Power and Energy Systems: Key Insights for a Sustainable Future

By Dr. Jeff Kleck

As we stand on the brink of unprecedented technological advancement and a pressing need for secure solutions, the transition to optimized energy sources has never been more crucial. This paper explores the current landscape of the energy sector and energy sources, evaluating their cost efficiency, land requirements, carbon dioxide equivalent emissions per kilowatt-hour (kWh), and capacity factor. Drawing inspiration from successful models and pioneering advancements in energy technologies, we propose a comprehensive vision for transforming energy systems.

The Power of Diverse Energy Sources:
Our vision embraces a diverse portfolio of energy sources, acknowledging that no singular solution is sufficient to meet rising energy demands and secure energy independence. Instead, a strategic combination of technologies is essential to creating resilient, adaptable power systems. Leveraging a spectrum of energy technologies, including fossil fuel, wind, solar, nuclear, geothermal, hydroelectric, and biofuels enables the U.S. to create resilient, self-sustaining energy systems. These systems optimize land use, lower operational costs, and minimize carbon footprints, all while ensuring energy security.

Each energy source contributes uniquely to this vision. Wind and solar power offer intermittent but abundant clean energy. Where they are available, geothermal and hydroelectric systems provide renewable options that generate continuous power, regardless of immediate weather conditions. Pairing these renewables with nuclear energy and natural gas, which provide a reliable baseload, can ensure a constant and stable energy supply. Meanwhile, advances in energy storage and microgrid technologies allow for better integration of these intermittent sources, reducing dependence on fossil fuels.

The energy landscape of the future will be decentralized, with power generated closer to where it is consumed. This approach not only minimizes transmission losses but also empowers local economies by reducing reliance on large, centralized power stations. By tailoring energy solutions to each region’s specific needs and resources, we can design more efficient systems that capitalize on the strengths of each energy source while mitigating their individual weaknesses. This flexible, diversified approach creates an energy infrastructure that is not only more sustainable but also more resilient to disruptions, making it adaptable to both technological advances and environmental challenges.

Evaluating Energy Sources:
To determine the most viable energy sources, we must consider several key factors:

1. Base Cost of Source Material per kilowatt-hour (kWh) - cost of the source material being used to generate energy (i.e. solar, water, oil, coal, etc.)
2. Land Requirements per kWh - land surface area required to generate energy
3. Carbon Dioxide Equivalent Emissions per kWh - how much carbon dioxide equivalents are released per kWh including all factors
4. Carbon Dioxide Equivalent Emissions per kWh from combustion only - the amount of carbon dioxide equivalents released solely due to combustion, representing unavoidable emissions inherent to the energy source
5. Capacity Factor of the energy source - the actual output of a power plant as a percentage of its maximum potential output

Cost Efficiency for Energy Sources:
Cost efficiency is a critical metric, as electricity underpins countless processes that can become uneconomical with even slight increases in energy costs. The table below summarizes the base energy source cost per kWh for various sources used in power production, ordered from lowest to highest. These numbers only include the cost of the energy source and do not factor in maintenance, regulation, material costs for the facility, etc:

Energy Source	**Base Cost (USD per kWh)**	**Times More Cost Than Lowest (non-zero)**
Geothermal	0.0	NA
Hydroelectric	0.0	NA
Solar PV	0.0	NA
Wind	0.0	NA
Nuclear (SMR)	0.003	Lowest (non-zero)
Nuclear (Conventional)	0.0054	1.8
Coal	0.026	8.7
Natural Gas	0.056	23
Biofuels (E85)	0.13	43
Oil	0.19	83

All data normalized to 2022 to ensure consistency, except SMR data which is normalized to 2024

Explanation:

- Geothermal, Hydroelectric, Solar PV, Wind: These sources have no ongoing cost for the source material itself, as they rely on natural, renewable inputs (sunlight, wind, water flow, and geothermal heat).
- Nuclear (SMR): Assumes the model is in production and this is the cost of making one more unit (NOAK) and factory fabrication and fully modular construction.
- Nuclear (Conventional): Includes the cost of mining, processing, and preparing nuclear fuel.
- Coal, Natural Gas, Oil: Includes the cost of extracting and processing the respective fossil fuels.
- Biofuels: Considers the cost of growing, harvesting, and processing corn to produce pure ethanol and extracting oil and processing it into gasoline to mix with the ethanol in a 85% ethanol, 15% gasoline formula.

References and Data Sources:
Nuclear Energy Institute, 2022; U.S. Energy Information Administration, 2022; U.S. Department of Energy, 2022; Aalo Atomics, 2024

Land Requirements for Power Systems:
Land availability poses a significant constraint on power generation, as energy is ideally produced near its point of consumption. And High-demand areas, like cities, often experience intense competition for their limited land. The table below highlights the land requirements for various energy sources, considering the entire surface area required for resource extraction, processing, etc.and not factoring in dual use:

Energy Source	**Land Use (km² per kWh)**	**Times More Land Use Than Lowest**
Nuclear (SMR)	1.3×10^{-10}	Lowest
Nuclear (Conventional)	1.9×10^{-10}	1.5
Natural Gas	8.3×10^{-10}	6.4
Coal	3.0×10^{-9}	23
Geothermal	4.0×10^{-9}	31
Oil (Onshore)	7.1×10^{-9}	55
Solar PV	8.0×10^{-9}	62
Wind	3.2×10^{-8}	250
Biofuels (E100)	3.3×10^{-6}	2600
Hydroelectric	6.7×10^{-7}	5200

All data normalized to 2022 to ensure consistency, except SMR data which is normalized to 2024

Explanation:

- Nuclear (SMR): Land use is lower for (advanced) SMR vs conventional nuclear, because EPZ is smaller.
- Nuclear (Conventional): Includes land for mining, waste management, and plants.
- Natural Gas: includes land for mining, pipelines, and plants.
- Coal: Includes land for mining, transport, and plants.
- Geothermal: Includes the land used by geothermal plants and associated infrastructure.
- Oil: Includes the land needed for the onshore wells, refineries and plants.
- Solar PV: Includes land for solar panel installations, including the land area directly covered by panels and space between them.
- Wind: Considers the entire wind farm space, not factoring in dual-use.

- Biofuels(E100): Includes the farmland for growing the corn, the land needed for processing the corn into pure ethanol (no gasoline added), and the land needed for the plants. E100 is included here to give a snapshot into the agricultural side of production, where in other tables it would be impractical to do so.
- Hydroelectric: Includes land for reservoirs, dam structures, and associated infrastructure.

References and Data Sources:
U.S. Energy Information Agency, 2022; U.S Geological Survey, 2022; U.S. Bureau of Land Management, 2022; Aalo Atomics, 2024

Lifecycle Carbon Dioxide (CO_2) Equivalent Emissions for Energy Sources:
Decarbonizing energy systems requires prioritizing low-carbon sources. The table below shows the carbon dioxide (CO_2) equivalent emissions for different energy sources, including combustion, processing, waste management, etc. ordered from lowest to highest:

Energy Source	CO_2 Equivalent (g per kWh)	Times More CO_2 Than Lowest
Nuclear (SMR)	9	Lowest
Nuclear (Conventional)	13	1.4
Wind	13	1.4
Hydroelectric	21	2.3
Geothermal	37	4.1
Solar PV	43	4.8
Biofuels (E85)	270	30
Natural Gas	490	54
Oil	920	102
Coal	1040	116

Data normalized to 2019 for Biofuels; Data normalized to 2021 for Geothermal, Wind, Hydroelectric, Solar PV, Nuclear, Natural Gas; Data normalized to 2023 for Oil and Coal, Data normalized to 2024 for SMR

Explanation:

- Nuclear (SMR): Carbon emissions are lower for SMRs, because less concrete and steel is required per MW capacity than traditional nuclear.
- Nuclear (Conventional): Emissions include the fuel cycle (mining, processing), operation, and waste management (handling and disposing of radioactive waste).
- Wind, Hydroelectric, Geothermal, Solar PV: Emissions cover manufacturing, installation, maintenance, and end-of-life disposal of equipment.
- Biofuels: Accounts for the full lifecycle emissions, including the growth, harvesting, processing, transportation, combustion of biomass, handling of residual biomass, land-use changes, and the extraction of oil and processing into gasoline.
- Natural Gas, Oil, Coal: Emissions include extraction, processing, combustion, and waste management (e.g., ash disposal for coal).

References and Data Sources:

U.S. Department of Agriculture, 2018; U.S. Environmental Protection Agency, 2022; U.S. Energy Information Administration, 2023; National Renewable Energy Laboratory, 2021; Aalo Atomics, 2024

Carbon Dioxide (CO_2) Equivalent Emissions for Energy Sources - Combustion Alone:
Decarbonizing energy systems requires prioritizing low-carbon sources. The table below shows the carbon dioxide (CO_2) equivalent emissions for different energy sources, only counting combustion of the fuel source if applicable:

Energy Source	**CO_2 Equivalent (g per kWh)**	**Percent of Total Lifecycle CO_2**
Nuclear (SMR)	0	0%
Nuclear (conventional)	0	0%
Wind	0	0%
Hydroelectric	0	0%
Geothermal	0	0%
Solar PV	0	0%
Biofuels (E85)	230	85%
Oil	250	51%
Natural Gas	390	42%
Coal	1010	97%

All data normalized to 2024 to ensure consistency

Explanation:

- Nuclear (SMR), Nuclear (Conventional), Wind, Hydroelectric, Geothermal, Solar PV: No hydrocarbons are combusted for energy production from these fuel sources.
- Biofuels, Oil, Natural Gas, Coal: these materials are combusted to produce energy, and in the process, carbon dioxide (CO_2) equivalents are released into the atmosphere.

References and Data Sources:
Environmental Protection Agency, 2024

Capacity Factor for Energy Sources:
Capacity factor is a crucial metric in evaluating the efficiency and reliability of different energy sources. It represents the actual output of a power plant as a percentage of its maximum potential output, or "nameplate capacity". A higher capacity factor indicates a more reliable and consistent energy source, while a lower capacity factor suggests variability and dependence on environmental conditions.This is important when transitioning to energy sources that have a different capacity factor than what is currently in place, especially when it is lower. The table below outlines the capacity factors for various energy sources:

Energy Source	Capacity Factor (%)	Inefficiency versus Best
Nuclear (SMR)	>95	Best
Nuclear (conventional)	93	2.1%
Geothermal	69	27%
Biofuels	60	37%
Natural Gas	59	38%
Coal	42	56%
Wind	36	62%
Hydroelectric	36	62%
Solar PV	25	74%
Oil	11	88%

All Data normalized to 2022 to insure consistency, except SMR data which is normalized to 2024

Explanation:

- Nuclear (SMR and Conventional): Both small modular reactors (SMRs) and traditional nuclear power plants have high capacity factors, reflecting their ability to operate continuously and provide a steady, reliable supply of power.
- Geothermal: Geothermal plants also have a relatively high capacity factor, as they can generate power continuously, independent of weather conditions.
- Biofuels (E85): The capacity factor for biofuels is moderate, influenced by the availability of raw materials and the efficiency of combustion processes.

- Natural Gas (Combined Cycle): Combined cycle natural gas plants are efficient, with a capacity factor reflecting their ability to quickly ramp up and down to meet demand. Data is for combined cycle only.
- Coal: Coal plants have a lower capacity factor due to economic and environmental pressures that limit their operation.
- Wind: Wind power has a variable capacity factor, heavily influenced by wind availability, which can be inconsistent across different regions and times.
- Hydroelectric: Hydroelectric plants have a similar capacity factor to wind, with output depending on water flow, which can vary seasonally.
- Solar PV: Solar photovoltaic systems have a lower capacity factor due to their dependence on sunlight, which varies daily and seasonally.
- Oil (Steam Turbine): Oil-fired steam turbines have the lowest capacity factor, reflecting their limited use due to high operating costs and environmental concerns. Data is for steam turbine only.

Importance of Capacity Factor:
Capacity factor is a key consideration for determining the suitability of different energy sources for specific roles within the power grid. High-capacity factor sources like nuclear and geothermal are ideal for baseload power, providing a consistent supply to meet the minimum demand. Conversely, sources with lower capacity factors, such as wind and solar, are better suited for supplementing baseload power during periods of high demand. However, they require storage or backup generation to ensure reliability.Understanding capacity factors helps in planning and optimizing the energy mix to balance cost, reliability, and environmental impact, supporting the transition to a more sustainable and resilient power grid.
References and Data Sources:

References and Data Sources:
U.S. Energy Information Administration, 2022; NuScale Power 2024

Energy Consumption by Sector:
Understanding power consumption by sector is imperative for optimizing energy systems and addressing the needs of different industries. The growing momentum for electrifying energy-intensive systems, such as personal vehicles, necessitates assessing the impact on electrical infrastructure and identifying the changes required to accommodate this transition. The table below provides a breakdown of power consumption by sector in the U.S., highlighting the dominant users and offering insights into how different sectors contribute to overall energy demand:

Sector	**Energy (kWh)**	**Percent of U.S. Energy Consumption (%)**
Electrical	9.34×10^{15}	34%
Transportation	8.25×10^{15}	30%
Industrial	6.60×10^{15}	24%
Residential	1.92×10^{15}	7%
Commercial	1.37×10^{15}	5%
TOTAL	**2.74×10^{16}**	**100%**

All Data normalized to 2023 to ensure consistency

Electrical Power Sector Spotlight: Electricity sales to consumers account for approximately 3.87×10^{15} kWh, or 41% of the electricity sector's energy usage. The other 5.54×10^{15} kWh, or 59% of the sector’s energy consumption are various losses.

Leading Causes of Loss: The largest source of energy loss is the conversion of heat energy from combustion for hydrocarbon fuels or the steam from nuclear plants into electrical energy. While this remains a significant inefficiency, new technologies that could bypass the need to convert into heat energy could greatly improve efficiency. It should be noted that this does not apply to solar, wind, hydroelectric, etc. because their source terms are converted directly into electrical energy. Additionally, transmission line losses represent a smaller but still substantial portion of energy wastage. Transitioning to decentralized microgrids, which reduce reliance on long-distance transmission, offers a promising solution for mitigating these losses.

References and Data Sources:
U.S. Energy Information Administration, 2023

Conclusion:
By embracing a diverse array of energy sources and strategically integrating them into our energy systems, we can achieve a transformation that is resilient, energy-independent, and adaptable to future challenges. Decentralized energy solutions, such as microgrids, further enhance this transformation by reducing transmission losses, enhancing resilience against disruptions, and empowering communities to take control of their energy needs.

For more information on sustainable energy collaborations, please contact Dr. Jeff Kleck at Jeff@OpenPowerEnergy.Net.

Citations

- U.S. Energy Information Administration
- U.S. Department of Energy
- Aalo Atomics (Contributed Data)
- U.S. Department of Agriculture
- U.S. Environmental Protection Agency
- National Renewable Energy Laboratory
- U.S. Geological Survey
- U.S Bureau of Land Management
- NuScale Power

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