RethinkX

Disruption, Implications, and Choices

Rethinking Energy

The Great Stranding: How Inaccurate Mainstream LCOE Estimates are Creating a Trillion-Dollar Bubble in Conventional Energy Assets

A RethinkX Sector Disruption Report

February 2021

Adam Dorr & Tony Seba

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The RethinkX Project

RethinkX is an independent think tank that analyzes and forecasts the speed and scale of technology-driven disruption and its implications across society. We produce impartial, data-driven analyses that identify pivotal choices to be made by investors, businesses, policymakers, and civic leaders.

We analyze the impacts of disruption, sector by sector, across the economy. We aim to produce analyses that reflect the reality of fast-paced, technology disruption S-curves. Mainstream analysts produce linear, mechanistic, and siloed forecasts that ignore systems complexity and thus consistently underplay the speed and extent of technological disruption – for example solar PV, electric vehicles, and smartphone adoption. By relying on these mainstream forecasts, policymakers, investors, and businesses risk locking in inadequate or misguided policies and investments, resource misallocation and negative feedbacks that lead to massive wealth, resource, and job destruction as well as increased social instability and vulnerability.

We take a systems approach to analyze the complex interplay between individuals, businesses, investors, and policymakers in driving disruption and the impact of this disruption as it ripples across the rest of society. Our methodology focuses primarily on market forces that are triggered by technology convergence, business model innovation, product innovation, and exponential improvements in both cost and capabilities.

Our aim is to inspire a global conversation about the threats and opportunities of technology-driven disruption and to focus attention on choices that can help lead to a more equitable, healthy, resilient, and stable society.

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Our thanks in no way implies agreement with all (or any) of our assumptions and findings. Any mistakes are our own.

Preface

RethinkX uses the Seba Technology Disruption Framework to model and forecast technology disruptions. The analysis in this report is based on detailed evaluation of data on the market, consumer, and regulatory dynamics that work together to drive disruption in the energy sector. We present an economic analysis based on existing solar photovoltaic, onshore wind, and lithium-ion battery technologies that have well-established cost curves, and on existing business models. We extrapolate data where we have credible insight into how these cost curves will continue in the near future. The disruption we analyze in this report could actually happen more quickly than we project if there is an acceleration of the cost curves, a breakthrough in the underlying technologies, or business-model innovations that bring the disruption timeline forward.

Our findings and their implications are based on following the data and applying our knowledge of finance, economics, technology adoption, and human behavior. Our findings show the speed, scale, and implications of the disruptions that we expect to unfold in a rational context. Scenarios can only be considered in terms of probabilities. We think the scenario we lay out in this report is far more probable than those currently forecast by others. In fact, we consider the underlying disruption of energy by solar, wind, and batteries to be inevitable. Ultimately, individual consumers, businesses, investors, and policymakers will make the decisions that determine how this disruption proceeds in any particular region. The analysis we present here marks the beginning of a series of reports about the disruption of the energy sector, and our aim is to provide insight that decision-makers can then utilize to benefit society.

Disclaimer

Executive Summary

A large and rapidly-expanding global financial bubble now exists around conventional coal, gas, nuclear, and hydro power energy assets. This bubble has in part been created by mainstream energy analyses that have, for the last decade, significantly underestimated the levelized cost of electricity (LCOE) from conventional power plants because they assume these plants will be able to successfully sell the same quantity of electricity each year from now through 2040 and beyond. This assumption has been false for at least ten years. The rates at which conventional power plants are utilized will continue to decrease as competitive pressure from near-zero marginal cost solar photovoltaic and onshore wind power, and battery energy storage continue to grow exponentially worldwide.

Since 2010, the LCOE figures published in mainstream analyses and used by policymakers, regulators, civic leaders, utilities, asset owners, and investors have significantly underestimated the actual cost of electricity generated by prospective coal, gas, nuclear, and hydro power plants. This in turn means that conventional energy asset valuations are heavily overstated. Fundamental valuation of an asset is based on expected future cash flows that are, in turn, dependent upon projected revenues and costs. The projected revenues and costs of any power plant are dependent upon its assumed capacity factor (or utilization rate), which is the fraction of its generating capacity it is actually able to produce and sell.

The LCOE methodologies used in virtually all mainstream analyses contain the same critical error: they assume a high and constant capacity factor (utilization rate) for the entire lifetime of any individual power plant. In doing so, they assume both existing and newly-built power plants will be able to produce and sell the same number of kilowatt-hours each year throughout their 20+ year operational life. Widely-cited sources that commit this error include the International Energy Agency (IEA)[1], the United States Energy Information Administration (U.S. EIA)[2], the World Bank[3], the International Renewable Energy Agency (IRENA)[4], the Department for Business, Energy & Industrial Strategy of the UK government[5], the Australian Energy Regulator[6], the National Renewable Energy Laboratory (NREL and OpenEI)[7,8], Lazard[9], Stanford University[10], the University of Texas at Austin[11], the MIT Energy Initiative[12], and the Natural Resources Defense Council (NRDC)[13].

Capacity factor of conventional coal, gas, nuclear, and hydro power plants will not remain high or constant, but will instead decline dramatically over the next 10 to 15 years as they are outcompeted and disrupted by the combination of solar photovoltaics, onshore wind, and lithium-ion batteries (SWB). In fact, capacity factor in conventional energy has been dropping since at least 2010. For instance, the average capacity factor of coal in the United States has fallen from 67% in 2010 to just 40% in 2020 – first because of competition with cheap gas from fracking, and now because of SWB.[14] In the United Kingdom, coal capacity factor has collapsed even faster, from 58% in 2013 to just 8% by 2019.[15]

Mainstream LCOE analyses thus artificially understate the cost of electricity of prospective coal, gas, nuclear, and hydro power plants based on false assumptions about their potential to continue selling a fixed and high percentage of their electricity output in the decades ahead. Because LCOE figures and asset valuations are very sensitive to the capacity factor parameter, these false assumptions have made conventional energy assets appear to be much more attractive than they actually are. As a result, they have attracted far more investment (over $2.2 trillion in fossil and nuclear energy in the electric power sector worldwide since 2010) than they otherwise would have based on a realistic assessment of capacity factor and LCOE.[16]

For instance, the United States Energy Information Administration (U.S. EIA) assumes that coal power plants entering service both today and in 2035 will enjoy a capacity factor of 85% for their entire operational lifetime, despite the fact that the real figure is already less than half of that, and thus inaccurately report their LCOE as about 7.5 cents per kilowatt-hour.[17] Our analysis indicates that even if such facilities could somehow retain a capacity factor of 10% after 2035, rather than collapsing altogether like they already have in the UK, the cost of their electricity would be more than 10 times higher than the U.S. EIA's published estimate. Investment in an asset class above and beyond what the fundamental value can return, based on shared and widespread false assumptions, is the very definition of a financial bubble.

In this report, we explain how the nonlinear dynamics of the SWB disruption of energy will rapidly drive the capacity factor of all conventional coal, gas, nuclear, and hydro power plants toward zero throughout the 2020s. The overwhelming majority of these conventional facilities will become financially unviable and their assets stranded over the next decade or so. Any of these facilities that linger on a few more years will have utilization and cost profiles comparable to those of today's peaking power plants, or peakers. It is important to note, however, that they will be 'peakers without peak prices' – meaning they will be unable to sell their electricity at the high prices needed to cover their costs because of competition from batteries. Thus, directly contrary to the prevailing narrative that SWB will require subsidies and other forms of support, governments may instead need to make market-distorting interventions to bail out and prop up coal, gas, nuclear, and hydro power plants in order to prevent electricity supply shortfalls from the stranding of these assets during the 2020s as the disruption unfolds.

If the gap between the mainstream mirage and reality is not corrected quickly, and incumbents continue to assume that coal, gas, nuclear, and hydro power plants will be utilized at 20th century historical rates in perpetuity, then pension/retirement funds and other asset managers may continue to be lured into investing not only in conventional power plants but in their entire value chains – including pipelines, ports, railways, and mines – under the false pretense that these are low-risk investments. At the same time, appropriate divestment from holdings that have little chance of performing as originally expected will be delayed as well. If we continue to accept deeply-flawed projections such as those of the U.S. EIA, whose Reference Case assumes that almost half of all new electricity generating capacity installed in the United States between now and 2050 will be natural gas (over 3 terawatts at a cost of roughly $3 trillion just for the power plants), then the conventional energy asset bubble that already exists could grow more dramatically during the 2020s.[17,18]

Our analysis has a number of important implications for energy and finance, as well as for society and the environment at large:

1. Conventional energy assets are severely mispriced, and their overvaluation is creating a growing asset valuation bubble in the conventional energy sector.
2. Coal, gas, nuclear, and hydro power are no longer competitive with the combination of SWB, even using inaccurate mainstream LCOE calculations.
3. Solar and wind power reached cost parity and became cheaper than coal, gas, nuclear, and hydro power several years sooner than mainstream analysts reported.
4. The widening gap between rapidly increasing conventional energy LCOE and rapidly decreasing SWB costs means that the SWB disruption will proceed faster than expected.
5. Coal and gas power plants with integrated carbon capture and storage (CCS) are doubly mispriced (overvalued).
6. Governments must protect people, not incumbent companies or industries, from the financial risk of the conventional energy asset bubble.
7. Carbon neutrality can be achieved more quickly and cheaply than generally expected.

The EIA, IEA, and other analysts are playing a critical role in mispricing conventional energy assets that is analogous to the role that the credit rating agencies played in mispricing subprime mortgage assets, which led to the housing bubble and financial crisis in 2007. We call on investors, policymakers, civic leaders, public utility commissions, and other decision-makers to demand reality-based conventional LCOE estimates in order to protect their stakeholders and society.

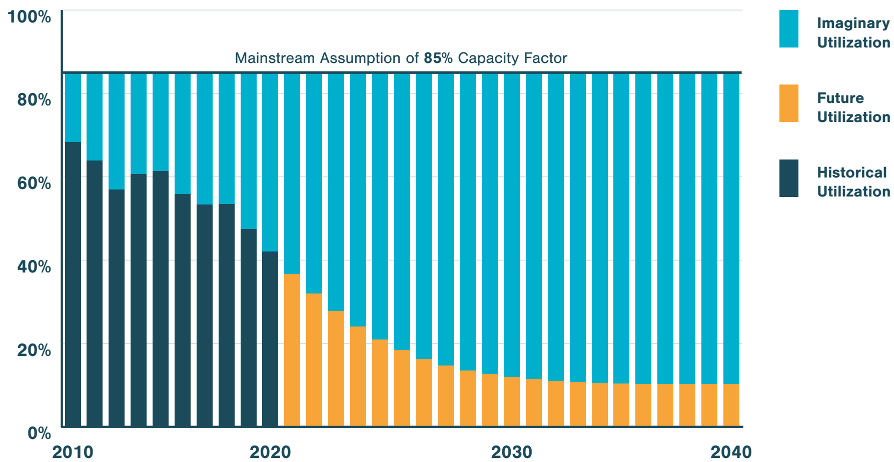
Rethinking LCOE Through the Lens of Disruption

Levelized Cost of Energy/Electricity (LCOE) is a widely used metric for comparing the cost of electricity produced by competing technologies. It is calculated by dividing all costs incurred in a given time frame across all units of electricity sold during that same time frame, giving an average, or levelized, cost per kilowatt-hour or megawatt-hour sold.[a]

The LCOE methodologies used by widely-cited sources such as the IEA[1], the U.S. EIA[2], the World Bank[3], IRENA[4], the Department for Business, Energy & Industrial Strategy of the UK government[5], the Australian Energy Regulator[6], the NREL and OpenEI[7,8], Lazard[9], Stanford University[10], the University of Texas at Austin[11], the MIT Energy Initiative[12], the NRDC[13], and many others all contain the same critical error – they assume a high and constant capacity factor for the entire lifetime of any individual power plant.[b] In doing so, they assume both existing and newly-built power plants will be able to generate and sell the same number of kilowatt-hours each year throughout their entire operational life.

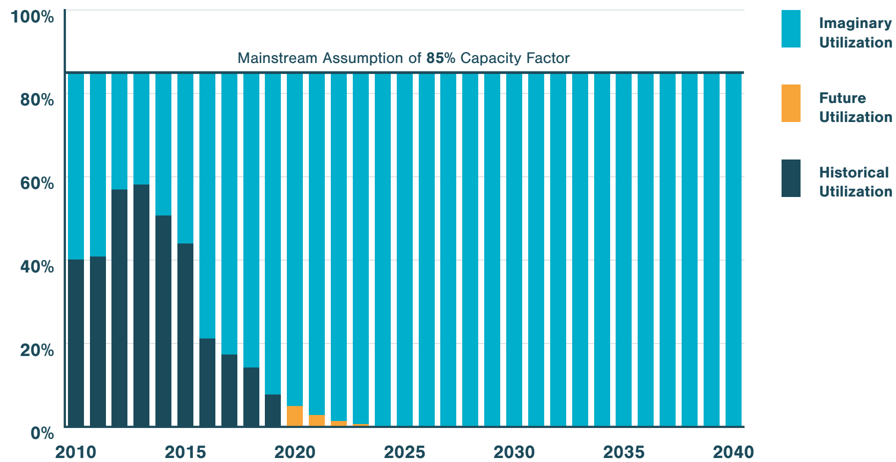
For example, it has already become much more difficult for coal power plants in the United States to successfully sell their electricity in the face of competition, first from cheaper gas from fracking, and now from solar and wind power. As a result, the average capacity factor reported for coal power plants in the United States has fallen from 67% in 2010 to just 40% in 2020.[14] In the United Kingdom the decline of coal capacity factor has been even more dramatic: from nearly 60% to less than 8% in just six years from 2013 to 2019.[15] Despite these dramatic declines, standard LCOE calculations for coal still assume a constant capacity factor of up to 85% for the entire life of prospective coal power plants (Figure 1).[2,9]

Figure 1: U.S. Coal Capacity Factor – 85% Assumption vs. Reality



The historical data for U.S. coal capacity factor show that the assumption of a high and constant capacity factor has been invalid for over a decade, and that going forward the majority of utilization (i.e. electricity generation and sales) presumed in mainstream LCOE calculations for U.S. coal power plants is imaginary.

Figure 2: U.K. Coal Capacity Factor – 85% Assumption vs. Reality



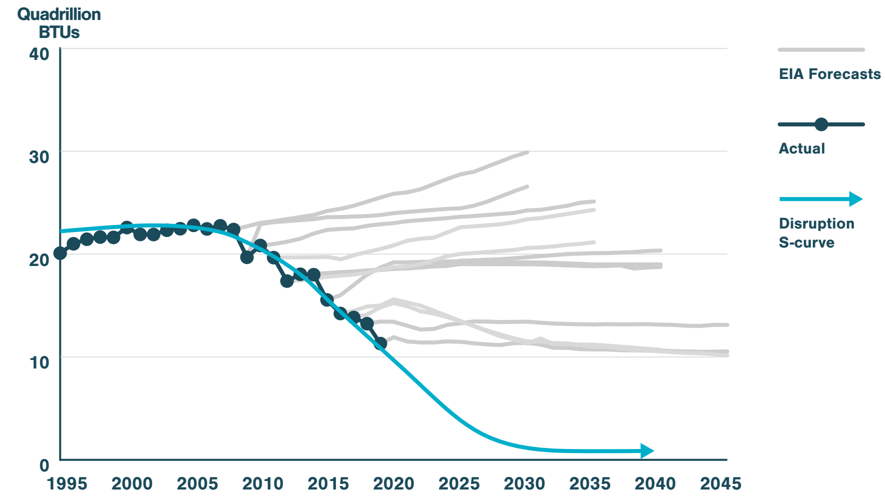
The historical data for U.K. coal capacity factor show that the assumption of a high and constant capacity factor has been invalid for over a decade, and that going forward virtually all utilization (i.e. electricity generation and sales) presumed in mainstream LCOE calculations for U.K. coal power plants is imaginary.

Assuming a high and constant capacity factor is a grievous error with manifest and damaging consequences. Calculations of LCOE are very sensitive to assumptions about capacity factor, and assuming a high and constant rather than declining capacity factor dramatically underestimates the cost of electricity generated by coal, gas, nuclear, and hydro power plants. In turn, this underestimation of coal, gas, and nuclear power plant LCOE strongly biases cost comparisons with SWB and other technologies in favor of these incumbents.[c]

Moreover, the calculation of LCOE itself presumes that a power plant will obtain sufficient revenues and cashflows to cover costs. This is because the levelized cost represents the break-even price per kilowatt-hour, meaning the average price at which a power plant would need to sell each unit of electricity in order to bring in sufficient revenues and cash flows to exactly cover all of its expenses. In competitive markets, neither the assumption that capacity factor will remain high and constant nor the assumption that electricity can be successfully sold at higher prices holds true. Whether a conventional baseload power plant is old and already fully amortized or newly constructed, its utilization profile and electricity selling prices will change during the 2020s, pushing it into competition not only with SWB but with existing peakers as well. Few, if any, coal, gas, nuclear, or hydro power facilities will survive this transition without aggressive government intervention.

We have already begun to see the incumbent technologies enter their death spiral. Coal in the United States was initially disrupted in the late 2000s by inexpensive gas produced domestically with unconventional, well-stimulation techniques (known as fracking), and now the disruption of coal has been taken over and accelerated by SWB. Conventional analyses that have failed to understand disruption have made consistently erroneous forecasts for the future of coal in the United States (Figure 3).

Figure 3: Disruption of Coal Power in the United States



Source: U.S. EIA Annual Energy Outlook series, 1995-2020.[18]

Coal use peaked in the U.S. in 2008 and is now charting a textbook disruption trajectory toward collapse. Conventional forecasts such as those from the U.S. EIA fail to understand disruption and have made linear projections for the recovery or stabilization of coal power each year for over a decade, with the latest projection for 2020 continuing the same erroneous pattern.

> **WHETHER** a conventional baseload power plant is old and already fully amortized, or newly constructed, its utilization profile and electricity selling prices will change during the 2020s, pushing it into competition not only with SWB but with existing peakers as well. Few, if any, coal, gas, nuclear, or hydro power facilities will survive this transition without aggressive government intervention.

Notwithstanding repeated forecasts for the recovery of coal by the U.S. EIA, the market capitalization of coal in the United States as reflected in the Dow Jones U.S. Coal Index has already collapsed by over 99% from a high of 500 in 2011 to less than 5 in 2020, at which point the index itself was quietly discontinued by S&P Global (Figure 4).[20]

Figure 4: Dow Jones U.S. Coal Index (DJUSCL) – Disruption and Collapse of Coal in the United States

Source: S&P Global, 2021.[20]

OUR projections for corrected LCOE calculations change only capacity factor, while leaving all other parameters unadjusted at industry-standard values, in order to show the sensitivity of LCOE to this single parameter when it correctly operates as a variable rather than as a constant in the relevant calculations.

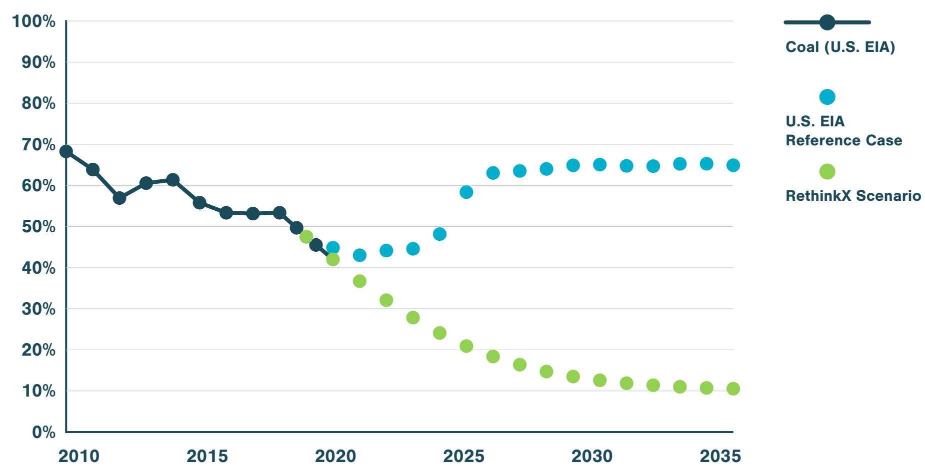
Competition from SWB is already reducing the quantity of electricity that conventional coal power plants are able to sell profitably, and thus coal capacity factor is declining accordingly (Figure 5). The rate at which this competitive pressure mounts will accelerate rapidly as the SWB disruption unfolds throughout the 2020s. Furthermore, because competitive wholesale electricity markets tend to clear at or near the marginal cost of electricity, prices at auction now regularly reach zero or even fall negative in regions such as California, Texas, and Germany that have been early adopters of SWB. Losses from selling electricity at zero or negative prices will accelerate the disruption because they must be recouped by the sale of higher-priced kilowatt-hours at other times.[d]

The analysis we present here uses LCOE figures reported by the U.S. EIA as our source of comparison. This analysis is limited to utility-scale generation and storage facilities. However, it is important to note that the SWB disruption as a whole will be driven not just by large, centralized facilities but by decentralized SWB installations at the commercial and residential scale as well. **Our projections for corrected LCOE calculations change only capacity factor, while leaving all other parameters unadjusted at industry-standard values, in order to show the sensitivity of LCOE to this single parameter when it correctly operates as a variable rather than as a constant in the relevant calculations.** We also ignore other considerations such as rising transmission and distribution costs, likely technological breakthroughs in solar PV and battery technology, and electric vehicles that will only accelerate the SWB disruption and further undermine the viability of conventional energy assets, as we describe in our report *Rethinking Energy 2020-2030: 100% Solar, Wind, and Batteries is Just the Beginning.*[21] Finally, note that for the illustrative purposes of this analysis we generously assume that the capacity factor of conventional coal, gas, nuclear, and hydro power plants will only decline to 10% rather than a full disruption and collapse all the way to 0% (which would result in an infinite LCOE by the 2030s).

Coal

The size of the coal fleet has shrunk dramatically over the last decade in both the United States (47% decline) and the United Kingdom (79% decline).[22,23] Conventional methods reported LCOE ranging from 6.5 to 15.9 cents per kilowatt-hour for newly-built coal power plants entering service in 2020.[2,9] However, these analyses typically assume a constant capacity factor of up to 85% for the entire 40-year technical life of the facility. In reality, the average capacity factor for coal power plants in the United States has been in severe decline for the last decade (Figure 5).

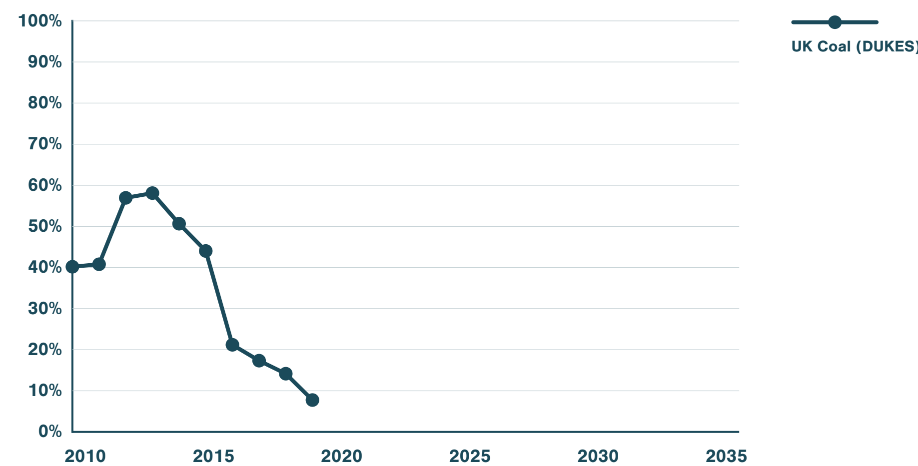
Figure 5: United States Coal Power Capacity Factor – U.S. EIA



Data Source: U.S. EIA, RethinkX.[14,18]

In the United Kingdom, the decline of coal capacity factor has been even more precipitous, as shown in Figure 6. (Note that we provide no scenario for future coal capacity factor in the United Kingdom because only 4 operational coal plants remain, these are slated for closure by 2025, and no new facilities are planned).[24]

Figure 6: United Kingdom Coal Power Capacity Factor



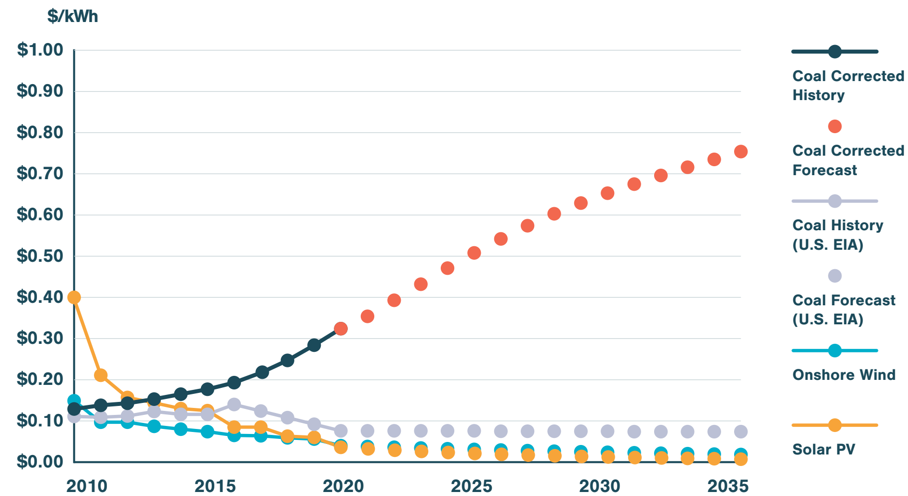
Data Source: DUKES.[15]

All else being equal, we would normally expect that as fleet size shrinks the remaining plants ought to retain their high capacity factor thanks to reduced competition. However, this has not always been the case, as indicated in Figure 5 and Figure 6, which show that coal has already been disrupted – first by gas, and now by SWB.

Figure 7 shows the LCOE figures for prospective coal power plants reported by the U.S. EIA for the last decade which assume a constant capacity factor of 85%. The agency did not report LCOE figures for 2017, 2018, or 2019, but did report a figure for 2020.[e] The new figure suggests a remarkable decline in LCOE during the missing years to just 7.6 cents per kilowatt-hour in 2020. Although the U.S. EIA does not explain how this number could have been achieved, it is possible they assume that all new coal plants incorporate dramatic improvements in the performance of ultra-supercritical coal power technology.[17] The U.S. EIA projects an LCOE of 7.3 cents per kilowatt-hour in 2019 dollars for coal power plants that enter service in 2040.[2] That is, they make the untenable assumption that the capacity factor for a coal plant will start at 85% in 2040, and that it will remain at 85% through at least 2060. The fact is that there's not a single regulated coal power plant that is competitive in the U.S. today. This means that the existing coal fleet is as good as stranded. It would be highly inaccurate to assume that prospective coal power plants could achieve anything more than peaker-like (low and shrinking) capacity factors going forward.

> **THE** "coal miracle" that is presented in the U.S. EIA Reference Case forecasts assumes unrealistically low capital and operating costs, as well as an unrealistically high and constant capacity factor.

Figure 7: United States Coal Power LCOE Comparison – U.S. EIA



Source: U.S. EIA, RethinkX.[2,17]

The LCOE for coal power reported by the U.S. EIA (gray) is artificially lowered by the assumption that newly-built coal power plants will achieve a capacity factor of 85% throughout their operational lifetime. This misrepresents the competitiveness of coal power compared to solar PV (orange) and onshore wind power (bright blue). (Note that the U.S. EIA did not publish values for coal LCOE for 2017, 2018, or 2019). When LCOE is recalculated using the actual values for average coal power capacity factor since 2010 (dark blue), it becomes clear that the corrected LCOE for coal power is far higher than reported. The gap between U.S. EIA projections and corrected LCOE widens dramatically as the capacity factor for coal power continues to collapse during the 2020s. Note also that solar and wind power achieved cost parity and became cheaper than the corrected coal LCOE several years earlier than the U.S. EIA reported.

> **BY** 2030, the LCOE of a new coal power plant is nearly 9 times greater than the U.S. EIA Reference Case assumption, at over 65 cents per kilowatt-hour.

For comparison, we provide corrections for both historical and forecasted LCOE of coal power plants in which capacity factor is not constant, but instead changes over a facility's lifetime.

First, we show corrected historical values for what coal LCOE would have been if the U.S. EIA had accurately anticipated the actual coal power capacity factor decline from 2010 through 2020, together with projected decline in capacity factor going forward as a consequence of the SWB disruption. The gap between these corrected values and the values reported by the U.S. EIA widens over time as real capacity factor falls, so that by 2020 the corrected LCOE of 32.4 cents per kilowatt-hour is over 4 times greater than the 7.6 cents reported by the U.S. EIA.

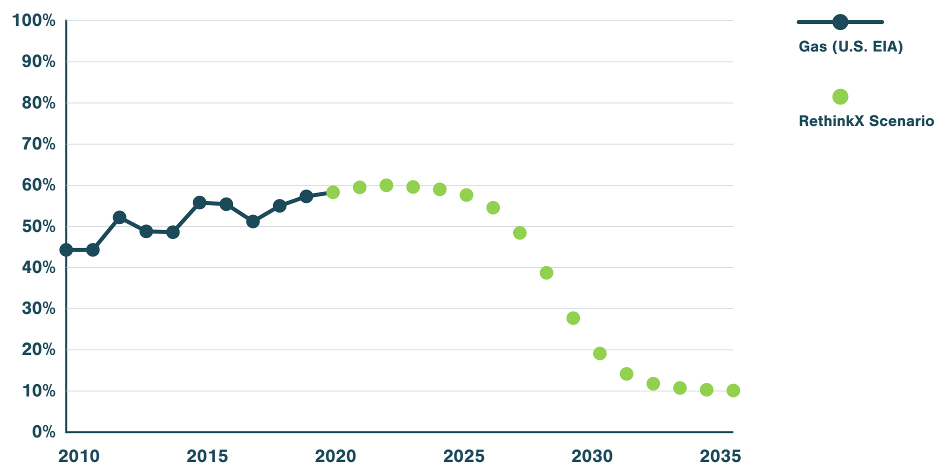
Second, we show projections for LCOE from 2020 forward, assuming an initial capacity factor of 40% (the actual 2020 value) that declines to 10% by 2035 as a result of the SWB disruption. Over the course of the 2020s, the corrected LCOE of new builds rises as average capacity factor continues to decline. **By 2030, the LCOE of a new coal power plant is nearly 9 times greater than the U.S. EIA Reference Case assumption, at 65.3 cents per kilowatt-hour.** (Note that this scenario is for illustrative purposes only. A more realistic outcome is full disruption and industry collapse as capacity factor approaches 0% and LCOE increases toward infinity).

The disruption of coal in the United States and the United Kingdom gives us a preview of the global disruption of all conventional electricity generation technologies that lies ahead in the next 10 to 15 years. Moreover, it also gives us an opportunity to recognize that the LCOE for coal power has been systematically underestimated compared to solar PV and onshore wind power for the last decade, and the distortion only grows looking ahead into the 2020s and 2030s. **The "coal miracle" that is presented in the U.S. EIA Reference Case forecasts assumes unrealistically low capital and operating costs, as well as an unrealistically high and constant capacity factor.** Moreover, the earliest a new ultra-supercritical coal power plant that began construction in 2021 could enter service in the United States is 2025, by which time the average capacity factor for coal power plants will have declined still further in the face of mounting competitive pressure from SWB.

Gas

The U.S. EIA reported an LCOE of 3.8 cents per kilowatt-hour for newly-built, combined-cycle gas power plants entering service in 2020.[17] The average capacity factor for advanced gas combined-cycle power plants in the United States has grown from 44% in 2010 to 58% in 2020 as a result of the emergence of fracking and the resulting disruption of coal power by gas (Figure 8). However, throughout that time, the U.S. EIA has assumed a constant capacity factor of 87% for the entire 20-year technical life of new gas power plants entering service, and continues to do so today. Other mainstream analyses have made similar assumptions.[2,9] At the same time, these analyses failed to accurately forecast the impacts of the fracking disruption on domestic gas production. The U.S. EIA, for example, predicted in 2005 that the United States would *import* 9 trillion cubic feet per year by 2025, but 10 years later the agency predicted that the United States would instead *export* 4 trillion cubic feet per year by 2025.[25]

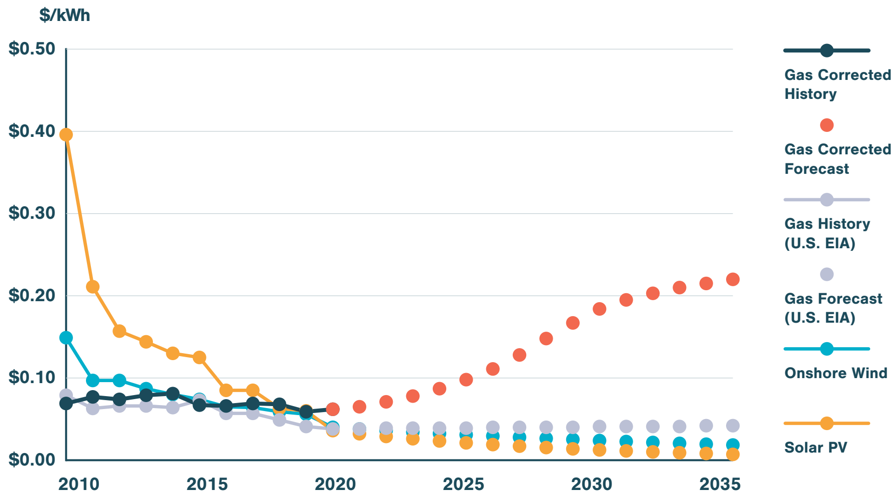
Figure 8: United States Gas Power Capacity Factor – U.S. EIA



Source: U.S. EIA, RethinkX.[14,18]

Figure 9 shows the LCOE figures for prospective advanced combined-cycle gas power plants reported by the U.S. EIA from 2010 through 2020, which assume a constant capacity factor of 87%. The agency projects an LCOE of 4.3 cents per kilowatt-hour in 2019 dollars for gas power plants that enter service in 2040.[2]

Figure 9: United States Gas Power LCOE Comparison – U.S. EIA



Source: U.S. EIA, RethinkX.[2,17]

The LCOE for gas power reported by the U.S. EIA (gray) is artificially lowered by the assumption that newly-built gas power plants will achieve a capacity factor of 87% throughout their operational lifetime. This misrepresents the competitiveness of gas power compared to solar PV (orange) and onshore wind power (bright blue). When LCOE is recalculated for average gas power capacity factor since 2010 (dark blue), a notable gap emerges, starting in 2016. The gap between U.S. EIA projections and corrected LCOE widens dramatically as the capacity factor for gas power collapses during the 2020s. Note also that solar and wind power achieved cost parity and became cheaper than the corrected gas LCOE several years earlier than the U.S. EIA reported.

For comparison, we provide corrections for both historical and forecasted LCOE of gas power plants in which capacity factor is not constant, but instead changes over the facility's lifetime.

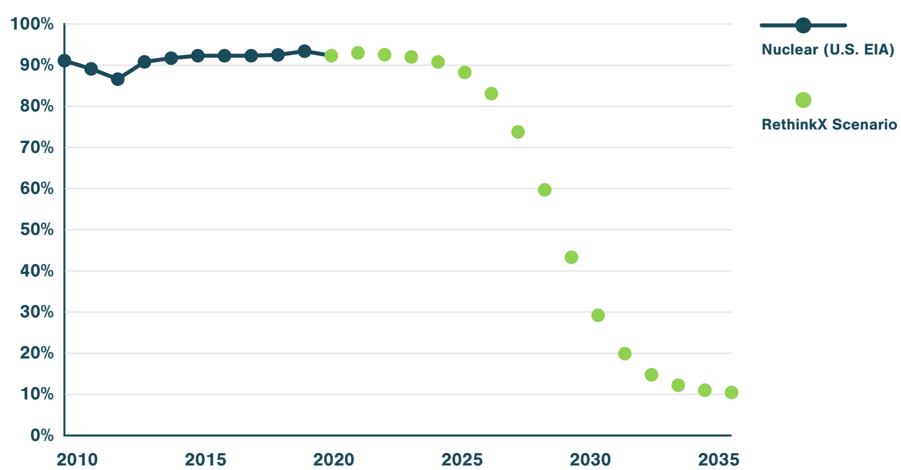
First, we show corrected historical values for what gas LCOE would have been from 2010 through 2020 based on actual capacity factor for that period, together with projected decline in capacity factor going forward as a consequence of the SWB disruption.

Second, we show projections for LCOE from 2020 forward assuming a maximum capacity factor of 60% reached in 2022, which then declines to 10% by 2035 as a result of disruption. In this scenario, gas power plants entering service in 2020 have an LCOE of 6.2 cents per kilowatt-hour – more than 60% greater the U.S. EIA's current estimate of 3.8 cents per kilowatt-hour. Over the course of the 2020s, the corrected LCOE of new builds rises as average capacity factor continues to decline. By 2030, the corrected LCOE of a new gas power plant is nearly 5 times greater than the U.S. EIA Reference Case assumption, at 18.4 cents per kilowatt-hour. (Note that this scenario is for illustrative purposes only. A more realistic outcome is full disruption and industry collapse as capacity factor approaches 0% and LCOE increases toward infinity).

Nuclear Power

The U.S. EIA reported an LCOE of 8.2 cents per kilowatt-hour for newly-built, advanced nuclear power plants in 2020.[9] However, this assumes a 90% capacity factor for the entire life of the facility. Note that the average capacity factor for nuclear power in the United States was in fact slightly higher than this – about 92% – for most of the decade from 2010 to 2020 (Figure 10).

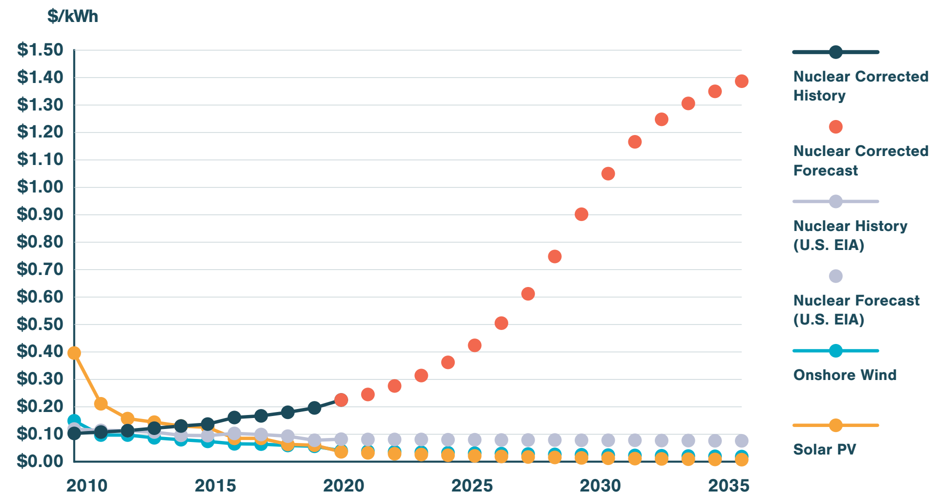
Figure 10: United States Nuclear Power Capacity Factor – U.S. EIA



Source: U.S. EIA, RethinkX.[18,26]

Figure 11 shows the LCOE figures for prospective advanced nuclear power plants reported by the U.S. EIA from 2010 through 2020, which assume a constant capacity factor of 90%. The agency projects an LCOE of 7.4 cents per kilowatt-hour in 2019 dollars for nuclear power plants that enter service in 2040.[2] Our previous research has already shown that the LCOE of nuclear is much higher than mainstream analysts claim, when costs such as decommissioning and full insurance costs are accounted for.[27]

Figure 11: United States Nuclear Power LCOE Comparison – U.S. EIA



Source: U.S. EIA, RethinkX.[2,17]

The LCOE for nuclear power reported by the U.S. EIA (gray) is artificially lowered by the assumption that newly-built nuclear power plants will achieve a capacity factor of 90% throughout their operational lifetime. This misrepresents the competitiveness of nuclear power compared to solar PV (orange) and onshore wind power (bright blue). When LCOE is recalculated for average nuclear power capacity factor since 2010 (dark blue), a notable gap emerges, starting in 2014. The gap between U.S. EIA projections and corrected LCOE widens dramatically as the capacity factor for nuclear power collapses during the 2020s. Note also that solar and wind power achieved cost parity and became cheaper than the corrected nuclear LCOE several years earlier than the U.S. EIA reported.

For comparison, we provide corrections for both historical and forecasted LCOE of nuclear power plants in which capacity factor is not constant, but instead changes over the facility's lifetime.

First, we show corrected historical values for what nuclear LCOE would have been from 2010 through 2020 based on actual capacity factor for that period, together with projected decline in capacity factor going forward as a consequence of the SWB disruption. Note that because the average capacity factor during this decade was slightly higher than the 90% that the agency assumed, our correction in the initial years is lower than the U.S. EIA's reported values. But by 2020, the corrected figure was almost three times higher than the reported figure.

Second, we show projections for LCOE from 2020 forward assuming a maximum capacity factor of 93% in 2021 that declines to 10% by 2035 as a result of disruption. (Note that this assumption may be unrealistically generous).[f] In this scenario, nuclear power plants entering service in 2020 have an LCOE of 22.5 cents per kilowatt-hour – 175% greater the U.S. EIA's current estimate of 8.2 cents per kilowatt-hour. Over the course of the 2020s, the corrected LCOE of new builds rises as average capacity factor continues to decline. **By 2030, the corrected LCOE of a new nuclear power plant is almost 14 times greater than the U.S. EIA Reference Case assumption, at 105 cents per kilowatt-hour.**

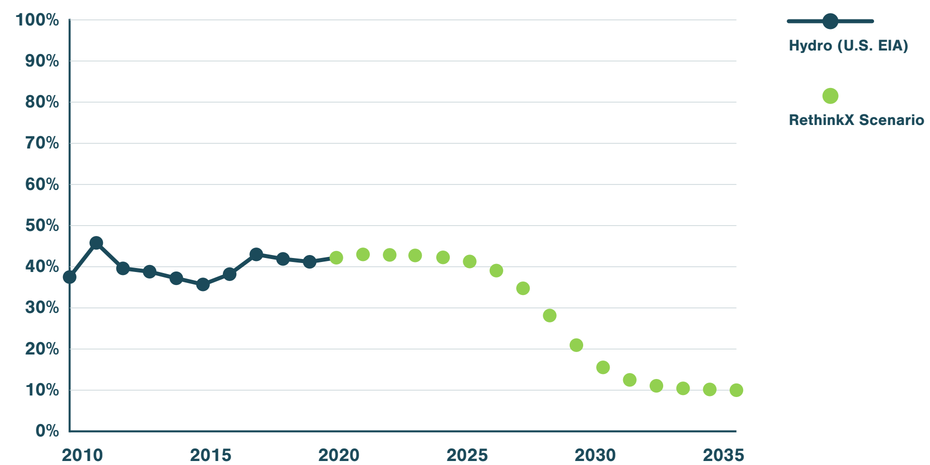
(Note that this scenario is for illustrative purposes only. A more realistic outcome is full disruption and industry collapse as capacity factor approaches 0% and LCOE increases toward infinity. However, nuclear power is subject to a number of important non-market forces and receives special consideration, prioritization, and protections because of its co-benefits to nuclear defense programs, and these will exert a strong influence on the choices that societies make about their civilian nuclear power industries).

BY 2030, the corrected LCOE of a new nuclear power plant is almost 14 times greater than the U.S. EIA Reference Case assumption, at 105 cents per kilowatt-hour.

Hydro Power

The U.S. EIA reported an LCOE of 6.6 cents per kilowatt-hour for newly-built hydro power plants in 2018.[28] However, this assumed a 65% capacity factor for the entire life of the facility. In 2019, however, the agency reported an LCOE of 3.9 cents per kilowatt-hour, based on the assumption of a 75% capacity factor for the entire life of the facility.[29] Then, in 2020, the agency reported an LCOE of 5.3 cents per kilowatt-hour, based on the assumption of a 59% capacity factor for the entire life of the facility.[30] Meanwhile, the actual average capacity factor for hydro power plants in the United States has grown slightly from 38% in 2010 to 42% in 2020, but at no time in the last decade has it exceeded 50% (Figure 12).

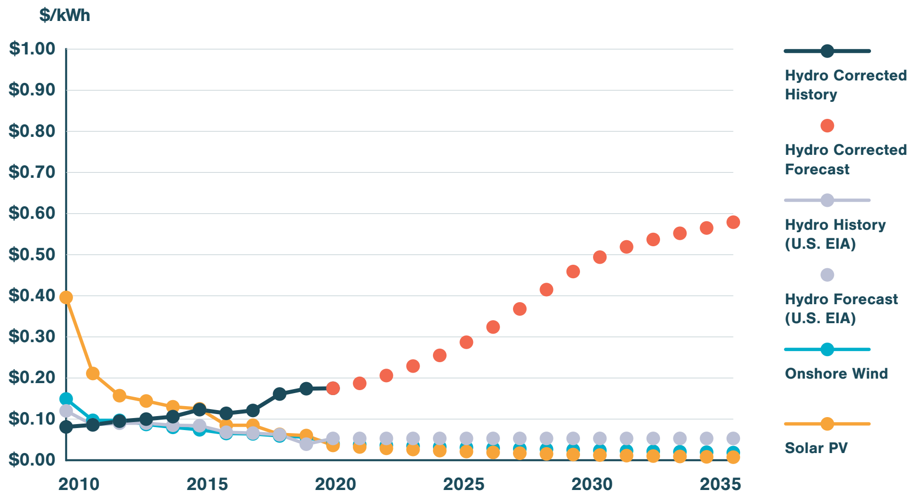
Figure 12: United States Hydro Power Capacity Factor – U.S. EIA



Source: U.S. EIA, RethinkX.[14,18]

Figure 13 shows the LCOE figures for prospective conventional hydro power plants reported by the U.S. EIA from 2010 through 2020, which assume a constant capacity factor throughout the lifetime of any newly-built facility. The agency projects an LCOE of 5.4 cents per kilowatt-hour in 2019 dollars for hydro power plants that enter service in 2040.[2]

Figure 13: United States Hydro Power LCOE Comparison – U.S. EIA



Source: U.S. EIA, RethinkX[2,17]

The LCOE for hydro power reported by the U.S. EIA (gray) is artificially lowered by the assumption that newly-built hydro power plants will obtain a high and constant capacity factor throughout their operational lifetime. This misrepresents the competitiveness of hydro power compared to solar PV (orange) and onshore wind power (bright blue). When LCOE is recalculated for average hydro power capacity factor since 2010 (dark blue), a notable gap emerges, starting in 2013. The gap between U.S. EIA projections and corrected LCOE widens dramatically as the capacity factor for hydro power collapses during the 2020s. Note also that solar and wind power achieved grid parity and became cheaper than the corrected hydro LCOE several years earlier than the U.S. EIA reported.

For comparison, we provide corrections for both historical and forecasted LCOE of hydro power plants in which capacity factor is not constant, but instead changes over the facility's lifetime.

First, we show corrected historical values for what hydro LCOE would have been from 2010 through 2020 based on actual capacity factor for that period, together with projected decline in capacity factor going forward as a consequence of the SWB disruption. By 2020, the corrected figure was almost three times higher than the reported figure.

Second, we show projections for LCOE from 2020 forward assuming a maximum capacity factor of 43% in 2021 that declines to 10% by 2035 as a result of disruption. In this scenario, hydro power plants entering service in 2020 have an LCOE of 17.5 cents per kilowatt-hour – 230% greater than the U.S. EIA's current estimate of 5.3 cents per kilowatt-hour. Over the course of the 2020s, the corrected LCOE of new builds rises as average capacity factor continues to decline. By 2030, the corrected LCOE of a new hydro power plant is nearly 10 times greater than the U.S. EIA Reference Case assumption, at 49.4 cents per kilowatt-hour.

(Note that this scenario is for illustrative purposes only. A more realistic outcome is full disruption and industry collapse as capacity factor approaches 0% and LCOE increases toward infinity. However, hydro power plants provide not just electricity generating capacity, but also water storage and, in many cases, pumped hydro energy storage services as well, so the decision of whether to invest or not in any specific hydro facility will depend upon the combination of these sources of value).

Implications

There is a growing gap between the real cost of conventional energy generation based on actual market dynamics and the levelized cost of energy (LCOE) reported by mainstream analyses based on the flawed assumption that the capacity factor for coal, gas, nuclear, and hydro power plants will remain high and constant over their entire operational lifetimes.

This divergence between real costs and the LCOE orthodoxy has been happening in the conventional power market since at least 2010. Today, this divergence is so large that mainstream analyses underestimate the per-kilowatt-hour cost of coal, gas, nuclear, and hydro power by up to a factor of 4, which badly misrepresents their competitiveness compared to solar photovoltaics, onshore wind, and battery energy storage (SWB), thus vastly overestimating the value of conventional energy assets.

Although our analysis focuses on capacity factor and LCOE, it is important to note that the same implications pertain to any method, metric, or analysis that ignores the reality of the SWB disruption and falsely assumes existing and/or new coal, gas, nuclear, and hydro power plants can continue successfully selling a fixed and high percentage of their electricity output in the decades ahead.

Our analysis has a number of important implications for energy and finance, as well as for society and the environment at large:

1. Conventional energy assets are severely mispriced, and their overvaluation is creating a growing asset valuation bubble in the conventional energy sector.
2. Coal, gas, nuclear, and hydro power are no longer competitive with the combination of SWB, even using inaccurate mainstream LCOE calculations.
3. Solar and wind power reached cost parity and became cheaper than coal, gas, nuclear, and hydro power several years sooner than mainstream analysts reported.
4. The widening gap between rapidly increasing conventional energy LCOE and rapidly decreasing SWB costs means that the SWB disruption will proceed faster than expected.
5. Coal and gas power plants with integrated carbon capture and storage (CCS) are doubly mispriced (overvalued).
6. Governments must protect people, not incumbent companies or industries, from the financial risk of the conventional energy asset bubble.
7. Carbon neutrality can be achieved more quickly and cheaply than generally expected.

1. Conventional energy assets are severely mispriced, and their overvaluation is creating a growing asset valuation bubble in the conventional energy sector

Widespread false assumptions about capacity factor and future cash flows of coal, gas, nuclear, and hydro power plants embedded in mainstream LCOE analyses have helped create a bubble in conventional energy assets worldwide that could exceed $1 trillion by 2030.

Modern finance states that the fundamental value of an asset (such as a gas power plant), property (such as commercial real estate), or security (such as stocks or bonds) is equal to the present value of the discounted cash flows generated by that asset. Future cash flows are based on the assumptions for future income minus costs.

Asset developers and managers make investment decisions largely based on assumptions about fundamental value that are determined by future cash flows and their associated risks. Long-term assets, such as those found in the conventional energy sector, are held by retirement and pension funds, university and foundation endowments, sovereign wealth funds, and insurance companies. Naturally, there are many unknowns when making investments in long-term assets such as power plants, pipelines, and ports, including geopolitics, resource constraints, and technology obsolescence.

However, throughout the 20th century, assumptions about the future cash flows of conventional energy assets were believed to be so reliable that LCOE was seen as sacrosanct, as if it were a constant of nature like the speed of light. But the world of energy has changed in the 21st century, first because of fracking and more dramatically because of SWB, whose near-zero marginal costs make them formidably competitive. In direct competition with SWB on open electricity markets, conventional baseload and peaker plants will rarely, if ever, be able to sell their electricity at prices high enough to cover their costs. As a result, trillions of dollars of investment is now based on a widely-held misperception of the fundamental value of coal, gas, nuclear, and hydro power assets because standard LCOE methodologies make false assumptions about the likely future cashflows of these facilities.

Our analysis shows that there is growing gap between the standard LCOE of conventional energy assets and their actual fundamental value. Since 2010, conventional LCOE analyses have consistently overestimated future cash flows from coal, gas, nuclear, and hydro power assets by ignoring the impacts of SWB disruption and assuming a high and constant capacity factor. In doing so, they have inflated the value of those cash flows and reported far lower LCOE than is actually justified.

Unrealistically low LCOE reported by conventional analyses for coal, gas, nuclear, and hydro power may have led governments and asset managers to make hundreds of billions of dollars in investments in conventional energy assets worldwide that they would not have otherwise made. Over $2 trillion has been invested in fossil and nuclear energy in the electric power sector worldwide since 2010.[16] If asset managers continue to invest in conventional energy technologies based on outdated LCOE estimates, there will be an increasing divergence between the book value and fundamental value of these assets. Continued over-investment in an asset class beyond what the fundamental value can possibly return is the very definition of a financial bubble.

Unless society makes immediate adjustments and starts valuing conventional energy assets using dynamic rather than static cost models, the misallocation of billions or even trillions of dollars worldwide will continue and the global conventional energy asset bubble will only grow. The bursting of this bubble could have serious consequences across the global economy that will only increase the longer the market delays making a correction.

2. Coal, gas, nuclear, and hydro power are no longer competitive with the combination of SWB, even using inaccurate mainstream LCOE calculations

In our 2020 report *Rethinking Energy 2020-2030: 100% Solar, Wind, and Batteries is Just the Beginning*, we showed that SWB power plants are already the cheapest form of electricity generation, and that their costs will fall a further 70% over the next 10 years as global deployment continues to expand exponentially. This means that SWB will continue to capture an increasing market share of power generation over the next decade, while conventional coal, gas, nuclear, and hydro power plants will compete among each other for a dwindling share of the market.

The question of which conventional energy assets will survive, if any, depends upon both market forces and regulatory action. In competitive wholesale markets, the sources of energy with the lowest marginal cost will survive and grow. Because SWB assets have near-zero marginal cost, they will naturally win any wholesale market auction in which they are allowed to participate freely without artificial constraints.

In principle, nuclear power plants should have a marginal cost lower than coal plants and competitive with some gas power plants.[2,9] In practice, however, prospective nuclear power plants are not economically viable in competitive electricity markets.[g] Conventional nuclear power has historically been one of the only major industries in the world with a negative learning rate: as we build additional plants, they become more rather than less expensive. However, history suggests that civilian nuclear programs are likely to persist despite their lack of economic viability due to direct and indirect subsidies and market-distorting support provided by national governments in order to preserve a critical mass of scientific, technological, and material resources necessary to maintain their military nuclear infrastructure.[27]

Hydro power also has a low marginal cost of energy, and thus, in a competitive market, existing hydro power assets will usually succeed in selling electricity when they are able to produce it. Although our analysis indicates that new hydro power is not competitive against new SWB, many existing hydro power facilities are also able to provide low-emission energy generation and storage, and so are likely to receive continued government support.

Altogether, this means that fossil fuel power plants will inevitably be disrupted both from below,[h] by utility scale SWB generation, and from the edge,[i] by distributed SWB generation, while simultaneously having to compete with legacy nuclear power plants propped up by regulators and existing hydro power plants with low marginal costs. Coal power has a higher marginal cost than gas in most markets worldwide, especially in the United States where the adoption of fracking has lowered the cost of gas even further, and so gas will likely be the conventional power generation of choice as the SWB disruption unfolds during the 2020s. As the social license for fossil fuels erodes, local political conditions will determine which fossil fuels temporarily receive regulatory and financial protection as they face disruption.

3. Solar and wind power reached cost parity and became cheaper than coal, gas, nuclear, and hydro power several years sooner than mainstream analysts reported

Mainstream analysts now agree that solar and wind power are the cheapest sources of electricity.[31] However, this crossover actually occurred several years earlier than the U.S. EIA and other widely-cited sources have reported. Our analysis shows that mainstream analysts have underestimated the LCOE of conventional power plants for the last decade. **When we retroactively recalculate LCOE accounting for a dynamic rather than static capacity factor, we find that solar PV reached cost parity in 2013 rather than 2016 for coal, in 2018 rather than 2020 for gas, in 2014 rather than 2016 for nuclear, and 2015 rather than 2020 for hydro power. Moreover, the cost gap between SWB and conventional power plants is widening much more rapidly than mainstream analysts are projecting. By the 2030s, the LCOE of a newly-built solar PV will be less than 1/20th that of any newly-built coal, gas, nuclear, or hydro power plant because these conventional plants will – at best – have a capacity factor and utilization profile comparable to today's peakers.**

BY the 2030s, the LCOE of a newly-built solar PV will be less than 1/20th that of any newly-built coal, gas, nuclear, or hydro power plant because these conventional plants will – at best – have a capacity factor and utilization profile comparable to today's peakers.

4. The widening gap between rapidly increasing conventional energy LCOE and rapidly decreasing SWB costs means that the SWB disruption will proceed faster than expected

Much of the conventional energy industry pushback against the possibility of a rapid SWB disruption during the 2020s has been based on flawed LCOE calculations that have misrepresented the cost of coal or gas relative to SWB. There is a wide and growing gap between the mainstream LCOE figures that incumbents and analysts cite and the more realistic LCOE shown in our analysis that accounts for market dynamics and diminishing utilization of conventional coal, gas, nuclear, and hydro power assets caused by the SWB disruption.

History shows that once the divergence between costs reported by obsolete metrics becomes impossible for incumbents to hide, financial markets move swiftly to withhold new capital from the old industry and instead rapidly divert investments into building out the new industry instead. We have seen this dynamic play out many times in recent years, including in telecoms as landlines were disrupted by cellular phones (which were then disrupted by smartphones), in photography as celluloid film cameras were disrupted by digital cameras (which were then disrupted by smartphones), and in music, film, and television as physical records (vinyl, tapes, CDs, and DVDs) were disrupted by streaming services. GE, an American powerhouse for a century, lost more than 74% of its market valuation in 2017/2018 as Wall Street support for thermal (coal, gas, and nuclear) power collapsed. We then saw how market valuations in the electric vehicle sector (including its value chain) rose by about an order of magnitude in capital markets in 2020.

5. Coal and gas power plants with integrated carbon capture and storage (CCS) are doubly mispriced (overvalued)

Incumbent industry advocacy for CCS technology intended to be utilized by "clean coal" and "clean gas" capitalizes on the underestimation of LCOE of these power plants by conventional cost analyses. The false narrative of "cheap" electricity from coal and gas feeds another false narrative – that investing billions or trillions of dollars in CCS infrastructure is a viable pathway to achieve a carbon-neutral electricity system.

The false promise of affordable carbon-neutral electricity from "clean coal" and gas plants utilizing CCS technology diverts attention and investment away from SWB, and is likely helping to inflate the conventional energy asset bubble.[32]

6. Governments must protect people, not incumbent companies or industries, from the financial risk of the conventional energy asset bubble

Faulty conventional LCOE analyses that have underestimated the cost of coal, gas, nuclear, and hydro power and thereby overstated their competitiveness and ability to forestall disruption by SWB have likely helped create a trillion-dollar bubble in conventional energy assets worldwide. Because pension, retirement, and endowment funds have substantial holdings in conventional energy assets, it is members of the public – regular people across all of society – who are exposed to the financial risk of the conventional energy asset bubble, not just wealthy investors. Unfortunately, long-term asset valuation bubbles are largely non-diversifiable risks, so it is possible that a portion of retirement funds, sovereign wealth funds, and education and foundation endowments could be lost over the next decade unless investors, policymakers, civic leaders, and other decision-makers act quickly to make appropriate divestments.

Governments must therefore take steps today and actively prepare to protect people from financial disaster when the bubble inevitably bursts and the majority of coal, gas, nuclear, and hydro power assets are stranded over the coming decade.

7. Carbon neutrality can be achieved more quickly and cheaply than generally expected

Our analysis shows that SWB is much more cost competitive with coal, gas, nuclear, and hydro power than is generally believed because the LCOE for conventional plants reported by mainstream analyses is unrealistically low. This means that eliminating emissions and achieving carbon neutrality in the electricity sector is more economically feasible than is widely believed, and that the transformation of the electricity sector can therefore be achieved more quickly than today's environment and climate change policies assume.

Equipped with this knowledge, **governments can and should recalibrate their emissions targets and bring forward their policy and planning timelines for achieving 100% clean energy into the 2030s from the 2050s and 2040s (which are based on flawed LCOE estimates).**

> **GOVERNMENTS** can and should recalibrate their emissions targets and bring forward their policy and planning timelines for achieving 100% clean energy into the 2030s from the 2050s and 2040s (which are based on flawed LCOE estimates).

Choices

Like most other instances of dogma, standard LCOE analysis is promulgated by a small number of self-appointed authorities within the electric power sector which form a citation ring that confirms and amplifies a fixed set of thoughts, beliefs, and biases. Like any dogma, standard LCOE analysis is cloaked in the mantle of received truth that few within the industry dare to question.

But continuing to accept the standard LCOE dogma is a choice. Investors, businesses, policymakers, and civic leaders should choose to reject this dogma and instead demand that all energy assets – from plants and refineries to pipelines and ports – adopt a dynamic and transparent LCOE model that more realistically reflects current as well as likely future market conditions and risks based on the reality of the SWB disruption.

With respect to dynamic LCOE, our analysis suggests that decision-makers should consider the following specific choices:

- Investors, businesses, policymakers, and civic leaders should demand that conventional power plant sponsors use a dynamic LCOE model in their cash flow calculations, rather than a static LCOE model that assumes capacity factor remains high and constant for the entire financial lifetime of a power plant.
- Dynamic LCOE models should assume that new power plants will begin operation with only the prevailing capacity factor found in the market. That is, if coal power plants have an average capacity factor of 40% in a given market, the dynamic LCOE model should assume only 40% capacity factor for the first year of operation.
- Assumptions about power plant operational lifetimes should also reflect the disruption and subsequent dominance of electricity markets by SWB. Again, the onus rests on analysts to justify how any new conventional power plant expects to compete in wholesale electricity markets against SWB that is both cheaper and cleaner in the 2020s and 2030s.
- Tax and accounting authorities should allow for faster depreciation schedules to reflect the fact that the useful life of conventional power plants is unlikely to be greater than 10 to 15 years because of the SWB disruption.

Open, transparent, and liquid markets can be much more responsive to new information than regulators and public utility commissions. For example, the equity value of coal companies reflected in the Dow Jones U.S. Coal Index (DJUSCL) fell 99% from 500 in 2011 to under 5 by 2020, and in September of 2020 S&P DJI delisted coal companies from its indices and ceased reporting the DJUSCL altogether. **The growing divergence between real costs and static LCOE shows that coal energy assets are still being priced as if this equity crash had not happened. Part of the reason why conventional energy assets are currently overvalued is that they are priced by incumbents within an information echo chamber using static LCOE and other obsolete valuation metrics. The growing divergence between reality and this echo chamber indicates that regulators have outsourced their responsibility for asset pricing to organizations like the IEA, U.S. EIA, a few mainstream consulting firms, and Wall Street analysts.** These organizations play the role that the credit rating agencies played in mispricing subprime mortgage assets which led to a housing bubble, financial crisis, and ultimately the Great Recession between 2007 and 2009. Just as it was then, this is a recipe for disaster.

With respect to markets, our analysis suggests that decision-makers should consider the following specific choices:

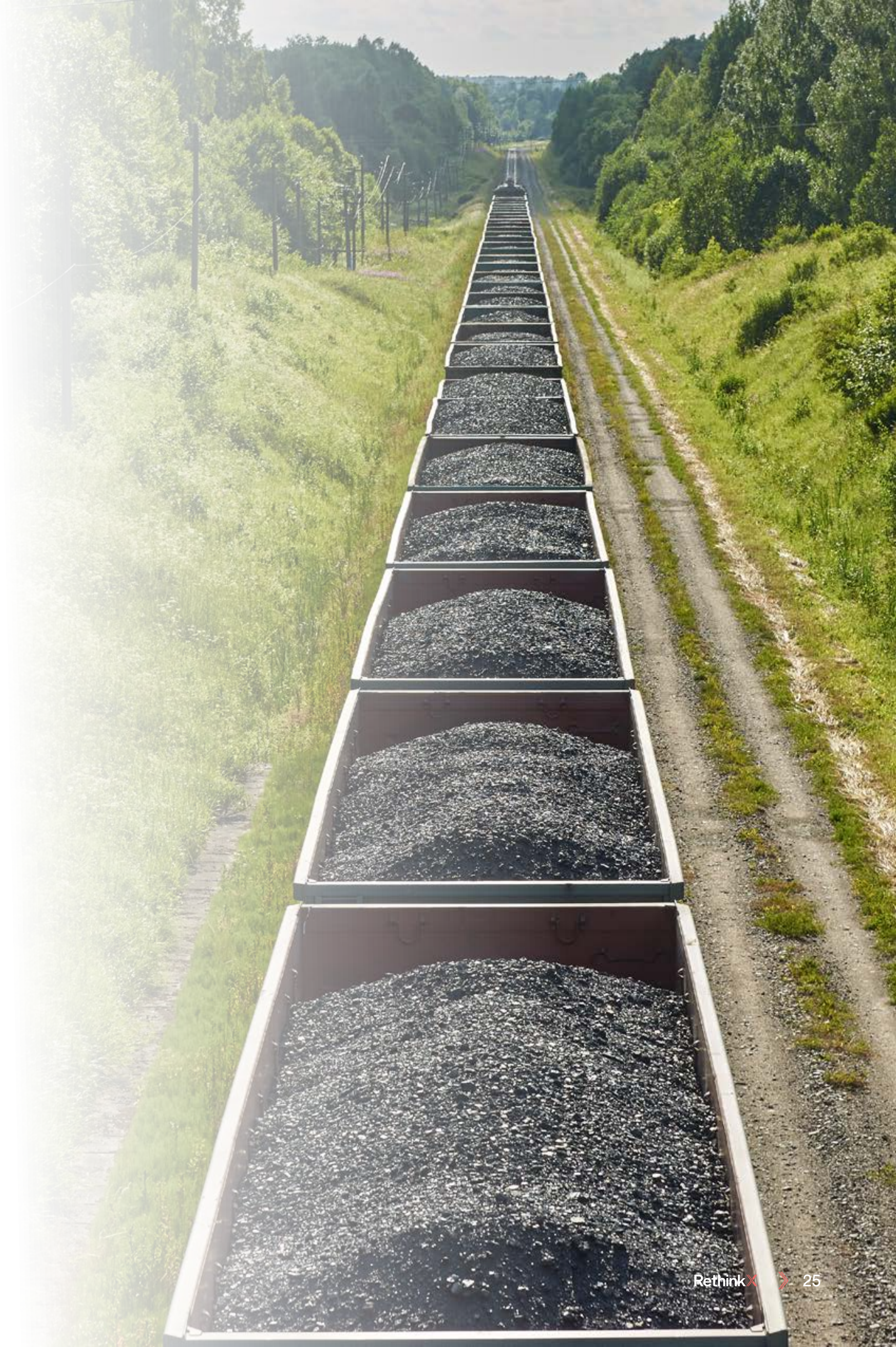
- Demand that analysts calculate LCOE on the basis of realistic, dynamic, market-based, assumptions for capacity factor (utilization rate) and all variables of their LCOE calculations both historic and projections.
- Demand that conventional energy project promoters calculate LCOE on the basis of realistic, dynamic market-based assumptions for capacity factor (utilization rate) and other variables.
- Review asset valuations of existing holdings of conventional energy assets on the basis realistic, dynamic LCOE calculations.
- Lenders should only lend to conventional energy asset owners on the basis of realistic, dynamic LCOE calculations.
- Valuation of supply chain assets (pipelines, mines, ports, etc.) should take into account a demand model based on realistic, dynamic LCOE calculations of conventional power plants.

- Government regulators, including public utility commissions that ostensibly approve power plant investments on behalf of the people, should not enlist ratepayers to subsidize, insure, or provide a backstop for any existing investments in conventional energy assets or their supply chains.[j]
- Utilities should be obligated to use shareholder (equity) capital in any new conventional energy investment, or to refinance existing conventional energy assets. If a project is not good enough for shareholders, it is certainly not good enough for captive ratepayers.

It is now obvious that new investments in conventional energy generation are not financially viable going forward. With such large financial commitments at stake, the public should hold policymakers, regulators, civic leaders, and investors accountable for ensuring that the pensions and retirement savings of regular people are protected from the conventional energy asset bubble.

With respect to protecting pensions and savings, our analysis suggests that decision-makers should consider the following specific choices:

- Financial institutions with public backing and multilateral financial organizations such as the World Bank and the International Monetary Fund should not use the public's money to invest in conventional energy assets or their supply chains – including power plants, refineries, pipelines, ports, and mines.
- Pension/retirement funds and other asset managers should not invest in conventional energy assets or their supply chains – including power plants, refineries, pipelines, ports, and mines – under the false pretense that these are low-risk commitments, but instead should be fully aware of the high-risk nature that all conventional energy asset investments represent in the face of disruption by SWB.
- Market openness, transparency, and liquidity should be requisite conditions for any investment of pension/retirement funds in conventional energy assets.
- Pension/retirement funds and other asset managers should not lend to conventional energy asset owners based on the mispriced book value of those assets because it is in those owners' economic interest to borrow against overvalued assets and thus offload risk from shareholders to debt holders.



Appendix A

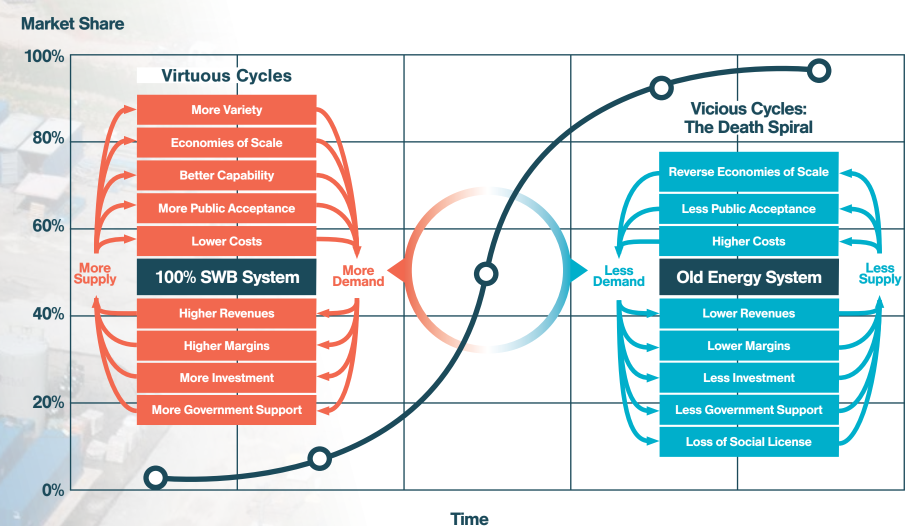
How Disruption Sends Conventional Technologies into a Death Spiral

How Disruption Sends Conventional Technologies into a Death Spiral

The disruption of the electric power sector by solar, wind, and batteries (SWB) during the 2020s will unfold much more rapidly than mainstream forecasts expect because the dynamics will be driven not just by falling costs of SWB, but also by rising costs of electricity generated by incumbent coal, gas, nuclear, and hydro power plants. These two mutually-reinforcing trends will amplify and accelerate one another as the disruption takes hold.

The dynamics of disruption are nonlinear and have already begun to affect the electric power sector. As with previous disruptions across other markets of all kinds, SWB will enjoy a virtuous cycle of accelerating adoption while incumbent technologies enter a death spiral as they are gripped by a vicious cycle of shrinking demand and rising costs. These dynamics are driven by causal feedback loops, the primary pathways of which are shown in Figure 14.

Figure 14: Feedback Loops Drive Disruption



History shows that technology disruptions are nonlinear because they are driven by reinforcing causal feedback loops. These loops interact with and amplify one another, accelerating the adoption of new technology in a virtuous cycle while at the same time accelerating the demise of old technology in a vicious cycle. The net result of these systems dynamics is that disruption tends to unfold with shocking swiftness, and the growth of new technologies charts a characteristic S-curve.

Like other technology disruptions throughout history, the virtuous cycle for SWB begins with falling costs, which increases demand. Demand drives industry growth, attracts investment, and garners increasing government support, leading to an expansion of supply. As supply grows, economies of scale are realized that improve capabilities and lower costs further, while at the same time public acceptance increases, all of which serves to increase demand further. The autocatalytic and self-reinforcing nature of this virtuous cycle means that the rate of adoption of new technologies always accelerates during the initial stage of disruption. This is why disruptions always chart an S-curve. In the specific case of the SWB disruption, the new technologies also bring social and environmental benefits over a conventional coal, gas, and nuclear technologies. These include reduction of greenhouse gas emissions, ending reliance on foreign energy imports, increased resilience and reliability of electricity supply, net job creation, and an enormous surplus of near-zero marginal cost energy production throughout much of the year that we refer to as “super power”.

Meanwhile, the vicious cycle for conventional coal, gas, nuclear, and hydro power will be driven by falling demand as they are progressively outcompeted by SWB. Less demand means less revenue with which to cover costs, and therefore narrower margins and less profit. At the same time, a decline in demand and less competitive economic prospects can result in the loss of government support for the technology. Shrinking profits and bleak prospects for the future discourages new investment, leading to a contraction of supply. As supply shrinks, the incumbents suffer reverse economies of scale, costs rise, and public acceptance of the risks and externalities of fossil and nuclear fuels erodes, all of which serves to reduce demand further, and so the cycle repeats and accelerates.

The loss of profitability and equity that signals a death spiral can swiftly trigger either a direct collapse that strands assets or a change in business strategy into rundown mode, which maximizes short-term profits by abandoning upkeep and other expenses required to maintain long-term viability (which then ultimately ends in the stranding of assets as well). In the case of conventional energy assets whose business models are characterized by low margins, high leverage, and dependence upon extremely consistent revenues, a relatively small decrease in demand can turn profits into losses, and solvency into bankruptcy.

The virtuous cycle enjoyed by SWB and the vicious cycle suffered by coal, gas, nuclear, and hydro power will feed into each other, because falling demand for the old and growing demand for the new serve to accelerate one another.
The net result of these nonlinear disruption dynamics, which we see again and again across industries of all kinds, is explosive growth of the disruptors and startlingly swift collapse of the incumbents. It is for this reason that disruption tends to take industries by surprise, and the electric power sector is poised to follow this same pattern.

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Notes

a Costs include: capital expenditures, interest on debt, fixed operating costs, variable operating costs including fuel, depreciation, taxes (and how these are affected by inflation), and, sometimes, equity returns on investment (i.e. earnings to be disbursed to investors). The calculation of LCOE is typically formulated in terms of net present value, which is presumed to be zero, as this has the effect of identifying the breakeven price at which each unit of electricity produced by that facility must be sold. This formulation allows the cost of capital to be computed using the discount rate (i.e. interest paid at the beginning of each period) rather than using the effective interest rate (i.e. interest paid at the end of each period). The timeframe in question varies from one technology to another according to the assumed lifetime of the facility – typically 20 to 40 years.

b A notable exception is Fraunhofer ISE, whose LCOE methodology does not make this error. (Fraunhofer ISE's LCOE methodology uses an assumed quantity of full load hours instead of computing this quantity from the facility's nameplate capacity using a capacity factor, but the end result is the same). Fraunhofer ISE assumes full load hours will decline each year for conventional coal, gas, and nuclear technologies.[19] It should be noted, however, that Fraunhofer ISE's projections for the rate of decline assume a slow energy transition and do not account for disruption, and as a result are unrealistically modest. Note that the term load factor is used synonymously with capacity factor by some analysts.

c This error is further magnified when the additional social and environmental costs of conventional energy assets are fully accounted for.

d Negative prices result primarily from conventional coal and nuclear power plants attempting to avoid the expense of ramping power output up and down. It is cheaper in some circumstances for these power plants to pay customers to take their power than to ramp up and down, thus leading to negative bids at auction. Because solar and wind power have near-zero marginal costs, wholesale prices clear near zero (or negative) in regions with substantial solar and wind capacity whenever when sunshine and wind resources are abundant.

e It appears that this is because no new coal power plants were scheduled for construction during that period.

f Nuclear power plants face unique technical challenges in ramping production up and down, and there are conflicting claims about how flexible the output of different power plants could be if their prioritization and protected status as baseload providers were revoked. It is therefore uncertain whether nuclear power plants could continue to operate at all below a given capacity factor threshold. For the purposes of this analysis, we assume that it is possible for newly-built nuclear power plants to continue to function regardless of how low their capacity factor falls, but we recognize that this may be an unrealistically generous assumption.

g The Flammanville nuclear power plant in France, the Hinkley Point nuclear power plant in the UK, and the Vogtle nuclear power plant in the U.S. are current examples of boondoggles with repeated delays, ongoing safety concerns, and enormous cost overruns.

h In the Seba Technology Disruption Framework, disruption from below occurs when a new technology emerges that is initially inferior to mainstream products, but improves its performance while decreasing costs at a faster rate than incumbent products.

i In the Seba Technology Disruption Framework, disruption from the edge occurs when a new technology radically changes the way products and services are produced, managed, delivered, and sold.

j Regulators effectively issue a 'regulatory put', whereby put options are issued (on behalf of the public) that allow asset owners to capture the upside while ratepayers (the public) are forced to assume the risk and pay for any externalities or downside. Because the party that bears the cost and risk of the asset (i.e. ratepayers) is captive and does not participate in setting the asset price, there is very little incentive for this regulatory process to price assets fairly.

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Adam Dorr is an environmental social scientist and technology theorist whose current research with RethinkX is focused on the disruption of the global energy sector by new energy generation and storage technologies, and its intersection with similar disruptions set to unfold across the economy. He completed his MS at the University of Michigan's School for the Environment and Sustainability and his PhD at UCLA's Luskin School of Public Affairs, where he studied the environmental politics, policy, and planning around disruptive technologies. He has a decade of teaching, lecturing, and presenting experience.

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The RethinkX Project

RethinkX is an independent think tank that analyzes and forecasts the speed and scale of technology-driven disruption and its implications across society. We produce impartial, data-driven analyses that identify pivotal choices to be made by investors, businesses, policymakers, and civic leaders.

Rethinking Energy 2020-2030

A large and rapidly-expanding global financial bubble now exists around conventional coal, gas, nuclear, and hydro power energy assets. This bubble has in part been created by mainstream energy analyses that have, for the last decade, significantly underestimated the levelized cost of electricity (LCOE) from conventional power plants because they assume these plants will be able to successfully sell the same quantity of electricity each year from now through 2040 and beyond. This assumption has been false for at least ten years. The rates at which conventional power plants are utilized will continue to decrease as competitive pressure from near-zero marginal cost solar photovoltaic and onshore wind power, and battery energy storage continue to grow exponentially worldwide.

Since 2010, the LCOE figures published in mainstream analyses and used by policymakers, regulators, civic leaders, utilities, asset owners, and investors have significantly underestimated the actual cost of electricity generated by prospective coal, gas, nuclear, and hydro power plants. This in turn means that conventional energy asset valuations are heavily overstated. Fundamental valuation of an asset is based on expected future cash flows that are, in turn, dependent upon projected revenues and costs. The projected revenues and costs of any power plant are dependent upon its assumed capacity factor (or utilization rate), which is the fraction of its generating capacity it is actually able to produce and sell.

The LCOE methodologies used in virtually all mainstream analyses contain the same critical error: they assume a high and constant capacity factor (utilization rate) for the entire lifetime of any individual power plant. In doing so, they assume both existing and newly-built power plants will be able to produce and sell the same number of kilowatt-hours each year throughout their 20+ year operational life. Widely-cited sources that commit this error include the International Energy Agency (IEA), the United States Energy Information Administration (U.S. EIA), the World Bank, the International Renewable Energy Agency (IRENA), the Department for Business, Energy & Industrial Strategy of the UK government, the Australian Energy Regulator, the National Renewable Energy Laboratory (NREL and OpenEI), Lazard, Stanford University, the University of Texas at Austin, the MIT Energy Initiative, and the Natural Resources Defense Council (NRDC).