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ISSUE BRIEF

Transitioning to the Clean Energy Grid: A Deep Dive into the Levelized Cost of Electricity

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Background

The US electricity system is at an inflection point. The current and future impacts of the climate crisis require the world to transition rapidly from fossil fuels to renewable energy. Renewable power is well positioned to meet energy transition goals, as renewable generators now produce electricity at a lower cost than fossil fuel generators, according to studies of the levelized cost of electricity (LCOE).[1] LCOE measures the average, net present cost at which a generator produces each unit of electricity over the asset's lifetime, measured in dollars per megawatt-hour (MWh).

While this metric is a critical tool for understanding the costs of generating electricity, it accounts for neither the cost of ensuring the reliability of intermittent renewable energy nor the cost of delivering that electricity to the consumer. As they stand, the aging US electric transmission system and the associated planning and permitting processes are not capable of meeting the demands of a new clean energy system. Electric power transmission lines are, on average, forty years old, with more than a quarter of projects built more than fifty years ago and 70 percent of lines more than twenty-five years old.[2] These decades-old transmission lines will in many cases need to be rebuilt or retrofitted even without the addition of renewable energy, but the intermittent, decentralized characteristics of renewable generation require that the grid be expanded with many new interconnection points and data-driven technologies that make the grid "smarter."[3]

The Atlantic Council **Global Energy Center** develops and promotes pragmatic and nonpartisan policy solutions designed to advance global energy security, enhance economic opportunity, and accelerate pathways to net-zero emissions.

1 Michael Taylor, Pablo Ralon, and Sonia Al-Zoghoul, *Renewable Power Generation Costs in 2021*, International Renewable Energy Agency (IRENA), July 2022, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jul/IRENA_Power_Generation_Costs_2021.pdf.

2 Christine Oumansour et al., "Modernizing Aging Transmission," *Public Utilities Fortnightly*, April 2020, https://www.marshmclennan.com/insights/publications/2020/apr/modernising-ageing-transmission.html?bsrc=mmc or for subscribers, https://www.fortnightly.com/fortnightly/2020/04/modernizing-aging-transmission; and Office of Electricity, "DOE Launches New Initiative from President Biden's Bipartisan Infrastructure Law to Modernize National Grid," US Department of Energy, January 12, 2022, https://www.energy.gov/oe/articles/doe-launches-new-initiative-president-bidens-bipartisan-infrastructure-law-modernize.

3 Jay Caspary and T. Bruce Tsuchida, "Unlocking the Queue with Grid Enhancing Technologies Case Study–Southwest Power Pool Study Approach," The Brattle Group, January 27, 2021, https://www.brattle.com/wp-content/uploads/2021/06/21200_unlocking_the_queue_with_grid_enhancing_technologies.pdf.

The planning and permitting process for new transmission lines is also highly inefficient and needs reforming. Applications for new transmission lines take five to ten years or longer to undergo review and approval. Reforms that shorten this lengthy timeline for project approvals would lower costs and enable a more rapid transition to a clean energy system. How the electric power industry rebuilds and expands the nation's electric power systems to utilize the cheapest form of electricity—in this case renewable power—at the lowest cost possible is a central challenge in the transition to net zero.

This is the first in a series of three issue briefs that will analyze these issues. This one reviews the most commonly used metric—the LCOE—that financial institutions, businesses, government agencies, intergovernmental organizations, nongovernmental organizations, and academic researchers use as an input within a larger model or as a direct proxy for comparing the cost of generating electricity using different technologies. Along with the urgency of addressing the climate crisis, the low cost of electricity generated by renewables relative to fossil fuels creates a strong economic incentive to rebuild the electric power system to take advantage of more cheaply generated electricity from renewable sources—supporting one of the cornerstones of addressing the climate crisis.

This paper goes further than analyzing the comparative cost of generating renewable energy. It also analyzes alternative metrics that assess the relative "value" of electricity generators to the power system and the whole system costs of reliably delivering electricity to consumers. The studies show that in some cases, the cost of integrating new renewable energy onto the grid can add substantial costs. They also enable power companies and policymakers to better understand which stages in the energy development process present cost-reduction opportunities that can further lower the price of delivering renewable energy.

The second issue brief will analyze how we can rebuild the system to deliver renewable energy at the lowest possible cost. It will consider the costs of integrating intermittent renewable generators into the transmission and distribution system, including planning, permitting, and reliability issues, how these costs affect the competitiveness of renewable energy, and what can be done to reduce these costs.

The third paper will discuss strategies for effectively communicating the costs and benefits of transitioning to renewable energy. Today's contentious political environment obscures the real costs and economic benefits of the transition. Complicating this picture further is the inherent difficulty in explaining the costs of competing sources of energy, which are not transparent. New narratives are required to make these costs as clear as possible.

Introduction

The latest report (2023) from the Intergovernmental Panel on Climate Change (IPCC) makes it crystal clear that the world has little time to transition to a clean energy economy and address the climate crisis:

> Climate change is a threat to human well-being and planetary health (very high confidence). There is a rapidly closing window of opportunity to secure a livable and sustainable future for all (very high confidence).[4]

Achieving a rapid transition to a clean energy economy will depend significantly on the extent to which renewable energy generators can outcompete fossil fuels. Renewable electricity generation has become cost competitive with fossil fuels due to technological maturation and economies of scale, and has surpassed conventional sources as the cheapest form of power in the United States and in many parts of the world. Coal power has been the first fossil fuel source to lose its competitive edge. In the United States, replacing the existing coal fleet with new wind and solar projects would generate cheaper electricity in 99 percent of cases.[5] Natural gas is 33 percent more expensive to generate than solar power and 44 percent more expensive to generate than onshore wind power on average in the United States.[6] In the Group of Twenty nations, almost two-thirds of installed renewable generating capacity in 2021 was less expensive

4 Hoesung Lee et. al., *AR6 Synthesis Report: Climate Change 2023*, Intergovernmental Panel on Climate Change, March 2023, https://www.ipcc.ch/report/sixth-assessment-report-cycle/.

5 Michelle Solomon et al., *Coal Cost Crossover 3.0: Local Renewables plus Storage Create New Opportunities for Customer Savings and Community Reinvestment*, Energy Innovation Policy and Technology LLC, February 2, 2023, https://energyinnovation.org/publication/coal-cost-crossover-3-0-local-renewables-plus-storage-create-new-opportunities-for-customer-savings-and-community-reinvestment/.

6 Angel Adegbesan, "Solar Is Now 33% Cheaper Than Gas Power in US, Guggenheim Says," Bloomberg, October 3, 2022, https://www.bloomberg.com/news/articles/2022-10-03/solar-is-now-33-cheaper-than-gas-power-in-us-guggenheim-says.

A view of windmills and power lines near Tracy, California, August 2022. REUTERS/Carlos Barria.

than the cheapest coal-fired power option available.[7] As a market signal of renewable energy's competitiveness, the IEA estimates that global investment in clean energy will reach 1.7 trillion dollars in 2023, far exceeding the investment in fossil fuels of just over a trillion dollars.[8]

LCOE validates the conclusion in these studies and others that globally, electricity is less expensive to generate using renewables instead of fossil fuels. The metric does not, however, address whole-system costs. A determination of the overall competitiveness of renewables requires a comprehensive evaluation of system integration costs, which includes the costs of building transmission infrastructure, maintaining system reliability, regulatory and compliance activity, financing, and utility and operator fees. In addition, the social cost burdens of fossil fuel energy, which degrade environmental and health outcomes, are absent from most analyses. Without an understanding of whole system costs, countries risk underdelivering on their renewable penetration commitments.

Cost Factors: What the LCOE Does and Does Not Capture

Comparing the costs of electricity generation projects is a complex exercise due to major differences in their components' prices. Hydroelectric dams have different cost profiles from solar farms, which in turn are different from wind farms, coal plants, or natural gas combined-cycle power plants.

The standard measurement that attempts this calculation and receives the most attention is the LCOE. It measures the total lifetime cost of a generation project with all its cost components divided by the total production of electricity, measured in dollars per MWh, or the average price per MWh at which a plant must sell generated

7 "38 Countries Launch Global Geothermal Alliance," IRENA, December 8, 2015, https://www.irena.org/news/pressreleases/2015/Dec/38-Countries-Launch-Global-Geothermal-Alliance.

8 "Clean Energy Investment Is Extending Its Lead Over Fossil Fuels, Boosted by Energy Security Strengths," International Energy Agency (IEA), May 25, 2023, https://www.iea.org/news/clean-energy-investment-is-extending-its-lead-over-fossil-fuels-boosted-by-energy-security-strengths.

electricity to break even. The simplified LCOE formula calculates the sum of a project's upfront capital costs, fixed and variable operations and maintenance (O&M) costs, and fuel costs over the lifetime of the project and then divides that by total electricity produced to yield the average price at which the project would need to sell each MWh of electricity to break even:

$$\frac{\text{Total lifetime capital cost + O\&M costs + fuel costs}}{\text{Total lifetime electricity produced}}$$

More complex LCOE calculations can also include variables such as government incentives, taxes, system degradation, or more granular location-specific factors.

Renewable technologies typically have high upfront costs, which include the cost of buying materials and building facilities—but much lower operating costs, given that fuel costs are negligible. By contrast, fossil fuel technologies are characterized by higher operating costs, as operators must supply fuel to the plant.

LCOE trends

LCOE data show that the cost of wind, solar, and other renewable sources of electricity have fallen significantly. Since 2009, the unsubsidized LCOE of utility-scale solar projects has fallen from a global average of $369 per MWh to $60/MWh in 2023, according to Lazard.[9] The unsubsidized LCOE of onshore wind projects has fallen from a global average of $135/MWh in 2009 to $50/MWh in 2023.[10] The global average unsubsidized LCOE of geothermal power was $82/MWh in Lazard's 2023 report, although its relatively higher costs are offset by its value to the grid as a baseload generator.[11] Offshore wind remains more expensive at $106/MWh in 2023, but can be as cheap as $72/MWh in certain markets, or as high as $140/MWh.[12] Innovative research in technology, manufacturing, and design lowered renewable project costs. As renewable projects proliferated, developers benefited from economies of scale and gained operating experience that further reduced prices.

The levelized costs of coal and natural gas power did not mirror the cost trajectory of renewable energy. Coal power has oscillated around $111/MWh since 2009 and was $117/MWh in 2021.[13] Natural gas power costs decreased from $83/MWh in 2009 to $70/MWh in 2021.[14] Fossil fuel power plants are mature technologies, so they do not benefit from the same technological maturation as renewables. Currently, only one coal plant in the United States is cheaper to run than it would be to replace it with new wind and solar projects.[15] In China, India, and Germany, new solar projects would be cheaper to run than existing coal or gas-fired plants, while the same is true about wind projects in Brazil, the United Kingdom, Poland, and Morocco.[16] Overall, if installed where there is need, renewable energy could be the cheapest power option for 67 percent of the world population.[17] The data are clear that renewable electricity generation is cheaper than fossil fuel electricity generation.

Factors beyond LCOE

Despite LCOE's utility, the metric cannot predict how countries will invest in energy. The LCOE of coal, for example, is much higher than that of renewables, yet some countries continue to install new coal capacity. Indonesia is allowing the construction of coal plants due to a regulatory loophole, legacy political influence of extractive industries, and an immediate need for energy—ironically, to power its "green industrial park."[18] China built six times as many coal plants as the rest of the world in 2022 to meet power demand after a drought reduced

9 "Levelized Cost of Energy+," Lazard, April 2023, https://www.lazard.com/research-insights/levelized-cost-of-energyplus/.

10 "Levelized Cost," Lazard.

11 "Levelized Cost," Lazard; Jack Kiruja et al., *Global Geothermal Market and Technology Assessment*, ed. Steven Kennedy, IRENA and International Geothermal Association, February 2023, https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Feb/IRENA_Global_geothermal_market_technology_assessment_2023.pdf.

12 "Levelized Cost," Lazard.

13 "Levelized Cost," Lazard.

14 "Levelized Cost," Lazard.

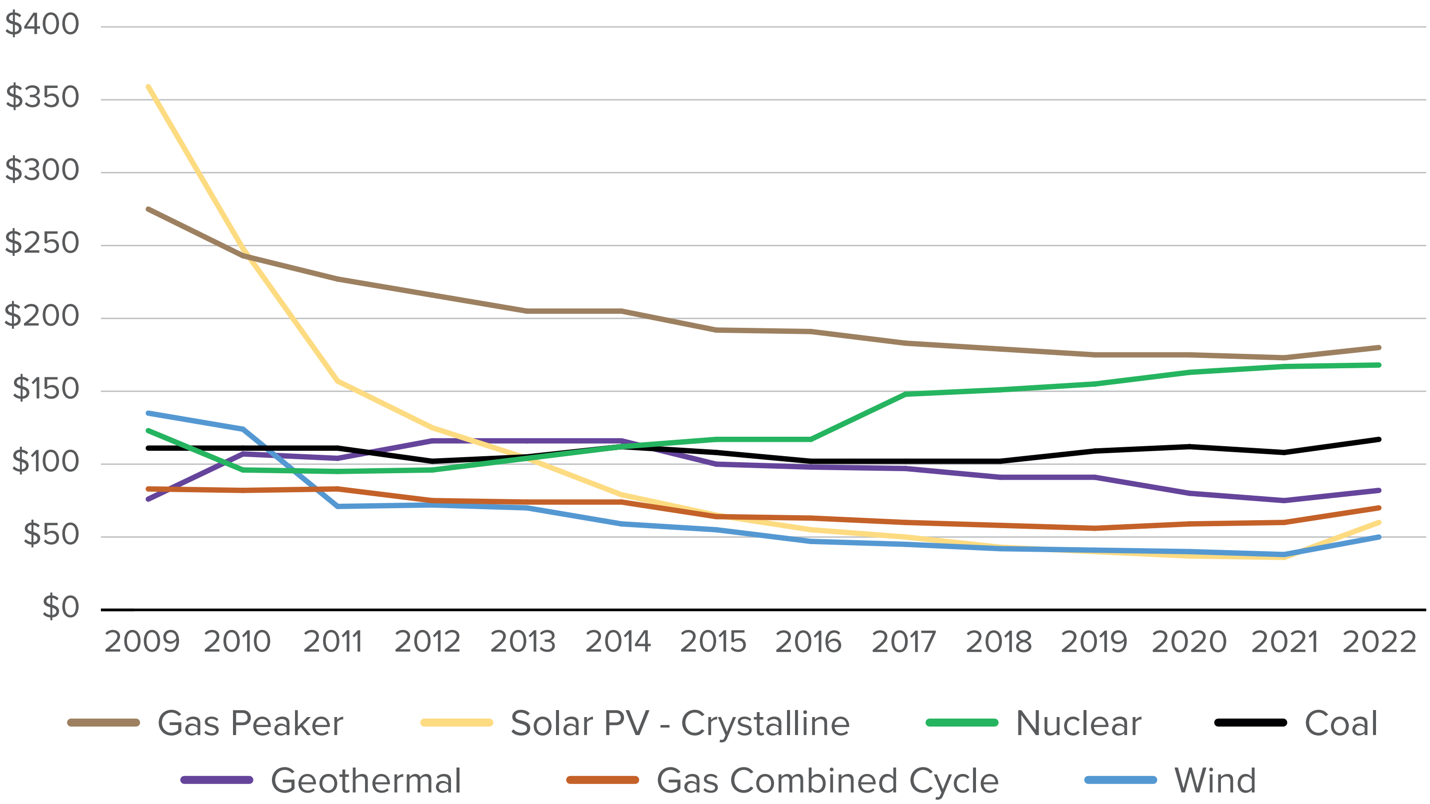
15 Michelle Solomon et al., *Coal Cost Crossover 3.0*.

16 Will Mathis, "Building New Renewables Is Cheaper Than Burning Fossil Fuels," Bloomberg, June 23, 2021, https://www.bloomberg.com/news/articles/2021-06-23/building-new-renewables-cheaper-than-running-fossil-fuel-plants.

17 Susan Tierney and Lori Bird, "Setting the Record Straight About Renewable Energy," World Resources Institute, May 12, 2020, https://www.wri.org/insights/setting-record-straight-about-renewable-energy.

18 Julia Simon, "Despite Billions to Get off Coal, Why Is Indonesia Still Building New Coal Plants?" National Public Radio, February 5, 2023, https://www.npr.org/2023/02/05/1152823939/despite-billions-to-get-off-coal-why-is-indonesia-still-building-new-coal-plants.

Figure 1: Historical mean unsubsidized LCOE values



Source: Levelized Cost of Energy+, Lazard, April 2023, https://www.lazard.com/research-insights/levelized-cost-of-energyplus/.

hydropower supply.[19] These countries consider coal power a viable option because it is readily available and can be used for heat as well as electricity. Coal's abundance, dispatchability, and the legacy political influence of its industry make the much-needed reduction of its use a central challenge to reaching net zero. On the other hand, despite the high cost of offshore wind installations, installed offshore wind capacity has more than tripled globally since 2017. Offshore wind projects produce more energy than their onshore counterparts, which make them an attractive option if developers can continue lowering costs by streamlining financing and construction and achieving technological breakthroughs. Without building new projects, the energy industry could not realize these gains. The coal and offshore wind cases exemplify the limitations of using LCOE to make system-wide energy sourcing decisions.

While dispatchable generation using natural gas and other fossil fuels can reliably meet electricity demand most of the time, alternative solutions are increasingly able to provide the same degree of reliability, an essential part of any electricity system that is priced into the cost of electricity to the end user. Such reliability is achievable in a clean energy future but will require large upfront investments in technological innovation and infrastructure changes. A study by the University of California, Berkeley (UC Berkeley) finds that the United States could achieve a 90 percent clean grid in 2035 that dependably meets electricity demand with existing hydropower, nuclear, and natural gas capacity, factoring in planned retirements and

19 Lauri Myllyvirta et al., "China Permits Two New Coal Power Plants per Week in 2022," Centre for Research on Energy and Clean Air, February 27, 2023, https://energyandcleanair.org/publication/china-permits-two-new-coal-power-plants-per-week-in-2022/.

new battery storage and renewable generation.[20] These scenarios involve multiple renewable energy systems, grid interconnections that enable more interregional electricity transfers, demand-response programs that anticipate peak demand and encourage users to shift their electricity usage, and long- and short-duration batteries.[21] Longer duration batteries and nuclear energy may soon be viable options that would help compensate for the intermittency of solar and wind.[22] Combined-cycle natural gas plants, the most efficient form of natural gas electricity generation, can support intermittent renewable energy generation as new technologies are developed. Though still a fossil fuel generation source, combined-cycle natural gas plants are a much cleaner alternative to simple-cycle natural gas or coal, especially if paired with carbon capture, utilization, and storage technologies.[23]

The additional costs of fossil fuels

Significant additional factors greatly affect the cost of electricity generated by fossil fuels that are not included in LCOE. These include the cost of refinancing stranded assets and the social costs of carbon emissions, factors that are not often considered in studies that assess cost competitiveness among different energy sources.

The risk that a newly built fossil fuel plant will become a stranded asset due to a forced closure to meet climate goals is not considered in most of these studies. Because most coal plants operate under long-term contracts and noncompetitive tariffs that insulate them from competing sources of electricity, coal plant owners or utilities must refinance their plants, oftentimes with public money, to make early closure possible.[24] Consumers often carry the cost burden of that retirement, though certain financing strategies like securitization can minimize the increase and in some cases, even lower consumer bills.[25] The cost of building a new onshore wind or solar PV project is approximately 40 percent less than building a new coal or natural gas plant.[26] Because of this widening gap in cost and because so many fossil fuel generators can already meet dispatchability needs, there remains little justification for constructing a new fossil fuel plant. The aforementioned UC Berkeley study to develop a 90 percent clean grid in 2035 is achievable without building any new coal or natural gas plants.[27]

Another cost related to fossil fuels that is not considered by LCOE is the social cost of carbon emissions, a measure of the health, environmental, and economic damages imposed on society from the burning of fossil fuels. Most markets do not have a pricing mechanism that accounts for the social cost of carbon emissions. The federal government estimates that the social cost of carbon dioxide is $51/metric ton (t), although the Environmental Protection Agency (EPA) proposed an updated price of $190/t at the end of 2022.[28] The EPA has estimated separate, higher social costs for methane and nitrous oxide emissions.[29] Factoring the current price of $51/t into the overall cost of electricity, natural gas would cost approximately $90.64/MWh to generate, a 29 percent increase over the natural gas price under the status quo. At the newly proposed price of $190/t, the cost of

20 Goldman School of Public Policy, *2035: The Report*, University of California, Berkeley, June 2020, https://www.2035report.com/electricity/downloads/.

21 "Demand Response–Analysis," IEA, September 2022, https://www.iea.org/reports/demand-response; Hiroshi Kawamura et al., "Frontier Technology Issues: Lithium-Ion Batteries: A Pillar for a Fossil Fuel-Free Economy?," United Nations Department of Economic and Social Affairs (DESA), July 8, 2021, https://www.un.org/development/desa/dpad/publication/frontier-technology-issues-lithium-ion-batteries-a-pillar-for-a-fossil-fuel-free-economy; Sheila Tandon Manz et al., *Economic, Reliability, and Resiliency Benefits of Interregional Transmission Capacity*, Natural Resources Defense Council, October 17, 2022, https://www.nrdc.org/sites/default/files/ge-nrdc-interregional-transmission-study-report-20221017.pdf; and Kathryne Cleary and Karen Palmer, "Renewables 101: Integrating Renewable Energy Resources into the Grid," Resources for the Future, updated March 24, 2022, https://www.rff.org/publications/explainers/renewables-101-integrating-renewables.

22 Laszlo Varro et al., "Nuclear Power in a Clean Energy System–Analysis," eds. Trevor Morgan and Caren Brown, IEA, May 2019, https://www.iea.org/reports/nuclear-power-in-a-clean-energy-system; and Katheryn Scott et al., *Pathways to Commercial Liftoff: Long Duration Energy Storage*, Department of Energy, March 2023, https://liftoff.energy.gov/wp-content/uploads/2023/05/Pathways-to-Commercial-Liftoff-LDES-May-5_UPDATED.pdf.

23 "Most combined-cycle power plants employ two combustion turbines with one steam turbine," April 25, 2022, U.S. Energy Information Administration. https://www.eia.gov/todayinenergy/detail.php?id=52158.

24 Paul Bodnar et al., *How To Retire Early: Making Accelerated Coal Phaseout Feasible and Just*, Rocky Mountain Institute (RMI), 2020, https://rmi.org/insight/how-to-retire-early.

25 Christian Fong and Sam Mardell, "Securitization in Action: How US States Are Shaping an Equitable Coal Transition," RMI, March 2021, https://rmi.org/securitization-in-action-how-us-states-are-shaping-an-equitable-coal-transition/.

26 David R. Baker, "Renewable Power Costs Rise, Just Not as Much as Fossil Fuels," Bloomberg, June 30, 2022, https://www.bloomberg.com/news/articles/2022-06-30/renewable-power-costs-rise-just-not-as-much-as-fossil-fuels.

27 Goldman School of Public Policy, *2035: The Report*.

28 Elijah Asdourian and David Wessel, "What Is the Social Cost of Carbon?" Brookings Institution, April 4, 2023, https://www.brookings.edu/2023/03/14/what-is-the-social-cost-of-carbon/.

29 Asdourian and Wessel, "What Is the Social Cost."

electricity generation from a natural gas combined-cycle plant would escalate to approximately $146.91/MWh, a staggering 110 percent increase.[30] Solar, wind, and other renewable assets also generate carbon emissions during manufacturing and transport. One study estimates that the cost of carbon emissions in the lifecycle of solar and wind projects is 0.1 euro cent per kilowatt-hour (kWh), while natural gas is 4.5 euro cents per kWh and coal is 9.0 euro cents per kWh, all at a price of €114/tCO2.[31] Lifecycle emissions are far lower for renewables than fossil fuels. In the United States and elsewhere, any mention of the social cost of carbon can be very controversial, but it is critical to the analysis of technology competitiveness.

Regional cost factors

The regional costs of renewable- and fossil fuel-based power options vary significantly given social, economic, technical, and regulatory barriers. Social barriers stem from public resistance due to a lack of awareness of the benefits of renewable energy, not-in-my-backyard (NIMBY) sentiment, and opportunity cost. Economic barriers include a lack of access to financing, high initial capital cost, cost of acquiring materials, and the presence of incentives and subsidies. Technical feasibility depends on the geographic conditions of a project site, which must have suitable land and sufficient sun, wind, or other resources given weather patterns. Regulatory barriers include a lack of national policies that support renewable energy, permitting inefficiencies, and market designs that disfavor the incorporation of renewable sources of electricity. These factors paint a much more complicated picture of project development and can determine whether renewable generators are able to connect to the grid at all in a timely and economically viable fashion. It is important to note that these variables apply to both renewables and fossil fuel projects, and to some extent must be evaluated on a project-by-project basis.

Assessing a Generator's Value

Estimating generation costs, often using LCOE alone, is just one of many factors that businesses, policymakers, regulators, and investors use to calculate the total costs and value of a project to the electricity system. A metric that often goes hand-in-hand with LCOE is the levelized avoided cost of electricity (LACE). Avoided cost, which is functionally equivalent to a project's "value," is a measure of the potential revenues that a generator can acquire over the lifetime of the project. LACE calculates the approximate revenues received from a generator selling at the marginal price of electricity on the market at the times when the generator is operating, plus any capacity payments for reliability, over the total generating output of the facility. LACE varies widely depending on the electricity market in which a generator is operating. The relevant utility's current generation profile, system needs, and pricing structure all impact LACE.

The values of LACE determine, in a rudimentary fashion, whether a project will profit and thus be viable for development. LACE studies conclude that wind, solar, coal, and natural gas power have similar value to the grid. The Energy Information Administration (EIA) conducted a study on the LCOE and LACE of new generators entering service in the United States in 2024, 2027, and 2040.[32] Figure 2 shows a side-by-side comparison of select technologies' ranges of LCOE and LACE values in the United States for new generation resources entering service in 2027. When LACE (in blue) overlaps with or is higher than LCOE (in orange), that project has the potential to be profitable when considering the few variables relevant to LCOE and LACE. The graph demonstrates that onshore wind, stand-alone and hybrid solar PV, hydroelectric, geothermal, and combined-cycle natural gas generators are all potentially profitable, but that it is highly dependent on location. Renewable energy is competitive with natural gas and outcompetes coal significantly on a cost-value basis, even without including the social costs described above.

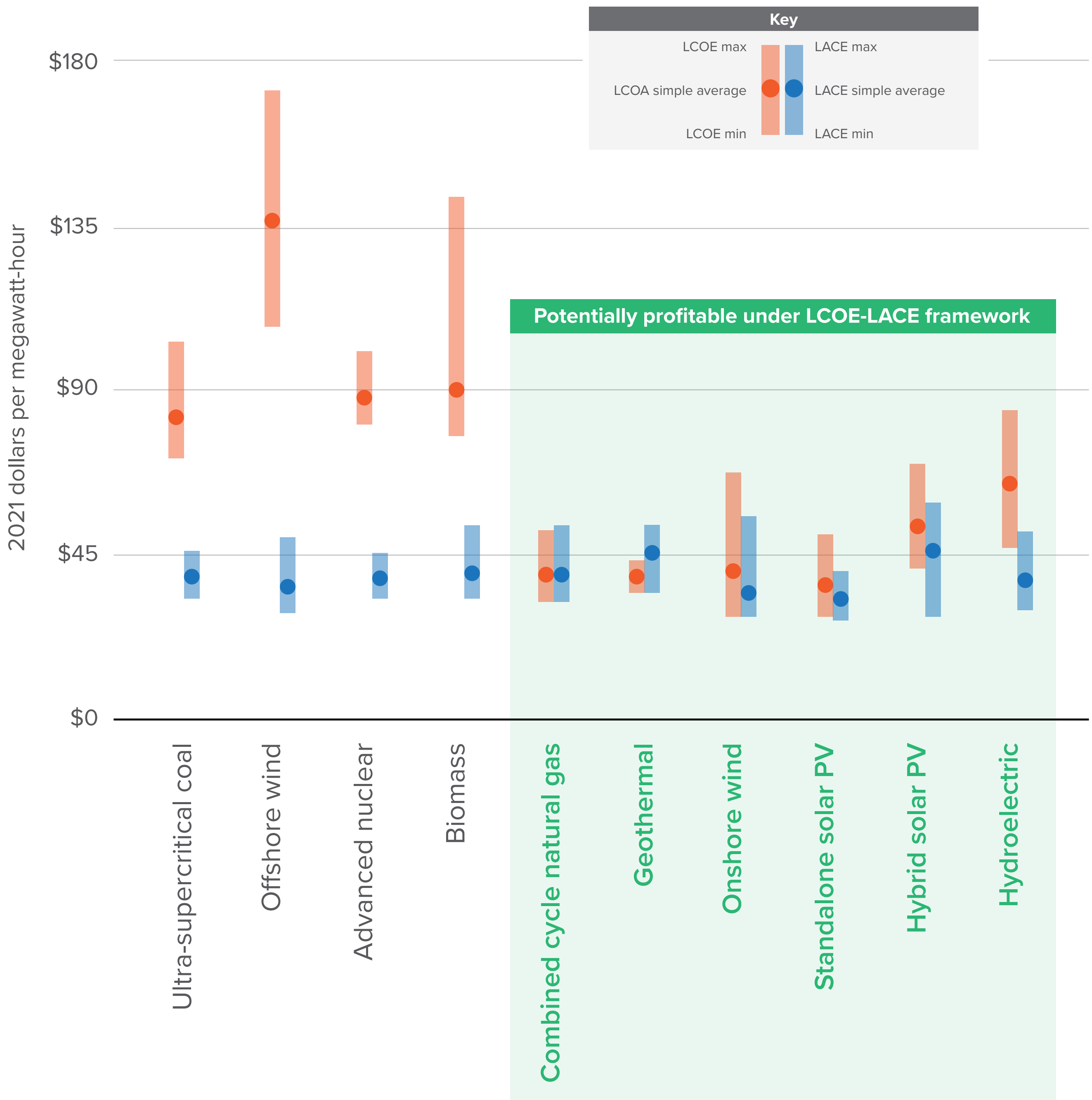
The value of renewable energy varies by time, location, and market share. However, many renewable projects are covered by power purchase agreements that standardize the purchase price so that the projects are not subject to volatile market prices. As renewable energy takes up a larger share of total generation, its market value tends to

30 "How Much Coal, Natural Gas, or Petroleum Is Used to Generate a Kilowatthour of Electricity?" US Energy Information Administration, accessed May 9, 2023, https://www.eia.gov/tools/faqs/faq.php?id=667&t=6. Using the average fuel rate of natural gas in the United States in 2021 at ~7.36 cubic feet/kWh, carbon emissions from burning natural gas of 0.0550 kg CO2/cubic foot, conversion from kilograms to metric tons of CO2, and the social costs of carbon at $51/tCO2 and $190/tCO2.

31 Sascha Samadi, "The Social Costs of Electricity Generation—Categorising Different Types of Costs and Evaluating Their Respective Relevance," *Energies* 10, no. 356 (March 13, 2017), https://epub.wupperinst.org/frontdoor/deliver/index/docId/6642/file/6642_Samadi.pdf.

32 "Levelized Costs of New Generation Resources in the *Annual Energy Outlook 2022*," US Energy Information Administration, March 2022, https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

Figure 2: Range of LCOE and LACE for generation technologies entering service in 2027 in the United States



Source: "Levelized Costs of New Generation Resources in the Annual Energy Outlook 2022," US Energy Information Administration, March 2022, https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.

decrease because of its intermittent availability.[33] Finally, certain markets may have conditions that favor renewable energy or lower penetration of renewables, which would increase the value of the asset.

Toward Whole-System Models

Beyond LCOE and LACE, there are other methods that incorporate both cost and value variables to assess overall profitability, and expansive models that include variables beyond generation. These metrics and models provide insight into the factors that will influence the pace of the transition to a clean energy grid.

Studies have proposed and compared many different profitability metrics.[34] The common theme between these alternative metrics is the incorporation of both value and system cost components in the calculation. The most robust measures are those that take into account both the cost and value of electricity. The resulting values can be helpful in better assessing a project's competitiveness and the potential future makeup of the power grid. Table 1 summarizes input variables of cost and value of electricity.

Given the aforementioned cost and value variables, it is clear that using LCOE alone to help predict the future makeup of the US power system would paint an incomplete picture. However, two models of greater complexity—the Regional Energy Deployment System (ReEDS) and a profitability-adjusted LCOE (PLCOE)—offer greater precision and have additional but distinct appeal as tools for forecasting the changing energy mix in the United States.[35] ReEDS is a detailed capacity expansion planning model designed by the National Renewable Energy Laboratory. Capacity expansion planning simulates the transmission and generation requirements of a future power system given a set of assumptions about future electricity demand, fuel costs, technology costs, and policy measures. These planning models are fairly robust and used by system operators to make real decisions about the power grid in combination with other tools. The PLCOE model accounts for both generation costs from LCOE as well as the value of the

Table 1: Cost and value components of electricity

LCOE-considered costs	Additional generation costs excluded	Integration costs	Miscellaneous costs	LACE-considered value	Additional generation value
Capital costs	Cost of financing	Interconnection	Regulatory compliance	Capacity/reliability services	Improved health outcomes
Operations and Maintenance	Project delays (political, regulatory, physical)	Transmission and distribution	Legal fees from arbitration or litigation	Non-curtailed electricity sales	Improved environmental outcomes
Fuel costs	Cost of materials/ supply chain	Permitting	Greenhouse gas emissions		Government incentives
	Research and development		Operator administrative fees		Progress toward policy goals
	Taxes				

Source: Information compiled by the authors.

33 Matthew Mowers, Bryan K. Mignone, and Daniel C. Steinberg, "Quantifying Value and Representing Competitiveness of Electricity System Technologies in Economic Models," *Applied Energy* 329 (January 1, 2023), https://www.sciencedirect.com/science/article/pii/S0306261922013897.

34 Matthew Mowers, and Trieu Mai, "An Evaluation of Electricity System Technology Competitiveness Metrics: The Case for Profitability," *The Electricity Journal*, vol 4 issue 34, May 2021, https://www.sciencedirect.com/science/article/abs/pii/S1040619021000221.

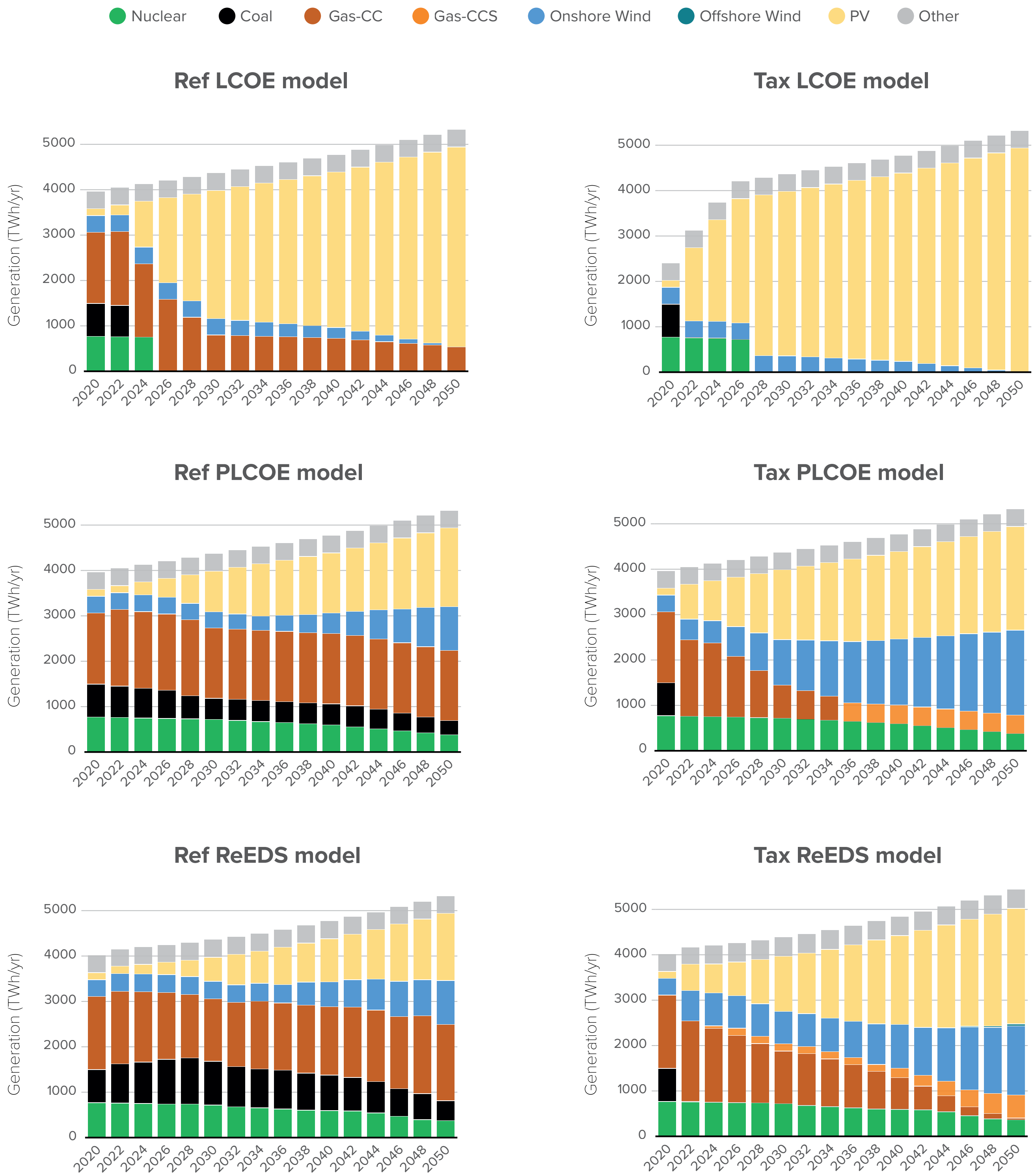
35 Mowers et al., "Quantifying Value."

Table 2: Comparison of inputs of the PLCOE and ReEDS models

PLCOE	ReEDS
Timesteps of one-tenth of a year.	Seventeen seasonal-diurnal **time periods** and hourly resolution for curtailment and capacity payments.
LCOE trajectories are independent of the model calculations and adjusted to incorporate upward sloping supply curves for **fuels, renewable materials, and transmission**, based on the market share of the technology. One representation for **resource output** for each technology based on a **single location**. Renewable **value factors** decrease linearly as market share increases. Fossil fuel **value factors** are higher and flat. There are **no cross-technology interactions**. Precurtailed **capacity factors** for renewables and maximum capacity factors for fossil fuels minus outages. **Federal and state policies** are excluded.	LCOE and **value factors** based on 365 resource **regions**, 134 modeled balancing areas, ten **resource classes**, and five **levels of transmission cost.** Material costs, fuel prices, and load growth are inputs based on projections from other models. Technology costs, fuel prices, and demand central estimates. **Cross-technology interactions are possible**. Does not have the resolution to detail individual operating behaviors, but calculates a capacity factor for each dispatchable technology based on project costs and value to the grid. **Can incorporate federal and state policies** governing the power sector (e.g., investment tax credit, production tax credit, tax credit for CCS, state renewable portfolio standards, air pollution, and carbon standards). The version of the model employed by the authors of the comparative study excludes these policies to display technology value more directly.
Early retirements are possible (when a new technology's PLCOE is lower than the existing technology's PLCOE using operational, maintenance, and fuel costs in the LCOE).	**Early retirements** when value to the grid is less than 50 percent of ongoing fixed operational and maintenance costs.
Gradually increasing **load growth** and consideration of planned retirements.	Increasing **load growth** based on national month-hour average electrical demand from regional data. Determines system requirements based on electrical energy demand, firm capacity reserve margin, three types of operating reserves (regulation, spinning contingency, and flexibility reserves).
Does not include any additional costs or value created by manufacturing, supply chain, learning by doing, permitting, or financing.	Does not include any additional costs or value created by manufacturing, supply chain, learning by doing, permitting, or financing.
Transmission exogenously priced into the model through the value factor, where renewable value decreases with market share.	Simplified representation of transmission networks and system-wide planning approach rather than considering the actions of existing market actors.
No social cost of carbon.	No social cost of carbon.

Source: Information compiled by authors from various sources

Figure 3: Generation share over time results of the LCOE, PLCOE, and ReEDS models



Source: Matthew Mowers, Bryan K. Mignone, and Daniel C. Steinberg, "Quantifying Value and Representing Competitiveness of Electricity System Technologies in Economic Models," Applied Energy 329 (2023).

generation asset by calculating a value factor using the levelized avoided cost of electricity—or levelized value of electricity—and a benchmark price. While not nearly as robust as ReEDS, PLCOE takes a composition of all electricity generators in 2020, using data from the ReEDS model, then considers the amount of generation for which new technologies can compete given increasing load growth and any planned retirements in one-tenth of a year increments. The comparatively low granularity of the PLCOE model is enumerated in Table 2, which lists the key inputs for the PLCOE and ReEDS models.

The results of a comparative study of LCOE, PLCOE, and ReEDS are shown in Figure 3, where the makeup of the future power system from 2020 to 2050 is displayed in two graphs for each model, with and without a carbon tax. The graphs on the right side include an escalating carbon tax imposed by the government, which leads to a faster phaseout of fossil fuel generators. The sharp contrast between the LCOE scenarios and those of PLCOE and ReEDS indicates how LCOE overestimates renewable deployment by excluding key additional factors that influence the relative cost and value of a generator to the grid. While solar power quickly dominates the market in the LCOE model, the PLCOE and ReEDS models reveal that the future power system is likely to make the transition to renewables more gradually.

The analysis also shows that PLCOE shares significant similarities with the detailed ReEDS model, but there are critical differences. PLCOE is not a capacity expansion planning model and therefore does not have near the level of granularity of ReEDS. PLCOE only considers one location for the cost and value of each technology, whereas the ReEDS model has 365 resource regions. The authors attribute some of the differences in results to how PLCOE calculates value factor as linear functions and assumes precurtailed capacity that overestimates

Table 3: Select metrics for assessing the cost and value of electricity

LCOE	$\frac{\text{Total lifetime cost}}{\text{Total lifetime electricity produced}}$
LACE	$\frac{\text{Value of consumed generated electricity + capacity payments}}{\text{Total electricity produced over lifetime}}$
Benchmark price (P)	Definitions vary. In this work: Average value per unit of energy (MWh) to meet a combination of system requirements
Value factor	$\frac{\text{Technology LACE}}{\text{Benchmark price}}$
PLCOE	$\frac{\text{LCOE}}{\text{Value factor}}$
ReEDS model	Detailed energy system model
Profitability metrics	Benefit-cost ratio = LACE/LCOE Return on investment = (LACE-LCOE)/LCOE Profit margin = (LACE-LCOE)/LACE

generation output. ReEDS has far higher resolution, and the purpose of PLCOE in this exercise is to show how including value components in the calculation leads the model to match much more closely the results of a robust model.

An additional important finding in this study is the efficacy of a carbon tax in reducing fossil fuel use. In the ReEDS carbon tax model, natural gas combined-cycle power plants without carbon capture and storage (Gas-CC) are eliminated by 2050, a notably slower pace than the PLCOE model. Natural gas plants with carbon capture and storage (Gas-CCS) never develop when carbon is not taxed, and remain a part of the generation fleet in both the PLCOE and ReEDS scenarios. While far more robust than the LCOE metric in assessing costs and value of generators, the PLCOE and ReEDS models exclude the impacts of any local, state, or regional policies that favor certain generating technologies such as renewable portfolio standards, emissions regulations, or technology mandates. While ReEDS is capable of including storage, this study does not consider storage technologies, so its application is limited to generation and does not reflect all possibilities currently available.

Even though models are increasingly improving estimates of renewable energy project costs, they still exclude important considerations. None of the discussed metrics include the value of reducing carbon emissions or the likelihood that new technologies will be developed that could fundamentally change renewables' intermittency issue, such as new competitive nuclear technologies or long-term battery technologies.

Additionally, none of the metrics in Table 3 can fully account for important variables that can impact the cost of renewable energy and many simplify or exclude inputs. All the metrics, except for the ReEDS model, assume a cost of capital that does not capture the variability in access to financing around the world and the rates at which developers of different technologies can acquire capital. Instead, a simplified, constant discount rate is defined. They also simplify a suite of financing costs when projects face risks such as interconnection or permitting delays, corruption and political risks, market instability, and many other country-specific risks. They do not include the cost of carbon, policy changes that would effectively raise or lower that cost, or the potential for new technologies to change their models. While subsidized analysis of LCOE and other metrics accounts for government incentives and taxes including the production and investment tax credits or even a carbon tax, LCOE cannot incorporate future regulatory regimes, grant funding, and other sources of public money.

Conclusion

LCOE demonstrates, with some limitations, that renewable electricity generation is competitive with fossil fuel electricity generation on a global scale. LCOE does not, however, analyze the system costs of new renewable energy generation and, as described in this paper, these costs are significant and must be understood when planning additions to the energy system.

Profitability metrics address some of the limitations of LCOE and lead to a more robust system cost analysis. These more comprehensive measurements emphasize the need to consider all costs beyond generation when transforming the energy mix to address climate change. These system models, such as ReEDS, are not widely accessible, are computationally complex, and cannot be used for large-scale analysis. To understand how the electricity system must evolve in a cost-effective manner, policymakers, stakeholders, and the public must consider whole system costs.

Nevertheless, understanding LCOE and that renewables generate energy more cheaply than fossil fuels is important for four major reasons:

First, understanding generation costs is valuable to policymakers and the public. The basic understanding that generating electricity is cheaper with renewable energy than fossil fuels provides a powerful incentive to rebuild the entire energy system in a way that delivers power to the public at the lowest cost possible.

Second, LCOE enables utilities—increasingly tasked with planning for a rapid clean energy transition—to determine the best ways to build their generation, transmission, and distribution systems to make use of this cheaply generated energy.

Third, it provides an objective cost evaluation with no value judgments about which factors to include in the cost comparison, a process that can otherwise become contentious. LCOE thus provides an analysis that sidesteps political controversy over what decision-makers consider reliable and expensive power options.

Fourth, critics of renewable energy regularly cite and are genuinely concerned about the cost of electricity generation. Having LCOE address that issue directly can be instrumental in convincing people to move forward with the transition.

In summary, renewable electricity generation is significantly cheaper than coal or natural gas electricity generation. However, when full system costs are taken into account in the models described in this issue brief, renewables can lose their cost advantage, which would theoretically slow their deployment compared to fossil fuels.

The current buildout of new electricity generation tells a different story. In 2022, 74.1 percent of electricity generation capacity additions were renewable.[36] In 2023, 82 percent of planned utility-scale generation capacity additions in the United States are renewable, with solar energy comprising 54 percent of the total. There also are a significant number of renewable facilities waiting in line to be connected to the grid.[37]

The huge buildout of renewables is happening because of the imperatives of addressing the climate crisis and the negative externalities of carbon emissions that are not included in the models. These factors have led to government mandates, incentives, and increasing public support, but the critical factor enabling this rapid deployment is the competitive, often cheaper cost of generating electricity with renewable energy. However, to combat climate change, these efforts must scale up even further. Lowering the cost of delivering renewable energy will garner greater public support and accelerate the buildout of additional renewable energy generators. The next issue brief will analyze how to reduce system buildout costs, particularly the costs of permitting, planning, and meeting reliability needs.

36 Michelle Lewis, "Renewables Supplied Nearly 75% of New US Electrical Generating Capacity in 2022," Electrek, February 8, 2023, https://electrek.co/2023/02/08/renewables-supplied-nearly-75-of-new-us-electrical-generating-capacity-in-2022.

37 Joe Rand, "Grid connection requests grow by 40% in 2022 as clean energy surges, despite backlogs and uncertainty," Lawrence Berkeley National Laboratory, April 6, 2023, https://emp.lbl.gov/news/grid-connection-requests-grow-40-2022-clean.

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Ken Berlin is a senior fellow and the director of the Financing and Achieving Cost Competitive Climate Solutions Project at the Atlantic Council's Global Energy Center. He has devoted his career to leadership on environmental, energy, and climate-change issues. From 2014 to May 2022, Berlin was the president and chief executive officer of the Climate Reality Project, an organization founded and chaired by former US Vice President Al Gore. He built the project into an international organization with offices in eleven countries and 130 chapters in the United States. The Climate Reality Project is dedicated to building public support for addressing the climate crisis. It has led multiday trainings for over forty thousand climate activists, gathered the activists into a powerful international grassroots network, and activated them to work on climate-crisis issues and solutions.

Earlier, Berlin was a co-founder with Reed Hundt of the Coalition for Green Capital, an organization that works with governments at the international, national, state, and local levels to establish "green bank" finance institutions to accelerate the deployment of renewable energy, energy efficiency, and clean transportation. Prior to that, he chaired the Environmental and Climate Change practices at the law firm of Skadden Arps, where he was recognized as one of the leading climate-change attorneys in the United States and internationally. He has extensive legal and policy expertise on US and international environmental issues including clean energy; corporate compliance; environmental, social, and corporate governance; biodiversity; and forestry.

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