Lecture 1: The Engineering Context of Nuclear Power: Notes

Intro to Nuclear Engineering – D. T. Leighton

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1 Electricity Requirements and Projections

- **Current US Generation (2024):** Total net generation reached approximately **4,401 TWh**. This marks a significant 3% year-over-year increase, the fifth-highest growth rate this century (Ember/EIA 2025 Report).
- **The Historical Plateau (2008–2022):** For nearly 15 years, US demand remained stagnant with an average growth rate of only **0.1% per year**, as efficiency gains (e.g., LED lighting) offset economic growth (EIA, May 2025).
- **The 2024–2030 Surge:** Demand is now projected to grow by **1.7% to 2.4% annually** through 2030, a sharp departure from the previous decade (EIA STEO, Dec 2025).
- **Growth Driver: Data Centers & AI**
  - In 2023, data centers consumed **176 TWh** ($\sim$4.4% of US load).
  - Consumption is projected to reach **6.7% to 12%** of total US electricity by 2028 (LBNL 2024 Report).
  - EPRI estimates that AI-specific queries require **10–20x** the power of a standard search (DOE 2024/2025 Resources).
- **Growth Driver: Transportation & Industry**
  - Light-duty EV demand reached **11 TWh** in 2024 and is scaling at a rate of 8%+ per year.
  - The "Reshoring" of semiconductor and battery fabrication is creating localized "Gigawatt-scale" demand clusters (Grid Strategies 2024).
- **Long-term Projection (2050):** To meet economy-wide Net-Zero goals, the IEA and DOE forecast a **doubling** of current electricity demand to $\sim$8,000 TWh to replace direct combustion in heating and transit (IEA WEO 2024).

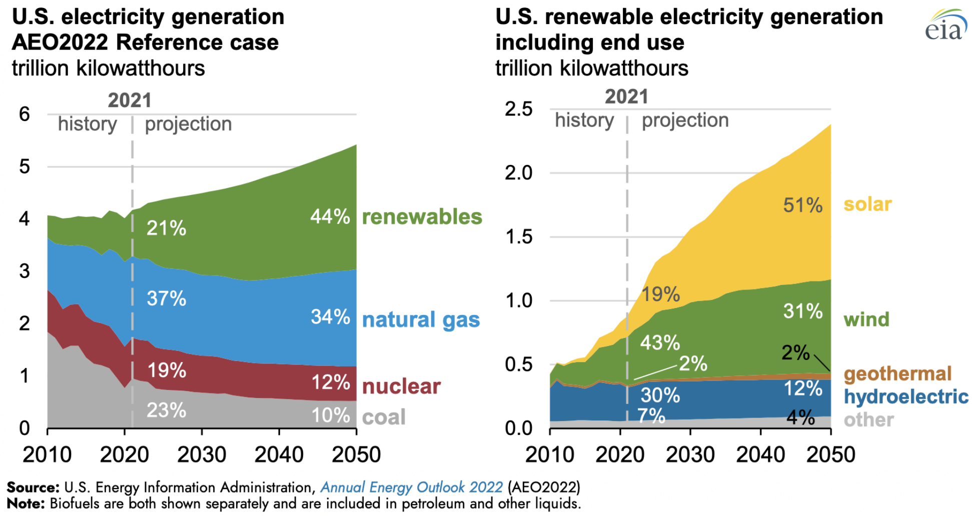


Figure 1: U.S. Electricity Generation by Fuel Type (2000–2050). Note the flat demand during the "Efficiency Plateau" (2008–2022) followed by the projected surge driven by electrification and data centers. Source: U.S. Energy Information Administration, Annual Energy Outlook (AEO).

2 Energy Sources: Magnitudes and Trends

- **The Current Mix (2024):** The U.S. generation profile is currently dominated by Natural Gas (43.1%) and Nuclear (18.6%). For the first time, combined Wind and Solar (17.5%) surpassed Coal (15.8%) (Ember 2025 Report).
- **The Low-Carbon Gap:** Approximately **44%** of the U.S. grid is now carbon-free. However, the majority of this "clean" energy is provided by Nuclear and Hydro, which are relatively stagnant in growth compared to the 27% annual growth rate of Solar (EIA 2025).
- **Capacity Factor (CF) vs. Nameplate Capacity:** Energy delivery is governed by the Capacity Factor, defined as the ratio of actual energy produced to the maximum possible energy output.
  - **Nuclear:** 93.1% — The highest of any source, providing "firm" baseline power.
  - **Natural Gas:** 59.7% — Primarily used for load-following.
  - **Wind:** 33.2% — Geographically and weather dependent.
  - **Solar:** 23.2% — Limited by diurnal cycles and cloud cover.
- **Engineering Implication:** To replace a single 1 GW nuclear plant while maintaining the same annual TWh, a system requires ∼3 GW of wind or ∼4 GW of solar capacity, necessitating a significantly larger physical footprint (MIT Climate Portal).

3 Intermittency and Grid Stability

- **The Temporal Mismatch:**
  - *Diurnal:* Solar peaks at noon; demand peaks at 7:00 PM.

– *Seasonal:* Multi-day periods of low wind/sun (*Dunkelflaute*) require long-duration backup.

- **The Duck Curve:** Visualizing the **Net Load** (Total Demand − Variable Renewables).
  - **The "Belly":** Midday overgeneration often leads to **Curtailment**—forced shutdown of renewables to prevent grid overvoltage (CAISO 2025).
  - **The "Neck":** Evening ramping requirements in California now exceed **15,000 MW in 3 hours**, requiring fast-reacting gas peakers or massive battery fleets.

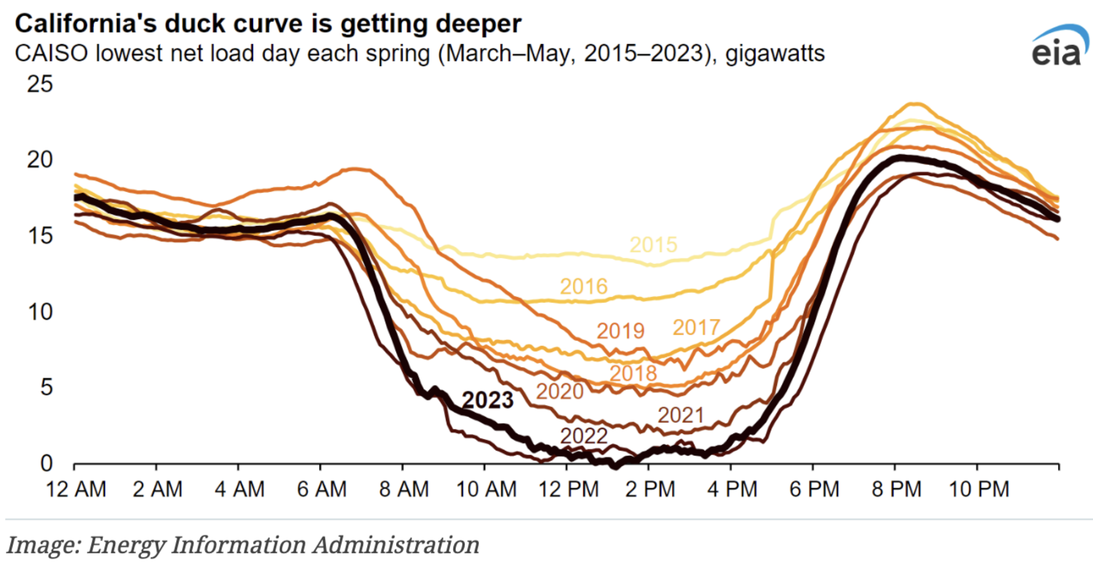


Figure 2: The CAISO "Duck Curve" showing Net Load (Total Demand minus Wind and Solar). The "belly" of the duck represents midday over-generation, while the "neck" represents the extreme ramp-up required as solar output vanishes at sunset. Source: California Independent System Operator (CAISO).

- **The Physics of Grid Stability:**
  - **Rotational Inertia:** Synchronous generators (Nuclear/Fossil) provide kinetic energy that naturally stabilizes grid frequency (60 Hz).
  - **Inverter-Based Resources (IBRs):** Solar/Wind lack physical inertia. High IBR penetration leads to a high **Rate of Change of Frequency (RoCoF)**, increasing the risk of widespread blackouts during minor disturbances (NREL 2025 Report).
  - **The Inertia Equation:** The relationship between power imbalance (ΔP) and frequency change (f) is governed by the Swing Equation:

$$\frac{2H}{f_0}\frac{df}{dt} = P_m - P_e$$

    Where H is the inertia constant. As $H \to 0$ (high inverter penetration), the frequency gradient $\frac{df}{dt}$ (RoCoF) becomes theoretically infinite for any power mismatch, leading to instantaneous system instability unless *Synthetic Inertia* is provided via fast-acting batteries (NERC IBR Resources).

4 Storage Options and Constraints

- **Diurnal Shifting:**
  - Utility-scale Li-ion is economically optimized for 4-hour "peak shaving."
  - Round-trip efficiency (∼85–90%) is high, but capacity degrades over 10–15 years.
- **The Multi-Day Problem: *Dunkelflaute***
  - Defined as periods of low wind/solar lasting 5–10 days.
  - These events occur 2–5 times per winter in northern latitudes (gridX 2025 Analysis).
  - Storage required for a 7-day "dark lull" for a national grid is currently cost-prohibitive.
- **Scaling Physics and Material Requirements:**
  - **Energy Density:** Fission energy density (7.9×10^7 MJ/kg) is approximately 8 orders of magnitude greater than electrochemical storage (0.75 MJ/kg).
  - **Material Intensity:** Grid-scale batteries require massive mineral throughput. IEA projections suggest a 40x increase in Lithium demand by 2040 (IEA 2024).
  - **Copper Bottleneck:** Low-density sources require extensive electrical interconnects, increasing copper usage by 400–1000% compared to centralized firm power (IDTechEx Report).
- **The Lithium Material Bottleneck:**
  - *Storage Goal:* 24-hour backup for the US Grid (≈11 TWh).
  - *Resource Intensity:* Modern LFP grid batteries require ≈0.1 kg of elemental lithium per kWh, which converts to ≈**0.53 kg of Lithium Carbonate Equivalent (LCE)** per kWh.
  - *Massive Scaling:* Providing just one day of backup requires ≈**5.8 million tonnes of LCE**.
  - *The Reality Check:* Total global lithium production in 2024 was ≈1.2 million tonnes LCE.
  - **Conclusion:** Backing up the US grid for a single day would consume **100% of global lithium production for 5 years**, assuming zero production for EVs or electronics (USGS 2025).

5 The Grid Backbone: Firm Capacity

- **Definition of Firm Power:** Power generation that is dispatchable and guaranteed to be available at any time, for any duration, regardless of weather conditions.
- **Backbone Requirements:**
  - Reliability requires that firm capacity (Nuclear, Hydro, or Fossil with CCS) should meet at least **80–100% of the minimum seasonal peak demand** (MIT 2018/2024 Update).

  - Systems without sufficient firm backbone rely on *load shedding* (controlled blackouts) during extreme weather events.

- **Economic Thresholds and System LCOE:**
  - **The Cost Convexity:** As renewable penetration increases, the marginal cost of adding the next MWh increases exponentially due to storage and transmission requirements.
  - **Avoided Costs:** Nuclear serves as a "system-cost minimizer." By providing firm power, it reduces the total amount of redundant "nameplate" capacity and storage the grid must maintain (OECD-NEA System Cost Study).
  - **Energy Security:** Firm capacity ensures "Black Start" capability—the ability to restart the grid from scratch after a total collapse.

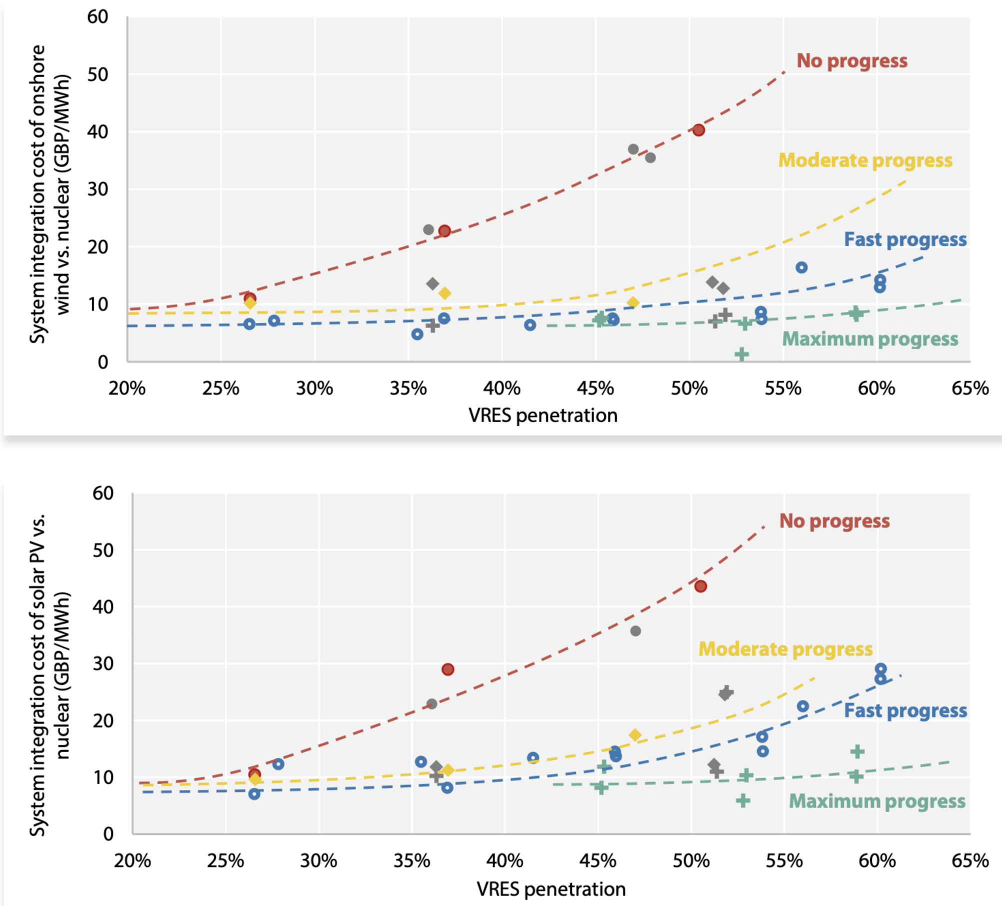
- **The LCOE Paradox: Plant vs. System Costs**

  Plant-Level LCOE: The nominal cost of generation "at the busbar":
    - *Renewables (Wind/Solar):* ≈\$30–\$50/MWh
    - *Nuclear (New Build):* ≈\$70–\$90/MWh

  The System-Level Reality: As variable renewable penetration approaches 100%, "System LCOE" can exceed **\$200/MWh** due to the massive capital requirements for multi-day storage and grid overbuilding.

  The Economic Sweet Spot: Modeling by the OECD-NEA suggests that a "firm backbone" of approximately 40% Nuclear results in the **lowest total cost to the consumer** by eliminating the most expensive 20% of required energy storage (OECD-NEA 2019/2024).

Figure 12. **System costs for wind (up) and solar PV (bottom) as a function of penetration level and progress on flexibility**



Source: Strbac and Aunedi, 2016.

Note: The different colours represent the different assumptions about the level of flexibility in the system; from "No progress" to "Maximum progress".

Figure 3: Total System LCOE vs. Variable Renewable Energy (VRE) Penetration. While the 'at-the-fence' cost of wind and solar is low, the total system cost increases exponentially as penetration exceeds 60–70% due to integration, backup, and grid costs. Source: OECD-NEA (2019/2024 update).

6 Fossil vs. Nuclear: The Thermal and Economic Comparison

- **The Heat Engine:** Both systems serve as heat sources for a Rankine steam cycle.
  - **Fossil:** Utilizes chemical combustion to produce steam.
  - **Nuclear:** Utilizes the kinetic energy of fission products to produce steam.
  - *Note:* While standard LWRs operate at lower temperatures (∼300–315°C) due to water-coolant constraints, the "fuel" itself is not the bottleneck; the thermal limits are determined by the chosen coolant and cladding.

- **Fuel Economics and Price Sensitivity:**
  - *Fossil:* High variable costs; fuel is **70–80%** of O&M. Operation is sensitive to commodity market fluctuations.
  - *Nuclear:* Low variable costs; fuel is ∼**15%** of O&M. The cost of electricity is largely fixed by the initial capital investment (NEI 2025).
- **Waste Streams and Externalities (per 1,000 MWe per Year):**
  - *Fossil (Coal):* ∼300,000 tonnes of solid ash; ∼6,000,000 tonnes of gaseous CO_2 released or sequestered (WNA 2024).
  - *Nuclear:* ∼25–30 tonnes of solid spent fuel.
  - **Containment Philosophy:** Nuclear relies on a "Capture and Contain" model; fossil historical relies on "Dilute and Disperse."

7 Course Roadmap: From Physics to Systems

- **Unit I: The Physics of the Nucleus (Weeks 1–4)**
  - Fundamental particles, binding energy, and mass defect.
  - Radioactive decay kinetics and ionizing radiation.
- **Unit II: The Neutron and the Chain Reaction (Weeks 5–9)**
  - Interaction probabilities (Cross-sections, σ).
  - Moderation, Diffusion Theory, and the Six-Factor Formula for Criticality (k_{eff}).
- **Unit III: Reactor Engineering & Safety (Weeks 10–14)**
  - Thermal-hydraulics, reactor designs (PWR, BWR, SMR), and the fuel cycle.

Additional References

1. **Boston University US Energy Charts** A nice visual guide to US electrical energy usage and sources over time.
   https://visualizingenergy.org/united-states-electricity-history-in-four-charts/