Electricity Markets

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Presentation Outline

1. Electricity
2. Generation
3. Transmission
4. Conclusion

What is Electricity?

- Electricity is the flow of electrical power or charge.
- It is a secondary energy source, meaning it is generated from the conversion of primary sources such as coal, natural gas, wind, or solar energy.
- Electricity is used widely for:
  - Powering homes, businesses, and industries.
  - Driving technological advancements.
  - Supporting essential services like healthcare and transportation.
- It plays a crucial role in modern economies and environmental policy.

Key Physical Features of Electricity

- **Voltage (V):** Measures the electrical potential energy per unit charge, akin to the ”pressure” driving electrons.
- **Current (I):** The rate at which electric charge flows, measured in amperes (A).
- **Resistance (R):** Opposition to the flow of electric current, measured in ohms (Ω).
- **Power (P):** The rate of energy transfer, calculated as $P = IV$, measured in watts (W).
- **Alternating Current (AC) vs. Direct Current (DC):**
  - AC: Electric charge flow periodically reverses direction (e.g., grid electricity).
  - DC: Electric charge flows in one direction (e.g., batteries).
- **Transmission and Losses:** Electricity must travel through transmission lines, experiencing losses due to resistance and inefficiencies.

Generating Electric Current

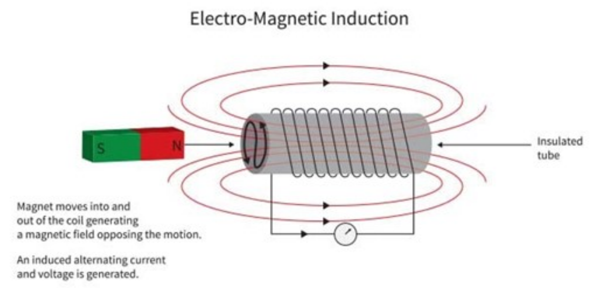


Figure 1: Moving a magnet around a coil of wire, or moving a coil of wire around a magnet, pushes the electrons in the wire and creates an electrical current

Electricity Generation Using Turbines

- Electricity is often generated using turbines, which convert mechanical energy into electrical energy.
- **How it Works:**
  1. A primary energy source (e.g., coal, natural gas, wind, water, nuclear, or solar) is used to produce mechanical energy.
  2. This energy is used to spin the blades of a turbine.
  3. The turbine is connected to a generator.
  4. Inside the generator, magnets and coils of wire interact to create a flow of electrons — this is electricity.

Electricity Generation Using Turbines

- **Common Types of Turbines:**
  - **Steam Turbines:** Use steam produced by heating water with coal, natural gas, nuclear energy, or concentrated solar power.
  - **Wind Turbines:** Harness kinetic energy from the wind to turn the blades.
  - **Hydroelectric Turbines:** Use the movement of water, often from dams, to spin the turbine.
  - **Gas Turbines:** Burn natural gas or other fuels to produce hot gases that drive the turbine.
- **Efficiency Considerations:** The efficiency of electricity generation varies by energy source, technology, and environmental conditions.

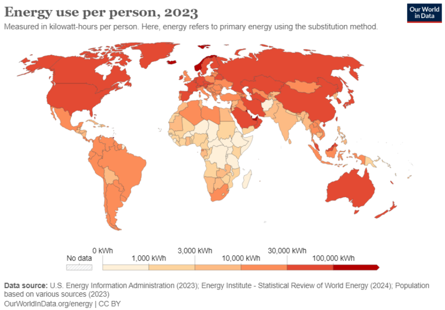
Why is Electricity Important?

- There's a reason they call it power!
- Electricity is what makes modern life possible and allows for complex transactions and actions to be performed

Why is Electricity Important?

- There's a reason they call it power!
- Electricity is what makes modern life possible and allows for complex transactions and actions to be performed
- **Capital without energy is a statue, labor without energy is a corpse!!!**

Life without Electricity



Energy use per person, 2023

Measured in kilowatt-hours per person. Here, energy refers to primary energy using the substitution method.

Data source: U.S. Energy Information Administration (2023); Energy Institute - Statistical Review of World Energy (2024); Population based on various sources (2023)
OurWorldInData.org/energy | CC BY

Figure 2: The Role of Electricity in Living Standards.

What makes Electricity Special?

- Difficult to store
- Market must balance continuously
- Highly inelastic demand curve
- Belief in need for near-constant reliability

Structure of Power Markets

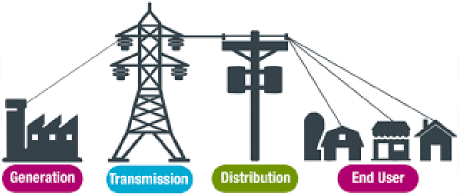


Figure 3: Three Parts of Electricity Market.

Generation: Producing Electricity

- Electricity is generated by converting primary energy sources into electrical energy.
- **Types of Generation:**
  - **Fossil Fuels:** Coal, natural gas, and oil are burned to produce steam or hot gases that drive turbines.
  - **Renewables:** Wind, solar, hydro, and geothermal directly harness natural processes.
  - **Nuclear:** Heat from nuclear reactions generates steam for turbines.
- **Economic Implications:**
  - Fuel costs and availability.
  - Environmental externalities, e.g., greenhouse gas emissions.
  - Policy incentives for renewables (e.g., tax credits, carbon pricing).

Transmission: Moving Electricity

- **High-Voltage Transmission:** Electricity is transported over long distances using high-voltage lines to minimize losses.
- **Components of the Grid:**
  - **Substations:** Step-up and step-down transformers adjust voltage levels.
  - **Transmission Lines:** High-voltage lines that connect generation to distribution networks.
- **Challenges:**
  - **Line Losses:** Electrical energy is lost as heat during transmission.
  - **Congestion:** When demand exceeds the capacity of transmission lines, prices rise, and some regions face supply issues.
  - **Infrastructure Costs:** Building and maintaining transmission networks requires significant investment.

Distribution: Delivering Electricity to Consumers

- **Local Networks:** Distribution systems take electricity from transmission lines and deliver it to homes, businesses, and industries.
- **Voltage Reduction:** Substations reduce voltage to safer levels for consumer use.
- **Consumer Types:**
    - **Residential:** Homes and small-scale users.
    - **Commercial:** Businesses, offices, and service industries.
    - **Industrial:** Factories and heavy-duty users with specific voltage needs.
- **Technological Trends:**
    - Smart grids and advanced metering infrastructure (AMI).
    - Distributed energy resources (e.g., rooftop solar, home batteries).

History of Electricity Markets

- **Late 19th Century: The Birth of Electricity**
  - 1879: Thomas Edison invented the practical incandescent light bulb.
  - 1882: The first power plant, the Pearl Street Station in New York, was established.
- **Early 20th Century: The Rise of Monopolies**
  - Electricity grids expanded, and vertically integrated monopolies controlled generation, transmission, and distribution.
  - Prices and access varied widely, leading to public demand for regulation.
- **Mid-20th Century: Regulation Era**
  - Government agencies, such as the Federal Power Commission (now FERC), began regulating electricity markets.
  - Focus on universal access and affordability through cost-based pricing.

History of Electricity Markets

- **1970s-1990s: Deregulation and Restructuring**
  - Energy crises in the 1970s highlighted inefficiencies in the regulated system.
  - 1990s: Electricity markets were restructured to introduce competition in generation (e.g., California, Texas, and PJM Interconnection).
- **21st Century: Modern Electricity Markets**
  - Integration of renewable energy sources and demand response programs.
  - Smart grids and advanced market designs to handle intermittent generation.
  - Increasing focus on decarbonization and sustainability.

Regulated vs. Deregulated Electricity Markets

- **Regulated Electricity Markets:**
    - Vertically integrated utilities control generation, transmission, and distribution.
    - Prices are set by regulatory authorities based on cost-of-service models.
    - Focus on universal access, reliability, and stable prices.
    - Examples: Southeast U.S., much of the Midwest.
- **Deregulated Electricity Markets:**
    - Generation is competitive, with independent power producers bidding into wholesale markets.
    - Transmission and distribution remain regulated as natural monopolies.
    - Prices are market-driven, reflecting supply and demand dynamics.
    - Consumers may choose electricity suppliers, fostering competition and innovation.
    - Examples: Texas (ERCOT), PJM Interconnection, California.

Key Differences between Types of Markets

- **Key Differences:**

	Regulated	**Deregulated**
Market Structure	Monopolistic	Competitive generation
Price Setting	Fixed by regulators	Market-based
Innovation	Limited	Encouraged
Consumer Choice	None	Multiple suppliers

Pros and Cons of Regulated vs. Deregulated Markets

	Regulated Markets	**Deregulated Markets**
Pros	● Stable, predictable prices. ● Focus on reliability and universal access. ● Easier long-term infrastructure planning.	● Encourages competition and innovation. ● Market-driven prices reflect supply and demand. ● Greater consumer choice and tailored solutions.
Cons	● Limited competition may lead to inefficiencies. ● Little incentive for innovation or renewables. ● Prices may not reflect real-time conditions.	● Price volatility can burden consumers. ● Risk of market manipulation or gaming. ● Reliability concerns with decentralized generation.

Table 1: Comparison of Pros and Cons of Regulated and Deregulated Markets

Deregulated vs. Centralized Electricty Markets

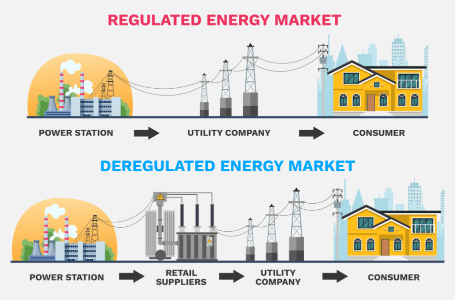


Figure 4: Regulated vs Deregulated Electricity Market.

Wholesale vs Retail Electricity Market

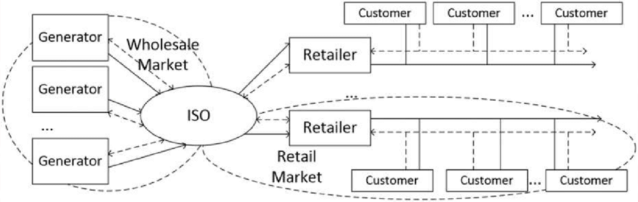


Figure 5: Relationships in Decentralized Markets

Grid Map

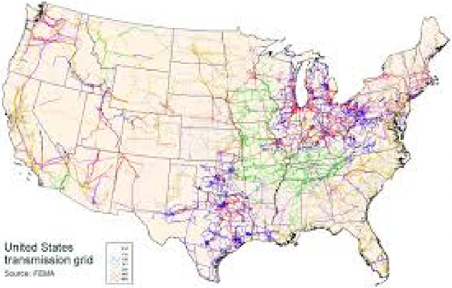


Figure 6: Current Electric Grid

Transmission Expansion

Figure 7: DC Making a comeback!

ISO Map

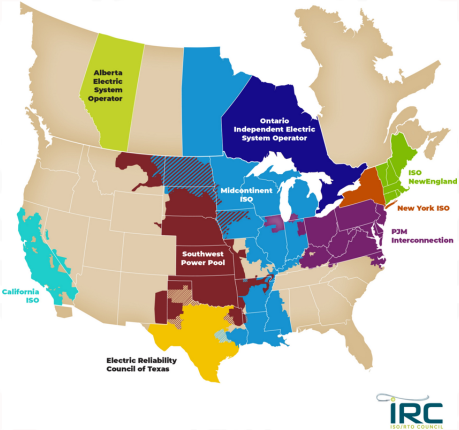


Figure 8: Three Grids, many markets

Types of Power Generation

Overview: Power generation can be classified based on the primary energy source and technology used to produce electricity.

Types of Generation:

- **Fossil Fuels:**
  - **Coal:** High carbon emissions, but historically dominant.
  - **Natural Gas:** Lower emissions, flexible, widely used in peaking plants.
  - **Oil:** Limited use, typically for backup or niche applications.
- **Renewable Energy:**
  - **Solar:** Harnesses sunlight, intermittent, requires storage or backup.
  - **Wind:** Utilizes wind turbines, intermittent, requires grid flexibility.
  - **Hydropower:** Reliable and long-lasting, but location-dependent.
  - **Biomass:** Uses organic materials, considered carbon-neutral.
- **Nuclear Power:**
  - Provides stable, large-scale baseload power with no direct emissions.
  - High upfront costs, long construction times.
- **Other Sources**

How the Fuel Mix Has Changed Over Time

Historical Trends:

- **Early Era:** Coal dominated due to its abundance and ease of transportation.
- **Mid-20th Century:**
  - Rise of oil and natural gas with advancements in extraction and pipelines.
  - Nuclear power emerged as a baseload source.
- **Recent Decades:**
  - Shift toward renewables driven by climate policies and falling costs.
  - Natural gas replaced coal in many regions due to lower emissions and cost-effectiveness.

Current Trends:

- Renewables (solar, wind) now represent the largest share of new capacity additions.
- Growing focus on energy storage and grid modernization.

Fuel Mix over Time

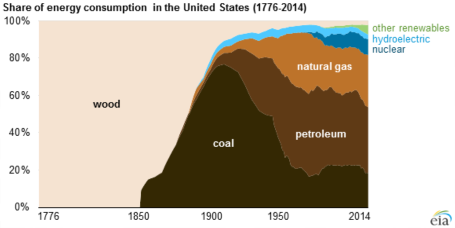


Figure 9: Let's go Solar!!!

Capacity Factors

Definition: The capacity factor measures how efficiently a power plant operates over a specific period compared to its maximum possible output.

$$\text{Capacity Factor} = \frac{\text{Actual Energy Generated}}{\text{Maximum Possible Energy}} \times 100\%$$

Key Points:

- **Actual Energy Generated:** The total electricity produced by the plant during the period (typically measured in MWh).
- **Maximum Possible Energy:** The plant's capacity multiplied by the total hours in the period.
- Expressed as a percentage, it provides insight into utilization.

Factors Impacting Capacity Factors

Typical Capacity Factors:

- **Nuclear:** 80–90%
- **Coal:** 40–70%
- **Wind:** 20–50%
- **Solar:** 10–30%

Factors Affecting Capacity:

- **Weather:** Impacts renewables like wind and solar.
- **Maintenance:** Downtime reduces capacity factor.
- **Demand:** If demand is low, plants may not operate at full capacity.

Example: Calculating Capacity Factor

Problem: A wind farm has a capacity of 100 MW and generates 175,200 MWh of electricity in a year. Calculate its capacity factor.

Solution:

- **Step 1: Calculate Maximum Possible Energy Output**

$$\text{Maximum Energy} = \text{Capacity} \times \text{Hours in a Year}$$

$$\text{Maximum Energy} = 100\,\text{MW} \times 8760\,\text{hours} = 876,000\,\text{MWh}$$

- **Step 2: Apply Capacity Factor Formula**

$$\text{Capacity Factor} = \frac{\text{Actual Energy Generated}}{\text{Maximum Possible Energy}} \times 100\%$$

$$\text{Capacity Factor} = \frac{175,200}{876,000} \times 100\% = 20\%$$

Conclusion: The wind farm operates at 20% of its full capacity over the year.

Cost of Electricity

Definition: The cost of electricity reflects the price required to produce and deliver electricity to consumers, covering all production, transmission, and distribution expenses.

Key Cost Components:

- **Capital Costs:** Initial investment in power plants, infrastructure, and equipment.
- **Operating and Maintenance (OM) Costs:** Regular expenses for running and maintaining power plants.
- **Fuel Costs:** For fossil fuel plants, fuel expenses dominate operational costs.
- **Transmission and Distribution Costs:** Costs to transport electricity from generation sites to consumers.

Importance:

- Determines competitiveness of different energy sources.
- Impacts electricity pricing for consumers and industries.

Example: Cost of Electricity Calculation

Problem: A power plant generates 1,000 MWh of electricity in a year. The total costs include:

- Capital Costs: \$500,000
- OM Costs: \$100,000
- Fuel Costs: \$50,000

Solution:

- **Step 1: Calculate Total Costs**

$$\text{Total Costs} = 500,000 + 100,000 + 50,000 = 650,000\,\$$$

- **Step 2: Calculate Cost per MWh**

$$\text{Cost per MWh} = \frac{\text{Total Costs}}{\text{Total Generation}}$$

$$\text{Cost per MWh} = \frac{650,000}{1,000} = 650\,\$/\text{MWh}$$

Conclusion: The cost of electricity for the plant is \$650 per MWh.

Factors Affecting Levelized Cost of Electricity (LCOE)

Definition: The LCOE is the average cost of electricity over a plant's lifetime, considering all costs and generation.

Key Factors:

- **Capital Costs:**
  - Cost of building the plant, including materials and labor.
  - Higher for renewable sources like wind and solar due to upfront investment.
- **Operating and Maintenance Costs:**
  - Regular expenses for operation and upkeep.
  - Vary by technology (e.g., low for solar, high for nuclear).
- **Fuel Costs:**
  - Relevant for fossil fuel plants, negligible for renewables.

Factors Affecting Levelized Cost of Electricity (LCOE)

- **Capacity Factor:**
    - Higher utilization reduces LCOE by spreading fixed costs over more output.
- **Discount Rate:**
    - Reflects the time value of money, impacting long-term cost estimates.

LCOE Calculation Formula

Levelized Cost of Electricity (LCOE) Formula:

$$\text{LCOE} = \frac{\sum_{t=1}^{T} \frac{I_t + O_t + F_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}}$$

Where:

- T: Project lifetime (in years).
- I_t: Investment costs in year t.
- O_t: Operating and maintenance costs in year t.
- F_t: Fuel costs in year t.
- E_t: Electricity generated in year t (MWh).
- r: Discount rate.

Interpretation:

- Numerator: Present value of total costs over the project lifetime.
- Denominator: Present value of total electricity generation.
- Units: Cost per MWh ($/MWh).

Example: LCOE Calculation

Problem: A solar plant has:

- Capital Cost (I): \$1,000,000
- Annual OM Cost (O): \$20,000
- No fuel costs ($F = 0$)
- Annual Generation (E): 5,000 MWh
- Project Lifetime (T): 20 years
- Discount Rate (r): 5%

Solution:

- **Step 1: Calculate Present Value of Costs**

$$\text{PV of Costs} = \frac{1,000,000}{(1+0.05)^0} + \sum_{t=1}^{20} \frac{20,000}{(1+0.05)^t} = 1,307,486$$

Example: LCOE Calculation

- **Step 2: Calculate Present Value of Generation**

$$\text{PV of Generation} = \sum_{t=1}^{20} \frac{5,000}{(1+0.05)^t} = 62,311\,\text{MWh}$$

- **Step 3: Calculate LCOE**

$$\text{LCOE} = \frac{1,307,486}{62,311} = 20.97\,\$/\text{MWh}$$

Conclusion: The LCOE for the solar plant is approximately \$20.97/MWh.

LCOE Sensitivity Analysis

Purpose: To understand how changes in key variables affect the Levelized Cost of Electricity (LCOE), helping stakeholders make informed decisions.

Key Parameters to Analyze:

- **Capital Costs:**
  - Impact of over- or under-budgeting for construction.
- **Operating and Maintenance (OM) Costs:**
  - Effect of higher or lower maintenance expenses.
- **Fuel Costs:**
  - Particularly important for fossil fuel-based generation.
- **Discount Rate:**
  - Captures the effect of financing and the time value of money.
- **Capacity Factor:**
  - Reflects variability in plant utilization due to operational or environmental factors.

Methods:

- **Scenario Analysis:** Evaluate LCOE under optimistic, baseline, and pessimistic scenarios.

Example: LCOE Sensitivity Analysis

Scenario: A wind farm project is evaluated for LCOE sensitivity to capital costs, capacity factor, and discount rate.

Baseline Assumptions:

- Capital Costs: \$1,500/kW
- Capacity Factor: 35%
- Discount Rate: 5%
- Operating Lifetime: 20 years
- OM Costs: \$30/kW/year

Sensitivity Results:

- **Impact of Capital Costs:**
    - If capital costs increase to \$1,800/kW, LCOE rises from \$50/MWh to \$60/MWh.
    - If costs decrease to \$1,200/kW, LCOE drops to \$40/MWh.

Frame Title

- **Impact of Capacity Factor:**
  - At 30% capacity factor, LCOE increases to \$58/MWh.
  - At 40%, LCOE decreases to \$43/MWh.
- **Impact of Discount Rate:**
  - At 7%, LCOE rises to \$55/MWh.
  - At 3%, LCOE decreases to \$45/MWh.

Conclusion: Capital costs and capacity factor are the most sensitive variables for this wind farm's LCOE.

Techno-Economic Analysis (TEA)

Definition: A comprehensive evaluation combining technical and economic factors to assess the feasibility, cost-effectiveness, and sustainability of a project or technology.

Key Components:

- **Technical Analysis:**
  - Evaluates system performance, efficiency, and scalability.
  - Includes assessments of technology readiness and operational feasibility.
- **Economic Analysis:**
  - Estimates capital costs, operating expenses, and revenues.
  - Includes metrics like net present value (NPV), levelized cost of electricity (LCOE), and payback period.

Applications:

- Renewable energy projects (e.g., solar farms, wind farms).
- Emerging technologies (e.g., battery storage, hydrogen production).
- Industrial processes and energy systems optimization.

Example: Techno-Economic Analysis for a Solar Farm

Scenario: Evaluate the feasibility of a 50 MW solar farm.

Technical Analysis:

- **Capacity Factor:** 25%.
- **Lifetime:** 25 years.
- **Degradation Rate:** 0.5% per year.
- **Annual Energy Output:**

$$E = \text{Capacity} \times \text{Capacity Factor} \times \text{Hours per Year}$$

$$E = 50\,\text{MW} \times 0.25 \times 8760 = 109,500\,\text{MWh/year}.$$

Example: Techno-Economic Analysis for a Solar Farm

Economic Analysis:

- **Capital Costs:** \$1,000/kW (\$50 million total).
- **OM Costs:** \$20/kW/year.
- **Discount Rate:** 6%.
- **Electricity Price:** \$50/MWh.
- **LCOE Calculation:**

$$\text{LCOE} = \frac{\sum \text{Discounted Costs}}{\sum \text{Discounted Energy Generation}} = 35\,\$/\text{MWh}.$$

- **NPV:**

$$\text{NPV} = \text{Discounted Revenues} - \text{Discounted Costs} = \$8\,\text{million}.$$

Conclusion:

- Technically viable with consistent energy output over 25 years.
- Economically competitive with a positive NPV and an LCOE below

Levelized Avoided Cost of Energy (LACE)

Definition: The LACE measures the economic value of electricity generated by a new resource compared to the cost of electricity it displaces or avoids in the grid.

Key Characteristics:

- Reflects the market value of energy from the new resource.
- Accounts for:
  - Wholesale electricity prices.
  - Avoided generation costs from displaced resources.
  - Grid reliability and resource availability.

Calculation:

$$\text{LACE} = \frac{\sum_{t=1}^{T} \frac{\text{Avoided Costs}_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{\text{Energy Generated}_t}{(1+r)^t}}$$

Example: LACE Calculation

Scenario: A 50 MW solar plant generates 109,500 MWh annually and avoids \$4.5 million in costs per year by displacing fossil fuel generation.

Parameters:

- **Avoided Cost per Year:** \$4,500,000.
- **Annual Energy Generation:** 109,500 MWh.
- **Project Lifetime:** 25 years.
- **Discount Rate:** 5%.

Example: LACE Calculation

Calculation:

- **Present Value of Avoided Costs:**

$$\text{PV Avoided Costs} = \sum_{t=1}^{25} \frac{4,500,000}{(1+0.05)^t} = 67,953,018\,\$$$

- **Present Value of Energy Generated:**

$$\text{PV Energy} = \sum_{t=1}^{25} \frac{109,500}{(1+0.05)^t} = 1,365,230\,\text{MWh}$$

- **LACE:**

$$\text{LACE} = \frac{\text{PV Avoided Costs}}{\text{PV Energy}} = \frac{67,953,018}{1,365,230} = 49.78\,\$/\text{MWh}.$$

Conclusion: The LACE of the solar plant is $49.78/MWh, reflecting its economic value in displacing fossil fuel generation.

Relationship Between LACE and LCOE

Key Relationship:

- Comparing LACE and LCOE provides a measure of economic viability for a new energy resource.
- **LACE $>$ LCOE:** The resource is economically attractive, as it provides greater value than its cost.
- **LACE $<$ LCOE:** The resource is less competitive economically.

Insights:

- **LCOE:** Measures the cost-effectiveness of generating electricity from a specific resource.
- **LACE:** Reflects the economic value of that electricity in the market.
- Together, they provide a holistic view of both cost and value, aiding investment decisions.

LACE Use Case: Policy and Investment Decisions

- Guides prioritization of projects based on economic competitiveness.
- Encourages deployment of resources that provide net benefits to the grid.

Example: If a wind farm has:

- LCOE = \$40/MWh.
- LACE = \$50/MWh.

Interpretation: The wind farm is economically viable and offers value to the grid.

Electricity Supply Curve

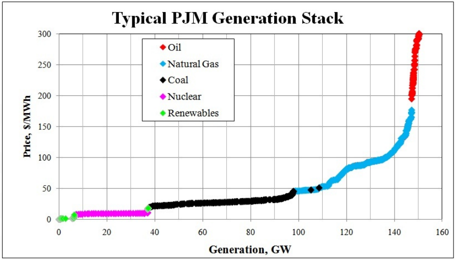


Figure 10: Supply Stack Based on Marginal Cost. Good?

Investments in Generation

Overview: Investments in power generation are driven by the need to meet energy demand, comply with regulatory requirements, and achieve economic returns. A critical metric used in evaluating these investments is the Levelized Cost of Electricity (LCOE).

Investment Decision Factors:

- **Capital Costs:**
  - Initial investment required to build the plant.
  - Includes land, equipment, and construction costs.
- **Operating Costs:**
  - Fixed costs (e.g., maintenance, staffing).
  - Variable costs (e.g., fuel expenses, emissions costs).
- **Regulatory and Policy Environment:**
  - Subsidies, tax incentives, and carbon pricing.
- **Market Conditions:**
  - Future energy prices and demand forecasts.
  - Competition from other generation sources.

LCOE and Investments in Generation

Role of LCOE:

- **Definition:** LCOE represents the average cost per unit of electricity generated over the lifetime of a generation asset.

$$\text{LCOE} = \frac{\text{Total Costs (Capital + Operating)}}{\text{Total Electricity Generated}}$$

- **Purpose:**
  - Facilitates comparison of different generation technologies (e.g., solar, wind, coal).
  - Accounts for the time value of money by discounting future costs and generation.
- **Limitations:**
  - Does not account for system-level impacts (e.g., intermittency, grid integration costs).
  - Assumes fixed generation and cost structure over time.

Conclusion: LCOE provides a standardized metric to guide investment decisions, but must be used alongside other considerations such as market

Overview of Transmission

What is Transmission?

- Transmission is the process of transporting electricity from generation facilities to distribution systems.
- Operates at high voltages to minimize energy losses over long distances.
- Connects generation plants to consumers via a network of transmission lines and substations.

Key Components of Transmission

- **Transmission Lines:**
  - High-voltage lines (e.g., 230 kV, 500 kV) for long-distance transmission.
  - Alternating Current (AC) and Direct Current (DC) lines.
- **Substations:**
  - Step-up transformers increase voltage for transmission.
  - Step-down transformers reduce voltage for distribution.
- **Control Centers:**
  - Manage grid stability, load balancing, and system reliability.
  - Use real-time monitoring and dispatch systems.

Challenges in Transmission

- **Congestion:** Limited capacity in high-demand regions.
- **Losses:** Energy loss due to resistance in lines.
- **Integration of Renewables:** Variable generation (solar, wind) requires grid flexibility.
- **Infrastructure Costs:** High cost of building new lines and upgrading existing ones.

Future Trends:

- Smart grids and advanced transmission technologies.
- Expansion of high-voltage direct current (HVDC) systems.
- Focus on interregional transmission to integrate renewable energy resources.

Conclusion: Transmission is the backbone of the electric grid, ensuring the reliable delivery of power while adapting to evolving energy demands and technologies.

The Optimal Dispatch Problem

What is the Optimal Dispatch Problem?

- The optimal dispatch problem determines the most cost-effective way to meet electricity demand while adhering to operational constraints.
- Objective: Minimize the total cost of generation while ensuring supply meets demand.

The Optimal Dispatch Problem

- **Objective Function:**

$$\text{Minimize: } \sum_i C_i(G_i)$$

where:

  - $C_i(G_i)$: Cost of generating power G_i at generator i.

Optimal Dispatch Problem Constraints

- **Constraints:**
  - **Power Balance:**

    $$\sum_i G_i = D$$

    Total generation must equal total demand D.
  - **Generator Limits:**

    $$G_i^{\text{min}} \leq G_i \leq G_i^{\text{max}}$$

    Each generator operates within its capacity limits.
  - **Transmission Constraints:**

    $$F_{ij} \leq F_{ij}^{\text{max}}$$

    Power flows F_{ij} between nodes must not exceed line capacity.

The Optimal Dispatch Problem

Solution Approach:

- Formulated as a linear programming (LP) or mixed-integer programming (MIP) problem.
- Solved using optimization techniques like simplex or interior-point methods.

Applications:

- Day-ahead and real-time electricity market operations.
- Optimal resource allocation during peak demand or contingencies.

Conclusion: The optimal dispatch problem ensures the efficient, reliable, and cost-effective operation of power systems under technical and market constraints.

Locational Marginal price (LMP)

- LMP is marginal cost of last economically dispatched generator
    - LMP=Cost of Energy+Line Losses+Cost of Congestion
- If no constraints, all prices equal
- With transmission constraints, some prices higher

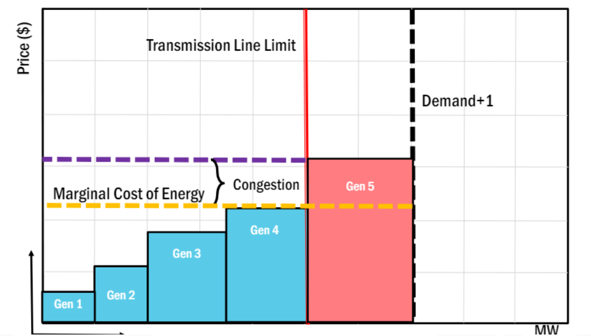


Figure 11: Locational Marginal Price. Source: NYISO

Congestion in Power Systems

What is Congestion?

- Congestion occurs when transmission lines cannot accommodate all desired electricity flows due to capacity limits.
- Results in differences in electricity prices across locations (locational marginal prices, or LMPs).

Causes of Congestion:

- High demand in certain regions exceeding local generation.
- Insufficient transmission infrastructure.
- Increased renewable generation in remote areas, requiring long-distance transport.
- Line outages or maintenance reducing available capacity.

Congestion in Power Systems

Impacts of Congestion:

- Higher electricity costs in constrained areas.
- Inefficient dispatch of generators (out-of-merit order).
- Curtailment of renewable energy generation.

Estimated Costs:

- U.S. electricity markets face congestion costs ranging from $5 billion to $10 billion annually (source: FERC, recent ISO reports).
- Example: In 2023, PJM reported $2.3 billion in congestion costs due to high demand and transmission constraints.
- Congestion costs account for a significant portion of total electricity market expenses.

Fixing Congestion

- Investment in new transmission lines and upgrades.
- Demand response programs to reduce peak loads.
- Energy storage to alleviate localized supply-demand imbalances.

Conclusion: Congestion represents a major operational and economic challenge for power markets, emphasizing the need for infrastructure investment and smart grid solutions.

LMP No Constraint

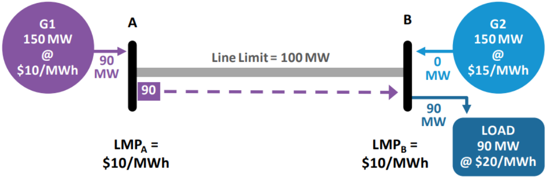


Figure 12: Prices equalize before losses

Congestion in LMP Network

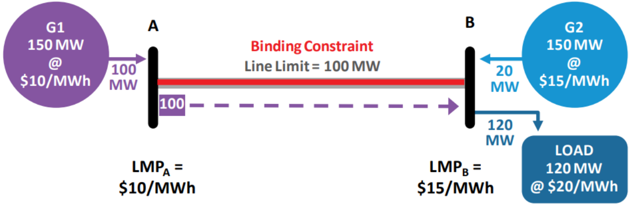


Figure 13: Congestion!

Potential for Renewable Generation by County

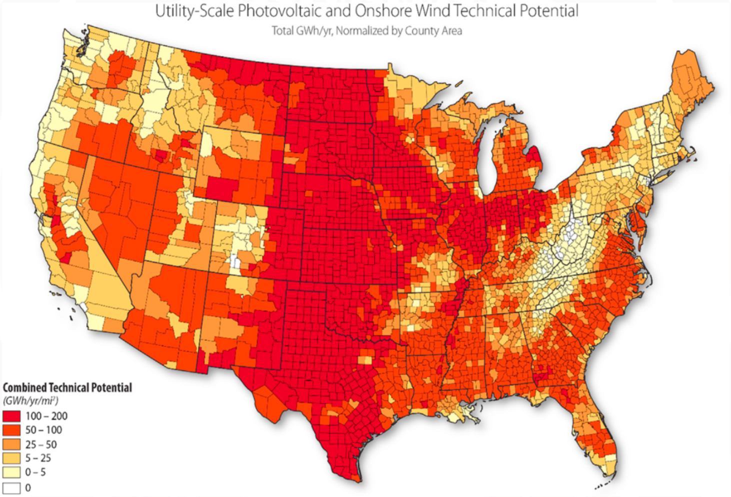


Figure 14: Potential for Wind and Solar Generation by County. Source: DoE

Current Renewable Capacity by Zone

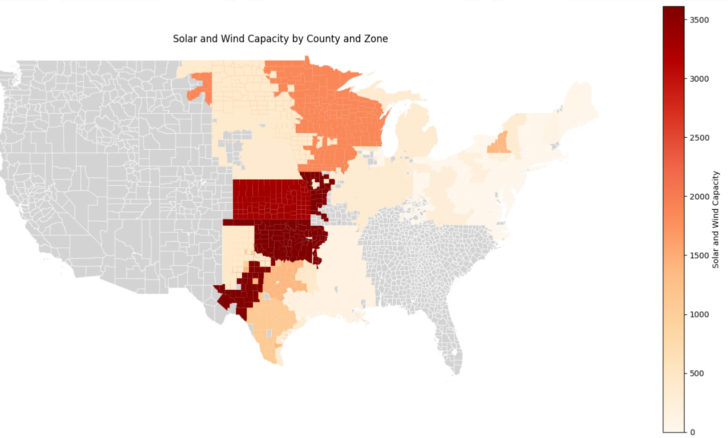


Figure 15: Solar and Wind Capacity by Zone.

Map of Prices by Zone

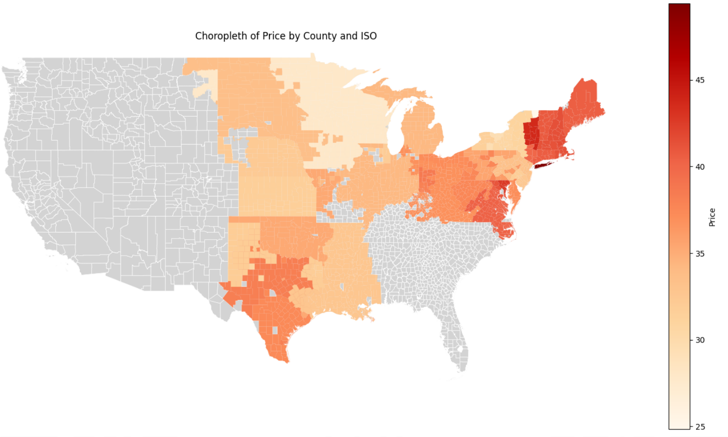


Figure 16: Prices by Zone.

Price Differential across Time and Space

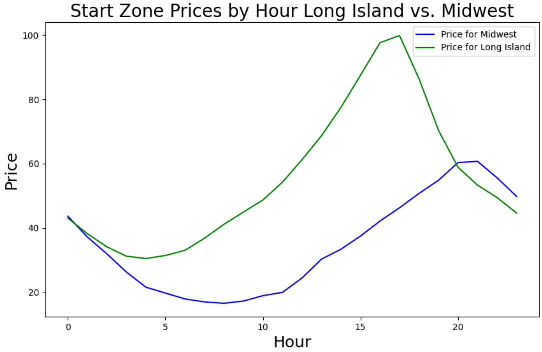


Figure 17: Price Differential by Hour.

Champlain Hudson Power Express

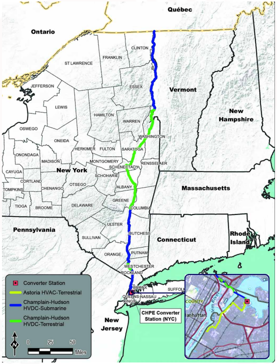


Figure 18: We love you Quebec Hydro!

Thank You So Much!

List of References