with remarkable economies of scale
- The United States has lost a lot of its nuclear knowledgebase and workforce

The Resurgance of Nuclear

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- It is making a comeback in the United States
- Microsoft has used a Purchase Power Agreement (PPA) to aid Constellation in restarting three mile Island
- Nuclear is special because it is baseload power with a high capacity factor and no carbon emissions

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- Nuclear is special because it is baseload power with a high capacity factor and no carbon emissions
- SMRs and new nuclear also have better profit margins
- The revitalization of the American nuclear energy will require a training of a new workforce of engineers and physicists... and of course economists!

Why nuclear has to be a part of the solution

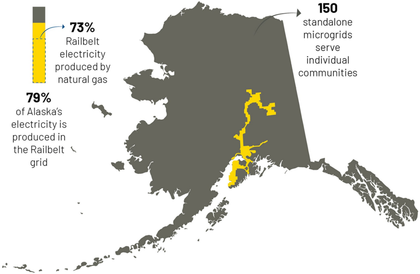

Figure 9: Alaska has a belt... a Railbelt!

Overview of Nuclear Power Costs

- **Total Construction Costs**: Includes site preparation, reactor construction, and auxiliary facilities.
- **Financing Costs and Lead Time**: Long lead times increase costs due to interest during construction.
- **Operations and Maintenance (O&M) Costs**: Include routine maintenance, staff salaries, and safety upgrades.
- **Fuel Costs**: A smaller fraction compared to other power sources.
- **Decommissioning and Waste Management Costs**: Incurred at the end of plant life.

Total Construction Costs

- Key components:
    - **Direct Costs**: Reactor, turbine, cooling systems.
    - **Indirect Costs**: Engineering, project management.
- **Equation for Total Cost ($\mathbf{C_{construction}}$):**

$$C_{\text{construction}} = \sum_{i=1}^{n} (C_{\text{direct},i} + C_{\text{indirect},i})$$

  where $C_{\text{direct},i}$ and $C_{\text{indirect},i}$ are the direct and indirect costs for project component i, and n is the number of components.

- **Cost Drivers**: Regulatory requirements, labor costs, materials.

Financing Costs and Lead Time

- Financing costs include interest accrued during the long construction period.
- **Equation for Financing Cost (F):**

$$F = \frac{C_{\text{construction}} \cdot r \cdot t}{2}$$

  where r is the annual interest rate, and t is the construction time in years.
- Lead time directly impacts overall cost:

$$C_{\text{total}} = C_{\text{construction}} + F$$

- Importance of minimizing delays to reduce costs.

Operations and Maintenance Costs

- O&M costs cover regular upkeep, safety inspections, and employee salaries.
- **Equation for Annual O&M Cost ($\mathbf{C_{O\&M}}$):**

$$C_{\text{O\&M}} = C_{\text{fixed}} + C_{\text{variable}}$$

  where:
    - C_{fixed}: Costs independent of power output (e.g., salaries, insurance).
    - C_{variable}: Costs dependent on power output (e.g., consumables, repairs).
- Key drivers:
    - Regulatory compliance.
    - Plant age and efficiency.

Nuclear Capacity Factors

- The **capacity factor** measures how effectively a nuclear power plant generates electricity compared to its maximum potential output.
- **Equation for Capacity Factor (CF):**

$$CF = \frac{\text{Actual Energy Generated (MWh)}}{\text{Maximum Possible Energy (MWh)}} \times 100$$

- Where:
  - **Actual Energy Generated**: Energy produced over a given time period.
  - **Maximum Possible Energy**: Rated capacity × hours in the time period.
- High capacity factors for nuclear plants:

$$CF \approx 90\% \text{ or higher}$$

Key drivers of high capacity factors

  - **Base-load operation**: Operates continuously except for maintenance or refueling.
  - **Reliability**: Fewer unscheduled outages compared to other sources.
- Comparison:

$$CF_{\text{Nuclear}} > CF_{\text{Wind}}, CF_{\text{Solar}}, CF_{\text{Coal}}$$

Levelized Cost of Electricity (LCOE) for Nuclear Power

- **LCOE** is the average cost per megawatt-hour (MWh) of electricity generated over a plant's lifetime.
- **Equation for LCOE:**

$$\text{LCOE} = \frac{\sum_{t=1}^{T} \left(\frac{C_{\text{construction}}}{(1+r)^t} + \frac{C_{\text{O\&M},t}}{(1+r)^t} + \frac{C_{\text{fuel},t}}{(1+r)^t} + \frac{C_{\text{decommission},t}}{(1+r)^t} \right)}{\sum_{t=1}^{T} \frac{\text{Electricity Generated}_t}{(1+r)^t}}$$

- Where:
  - $C_{\text{construction}}$: Total construction cost.
  - $C_{\text{O\&M},t}$: Operations and maintenance costs in year t.
  - $C_{\text{fuel},t}$: Fuel costs in year t.
  - $C_{\text{decommission},t}$: Decommissioning costs in year t.
  - r: Discount rate.
  - T: Plant lifetime.

Levelized Cost of Electricity (LCOE) for Nuclear Power

- Simplification using capacity factor (CF):

$$\text{Electricity Generated}_t = \text{Capacity} \times CF \times \text{Hours in a Year}$$

- **Insights**:
  - High construction costs and long lead times increase LCOE.
  - High capacity factors reduce LCOE by maximizing generation.

Capital Recovery Factor (CRF)

- The **Capital Recovery Factor (CRF)** converts an upfront capital cost into an equivalent annual cost over the lifetime of a project.
- **Equation for CRF:**

$$CRF = \frac{r(1+r)^T}{(1+r)^T - 1}$$

- Where:
  - r: Discount rate (annual interest rate).
  - T: Project lifetime (years).
- **Annualized Cost (A):**

$$A = C_{\text{capital}} \cdot CRF$$

Where:

  - C_{capital}: Total upfront capital cost.
  - A: Equivalent annual cost.

Capital Recovery Factor (CRF)

- **Example Calculation**:
    - $C_{\text{capital}} = \$10\,\text{billion},\ r = 5\%,\ T = 40\,\text{years}.$
    - Calculate $CRF = \frac{0.05(1+0.05)^{40}}{(1+0.05)^{40}-1}$.
- **Importance**:
    - Used in LCOE calculations to distribute capital costs over the plant's lifetime.
    - Helps compare projects with different lifetimes and financing conditions.

Decommissioning Costs and the Nuclear Trust

- **Decommissioning Costs**:
    - Incurred at the end of the nuclear plant's operational life.
    - Include dismantling structures, safely disposing of radioactive materials, and site restoration.
    - Typical cost range: **$300–$1,000 million per plant**.
- **Nuclear Trust Funds**:
    - Funds are set aside during the operational life of the plant to cover decommissioning costs.
    - Managed as part of regulatory requirements to ensure sufficient resources are available.
    - Investment growth reduces the upfront burden on ratepayers.
- **Equation for Trust Fund Growth (F_t):**

$$F_t = F_0 \cdot (1 + r)^t + \sum_{i=1}^{t} C_{\text{annual}} \cdot (1 + r)^{t-i}$$

Nth-of-a-Kind Models for New Nuclear Capital Costs

- **Overview**:
  - Capital costs for nuclear plants decrease as more units are built, leveraging learning effects and economies of scale.
  - **First-of-a-Kind (FOAK)**: Higher costs due to initial design, regulatory approvals, and lack of standardization.
  - **Nth-of-a-Kind (NOAK)**: Lower costs for subsequent units due to learning and replication.
- **Cost Reduction Dynamics**:
  - Learning-by-doing reduces costs per unit.
  - Standardized designs simplify construction.
  - Supply chain improvements and regulatory streamlining.

Nth-of-a-Kind Models for New Nuclear Capital Costs

- **Equation for Cost Reduction**:

  $$C_n = C_1 \cdot n^{-\lambda}$$

  Where:
  - C_n: Cost of the n-th unit.
  - C_1: Cost of the first unit.
  - n: Unit number.
  - λ: Learning rate parameter ($\lambda > 0$).
- **Implications**:
  - Policy support for multiple plants can accelerate cost reductions.
  - Reduces financial risk for developers over time.
  - Critical for the competitiveness of advanced nuclear technologies.
- **Challenges**:
  - High initial costs for FOAK projects.
  - Dependence on consistent demand and policy frameworks.

Comparing Cost Structures: Traditional vs. New Nuclear

- **Overview**:
  - Traditional nuclear plants (large-scale reactors) and new nuclear designs (small modular reactors, advanced reactors) differ in their cost structures and economic considerations.

Comparing Cost Structures: Traditional vs. New Nuclear

Cost Component	**Traditional Nuclear**	**New Nuclear**
Capital Costs	Very high, driven by custom designs and scale	Lower due to modular design and factory production
Construction Time	Long (10-15 years), increasing financing costs	Shorter (3-7 years), reducing financial risks
Operations & Maintenance	High, due to complex systems and large workforce	Lower, with fewer staff and automated operations
Decommissioning Costs	Significant, due to large-scale waste management	Smaller scale leads to reduced decommissioning costs
Flexibility	Designed for base load operation only	More flexible; can follow variable demand

Comparing Cost Structures: Traditional vs. New Nuclear

- **Key Implications**:
  - New nuclear designs aim to lower upfront and ongoing costs, improving economic feasibility.
  - Shorter construction times reduce financing burdens.
  - Modular designs allow incremental capacity additions.

Levelized Costs and Cost Risk in a Generator Portfolio

- **Overview**:
  - Portfolio generation planning considers not only levelized costs but also cost risk.
  - Diversification reduces exposure to volatile fuel prices and construction delays.
- **Levelized Cost Calculation**:

$$\text{Portfolio LCOE} = \sum_{i=1}^{N} w_i \cdot \text{LCOE}_i$$

Where:

- N: Number of generator types.
- w_i: Weight (share of generation) of generator i in the portfolio.
- LCOE_i: Levelized cost of electricity for generator i.

Example Portfolio

- **Nuclear**: $w_{\text{nuclear}} = 0.4$, $\text{LCOE}_{\text{nuclear}} = \$70/\text{MWh}$.
- **Natural Gas**: $w_{\text{gas}} = 0.4$, $\text{LCOE}_{\text{gas}} = \$50/\text{MWh}$.
- **Renewables**: $w_{\text{renewables}} = 0.2$, $\text{LCOE}_{\text{renewables}} = \$30/\text{MWh}$.

Portfolio LCOE Calculation:

$$\text{Portfolio LCOE} = (0.4 \cdot 70) + (0.4 \cdot 50) + (0.2 \cdot 30) = \$54/\text{MWh}$$

Example Portfolio

- **Volatility**: Fuel price uncertainty (e.g., gas prices).
- **Mitigation**: Nuclear and renewables provide stability due to fixed costs and no fuel dependency.
- **Portfolio Variance**: Combines individual cost variances:

$$\sigma^2_{\text{portfolio}} = \sum_{i=1}^{N} w_i^2 \cdot \sigma_i^2 + \sum_{i \neq j} w_i w_j \cdot \rho_{ij} \cdot \sigma_i \cdot \sigma_j$$

Where ρ_{ij} is the correlation between cost risks of generators i and j.

Implications:

- A balanced portfolio reduces cost volatility.
- Nuclear adds stability but increases upfront costs.

Thank You So Much!

List of References