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Executive Summary

The Sun Has Won, Part 1: Market Inevitabilities In Electricity Production

The Sun has won. Solar power now provides “the cheapest electricity in history”, according to the International Renewable Energy Agency. Solar power costs continue to fall due to a combination of technological progress and expanding economies of scale. Annual solar installations have grown exponentially for decades, and now that solar has a fundamental cost advantage over fossil fuels this trend will continue for decades to come. In contrast, costs for coal power are flat or rising, depending on the region, largely because utilization rates at power generation facilities have fallen to all-time lows. Military conflict now disrupting fossil fuel supplies is accelerating these trends. Any war-related increases in fossil fuel production and use are, with virtual certainty, temporary.

The long term cost advantage of solar, and more generally of all renewables, is a death knell for the fossil fuel age. Nevertheless, because coal is still used to generate 60% to 70% of electricity for China and India, the ground truth is that coal will be burned for many years to come. Yet producing electricity using inefficient combustion of an expensive fuel now levies a heavy, ongoing economic toll. The prospect of shifting from coal to gas as a fuel gives little respite from the competition from solar; the combination of new solar power and battery storage is expected to outcompete the marginal cost of operating gas plants by 2025. That is, new installations that combine solar and batteries will soon cost less than the fuel burned in existing gas-fueled electricity generation stations. It is frequently argued that gas is a bridge fuel, but instead natural gas is a bridge to nowhere. The lifetime of coal and gas will be circumscribed by the project timelines to build out wind and solar generating capacity.

Continued investment in fossil fuels, whether by public or private entities, will be investment in capital-inefficient, uncompetitive energy production. To put that another way, most organizations that continue to build and operate gas- or coal-fired power plants after 2025 will not be making decisions based on rational energy economics, nor on purported calculations related to grid stability. In most cases, a dollar, yuan, or euro spent on fossil fuels already delivers substantially less useful energy to the end user than the same amount spent on renewable energy.

Paying the energy and capital efficiency penalties inherent in fossil fuel mining and combustion made economic sense for centuries because there were few competitive alternatives. Now, however, renewable electricity both 1) outcompetes fossil fuels economically in spot markets and 2) provides an economy-wide structural competitive advantage over combustion. States that rapidly adopt renewables will enable more capital-efficient economic activity, thereby freeing up funds for other investments, and will therefore have a greater competitive edge in global markets than those nation states that continue to burn fossil fuels.

The advantage for renewables exists regardless of the volume of domestic fossil fuel energy production or consumption, and that advantage is growing; there are ever fewer locations in which mining and combustion are better means to produce either work or heat than renewable electricity. Moreover, whereas the marginal cost of electricity production by photovoltaics (PV) and wind is approximately zero, to produce ongoing value from fossil-fueled electricity plants requires the constant incineration of assets, and thus the constant incineration of capital. Continuing to burn fossil fuels thereby carries a significant economic cost, and constitutes a self-imposed financial penalty. This combustion penalty applies to every year in which a nation chooses to burn fossil fuels rather than install renewables, and ultimately degrades that nation's long-term global competitiveness. The penalty is also cumulative, because capital deployed to build renewables rather than spent on fossil fuels is more efficiently used, produces an equivalent or better return, and carries a lower total cost. Continuing to burn fossil fuels will become a symbol of backwards thinking and poor planning.

New renewables first clearly became less expensive than most fossil fuel combustion in 2016. In the years since, it has become increasingly difficult for a rational economic actor to favor new fossil fuel projects over renewables. To the extent that local energy costs for manufacturing and services determine global competitiveness, the cost advantage brought by deploying low-cost solar will drive adoption in regions that wish to remain competitive. Going forward, any new fossil fuel combustion capacity will be driven by subsidies and policy considerations, such as ensuring short-term energy supplies, which will, nevertheless, arguably reduce economic competitiveness. The continued roll out of battery storage globally will further accentuate the economic advantage of renewable electricity by enabling time-shifting of supply and by reducing intermittency. In geographies in which installing new wind and PV today costs less than the marginal cost of coal and gas as fuel, even continuing to operate the existing combustion fleet impairs economic competitiveness.

The implications of eliminating the combustion penalty appear to be frequently misunderstood by many journalists and investors; the vast majority of spending on renewables over the next several decades will simply be redirecting capital toward more efficient energy supply. That is, the large sums that will be invested in renewable power, and that are all too frequently portrayed as “extra” spending, will in fact be directed to renewables *instead of* fossil power. That spending will produce more useful electricity from wind and solar than it would have from burning fossil fuels, because renewables are more capital-efficient than are fossil fuels, which is an incentive to shift investment from fossil fuels to renewables with haste. This transition can already be seen in the emerging dominance of renewables in debt financing, total investment, and most obviously, in new annual generation capacity. The advent of war in Europe, in which the production and distribution of fossil fuels has been weaponized, serves as a lens to focus attention on the advantages of distributed production of electricity.

The cost of wind or of light from the sun does not depend on the price of coal or gas, nor upon any state of war. The price of electricity produced using renewable resources is quite stable over time, and the use of that energy for commercial operations is both lower cost and lower risk than reliance on fossil fuels, which fluctuate in price and availability. Moreover, as photovoltaic modules, and all their constituent components, are increasingly manufactured using electricity itself produced using solar power, the cost of new modules will become decoupled from the price of fossil fuels and will fall even further, creating an expanding economic advantage over fossil fuels. The implication of the long term cost trend is very clear; solar power is the future of electricity generation.

About Planetary Technologies™, LLC

Planetary Technologies, LLC invests at the leading edge of industrial revolutions. Our mission is to find and fund scalable technologies that can help the world mature beyond fossil fuels at the pace necessary to avoid unsustainable warming. The Planetary Technologies team has a combined five decades of experience in startup operations, engineering, product development, science, strategy, techno-economic analysis and forecasting, and venture capital. Our strategic analysis and quantitative research is cited prominently by governmental policies and roadmaps produced by the United States, Great Britain, the European Union, the OECD, and the UN. We are right early, and right often.

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The Sun Has Won, Part 1: Market Inevitabilities In Electricity Production

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Summary: Solar power now provides the lowest cost electricity generation in history. The continuing decrease in solar costs is driven by technological change, economies of scale, and by learning effects derived from the expansion of manufacturing. This cost trend is coupled to an annual exponential increase in solar installation that has run for more than 25 years and that is likely to continue, if not accelerate. Falling costs for solar power are accompanied by a long-term shift in the structure of investment; in 2021 more money was invested on an annual basis into renewables projects than into fossil fuel projects, more new solar power was built than any other generating capacity, and the cost of capital for solar projects was at least 4X lower than for fossil fuel projects. As a result, new solar installation now constitutes more capital-efficient electricity generation than any other source with the exception of wind, which is economically and physically efficient only when installed at very large scales. Taken together, these factors reveal that solar power is now a better, and lower risk, investment than new fossil-fueled electricity projects. Despite this cost advantage, many countries will continue to build and operate coal and gas generating capacity because 1) these facilities provide both electricity generation and employment, and 2) constructing adequate manufacturing capacity for renewables to fully replace fossil fuels is likely the work of decades. Yet by approximately 2025, operating the vast majority of existing fossil fuel power production will be inefficient and uncompetitive when compared to the combination of new solar power and battery storage. To the extent that local energy costs for manufacturing and services determine global competitiveness—particularly in any manufacturing process that uses, or can be adapted to use, electricity—the cost advantage brought by deploying low-cost solar will drive adoption in regions that wish to succeed economically. The economic and financial advantages of solar relative to fossil fuels suggest that the next thirty years will see solar power come to dominate global electricity production.

1. Introduction

The Sun has won. Solar power now provides “the cheapest electricity in history” according to the International Renewable Energy Agency (IRENA).[1] Solar energy costs continue to fall due to a combination of technological progress, economies of scale, and learning effects. In contrast, costs for coal power are flat or rising, depending on the region, largely because utilization rates at power generation facilities have fallen to all-time lows.[2] Military conflict in Europe now disrupting fossil fuel supplies appears to be accelerating these trends. The long-term cost advantage of solar, and more generally of all renewables, is a death knell for the fossil fuel age.

The fundamental advantage of solar power over fossil fuels is that, for the same total investment, solar produces more useful energy than does combusting fossil fuels. That is, solar power is more capital-efficient than fossil fuels. Therefore, continued spending on fossil fuels is spending on economically uncompetitive electricity production. To be sure, there remains money to be made from fossil fuels in the short term because most electricity production capacity extant today requires combustion; it will be the work of decades to replace it. Nevertheless, over the long term, public or private organizations that continue to invest in fossil fuels will be building structurally inefficient infrastructure, with attendant higher operating costs, that will hinder economic performance.

How should we measure the financial advantage of solar over fossil fuels, and with which units? Capital efficiency is typically defined to be a ratio that describes return on investment or on operational spending, where the specific

1 “Solar is now ‘cheapest electricity in history’, confirms IEA”, Sim Evans, *CarbonBrief*, 13 October, 2020. https://www.carbonbrief.org/solar-is-now-cheapest-electricity-in-history-confirms-iea

2 See figure “Global coal fleet now running less than half the time”, part of “Wind And Solar Now Generate One-Tenth Of Global Electricity”, Dave Jones, Euan Graham and Pete Tunbridge, EMBER, 13 August, 2020. https://ember-climate.org/project/global-electricity-h12020/

numerator and denominator might be an absolute amount of investment or a rate of investment and are typically chosen to suit a particular narrative of financial performance. Here I define Capital Efficiency as energy produced per dollar invested over the lifetime of a power plant, in units of MegaWatt*hours per dollar (MWh/$), which is the inverse of the unsubsidized Levelized Cost of Energy (LCOE) for utility scale generation (Figure 1).

The LCOE (inset, Figure 1) takes into account all contributions to lifetime cost, including maintenance and finance, and is therefore a means to compare disparate energy production technologies.[3] The LCOE of solar has fallen steeply over the last 15 years. However, pandemic-related supply chain issues have affected solar power hardware costs in the same way as costs in other sectors. The prices for solar module components such as silicon, aluminum, and glass have followed the price of energy where it is set by the cost of fossil fuels, which rose through the 12 months prior to the publication of this document, and which increases will undoubtedly show up in future LCOE data sets.[4],[5] Further price impacts may be felt from the outbreak of hostilities in Europe and subsequent sanctions.

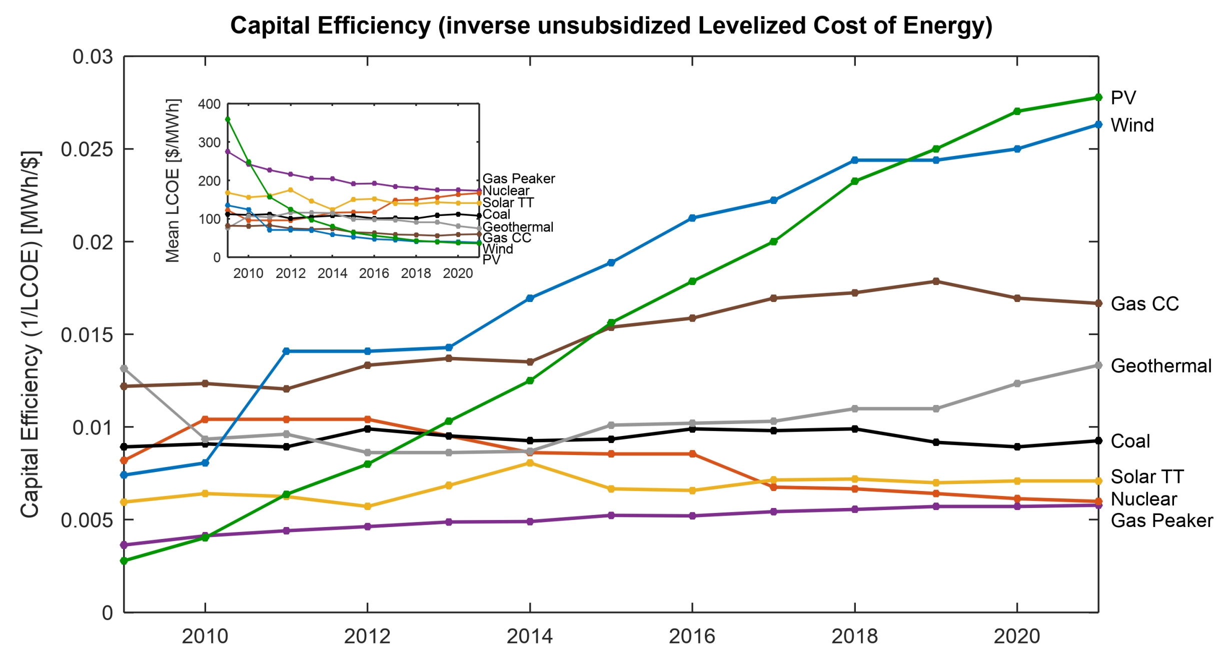

Figure 1: The Capital Efficiency for utility scale generation, here defined as the inverse of the Levelized Cost of Energy (LCOE) (Inset: Lazard's mean LCOE). The LCOE takes into account all contributions to lifetime cost and is therefore a means to compare disparate energy production technologies (Source: Lazard, Planetary Technologies).

Yet the cost of electricity from already-operating solar has not been affected by fossil fuel price fluctuations because the cost of sunlight does not depend on the price of coal or gas, nor upon any state of war. Prices for renewable energy are quite stable over time, and the use of that energy for commercial operations comes at a lower cost and carries a lower risk than reliance on fossil fuels, which fluctuate in price and availability. This fact points to an

3 pg. 8, "Historical Utility-Scale Generation Comparison", Lazard's Levelized Cost of Energy Analysis, Version 15, *Lazard*. October 2021. https://www.lazard.com/media/451881/lazards-levelized-cost-of-energy-version-150-vf.pdf

4 "Power Plants Get More Expensive But Renewables Still Cheapest", Will Wade, *Bloomberg*, 21 December, 2021. https://www.bloomberg.com/news/articles/2021-12-21/power-plants-get-more-expensive-but-renewables-still-cheapest

5 "Hold That Tesla! Inflation Will Be Made of Aluminum", Javier Blas, *Bloomberg*, 13 February, 2022. https://www.bloomberg.com/opinion/articles/2022-02-14/aluminum-will-intensify-the-inflationary-wave-washing-around-the-world

inevitable future. As photovoltaic modules, and all their constituent components, are increasingly manufactured using electricity produced by photovoltaic module installations, the cost of new modules will become decoupled from the price of fossil fuels and will fall even further. The implication of the long term cost trend is very clear; solar power is the future of electricity generation.

The economic reality that solar power is less expensive than fossil fuels creates certain market inevitabilities:

1. Most obviously, the cost advantage of solar power will accelerate the installation of photovoltaic (PV) electricity generation around the globe. This expansion will proceed even without significant improvements in PV efficiency due to extant cost advantages, and the resulting increase in PV manufacturing will by itself continue to expand these cost advantages modestly due to improved economies of scale and learning effects.

2. Because renewables in general, and PV in particular, are more capital-efficient than fossil-fueled electricity generation, investment will increasingly shift from fossil fuel projects to renewables. To sharpen that conclusion: money that is now spent on fossil fuels will instead be spent on renewables. Headlines and commentaries that fret about the costs of the electrification transition fail to recognize that investment in renewables represents not additional spending, but rather displacement of spending on fossil fuels. Because renewables are more Capital Efficient than fossil fuels, this shift will free up significant capital that may be invested in more lucrative and beneficial projects.

3. A corollary of the cost and competitive advantage of renewables is that energy and climate scenarios that posit any significant coal or gas combustion in 2050 are assuming highly irrational economic behavior occurring not just once, but persisting over the next three decades. Such scenarios are likely of limited utility as planning tools for guiding policy and investment.

4. Finally, now that PV has crossed below the cost threshold at which fossil fuels operate, PV will begin competing with itself and other low-cost renewables (e.g., wind) rather than with fossil fuels. Given that solar is already improving exponentially, competition will spark an intense demand for technical improvements that reduce the installed cost per watt. Schumpeter's gale will blow through the solar industry just as it is doing in the rest of the energy industry.

This document was written largely before the outbreak of hostilities in Europe; all of the observations above have become more important, and will have a more consequent economic impact, due to local conflict and the global weaponization of fossil fuel supplies. Any war-related increases in investment in fossil fuel production and distribution are, with virtual certainty, temporary and will eventually be revealed as a fluctuation away from the long-term downward trend.

Below I present an economic and financial analysis of the future course of solar power deployment; the simple summary of this analysis is that installation of solar is set to continue growing for decades to come. This analysis is not focused on whether PV can be cost competitive, nor on how those costs may change over time, but rather on whether there will be sufficient capital, and at low enough cost, to maintain the current growth rate of PV installation. The implications of this analysis point towards even greater installation of solar than we have seen thus far, primarily because solar power provides a competitive economic advantage over fossil fuels. That advantage will grow as all stages of solar module manufacturing transition to being powered by PV and wind, creating a lower cost and more stable price structure for module components than result from today's reliance on fossil fuels. Future reports in this series will consider additional aspects of the electrification transformation, including materials requirements, manufacturing capacity, distribution, storage, new applications opened up by technological change, and how policy may accelerate, or impede, the deployment of renewable energy.

2. The Sun Is Up

2.1 Annual solar installations have grown exponentially for decades, and, now that solar has a fundamental cost advantage over fossil fuels, this trend is likely to continue for decades to come

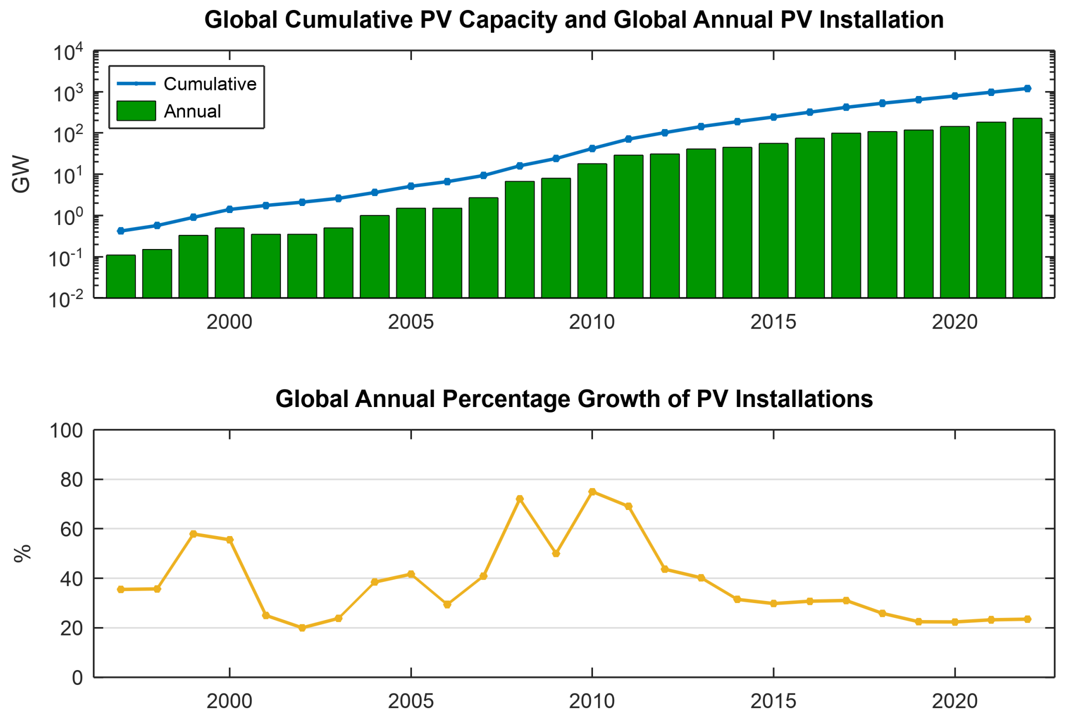

Figure 2: (Top panel) Global installation of new PV power has risen exponentially for 25 years (blue line), driven by installations that have now surpassed 200 GW annually (bars) (Source: BP and BloombergNEF. 2021 and 2022 Projections: BloombergNEF). (Bottom panel) The annual growth rate of PV installation has remained above 20% for more than two decades (Source: Planetary Technologies).

Globally, the market for PV continues to grow exponentially (Figure 2). PV installations over the last 25 years have increased by an average of 39% annually, never falling below 20%. BloombergNEF (BNEF) estimates that annual solar PV installations rose from 144 GW in 2020 to an estimated 187 GW in 2021, and will increase again to as much as 238 GW in 2023.[6],[7],[8],[9] BNEF further estimates that achieving global "Net Zero" carbon emissions by 2050 will require installing an average of 455 GW each year through 2030, with a total of 20 TW installed by 2050.[10] While reaching that goal would amount to a 20-fold increase in cumulative PV installed around the world, it would require

6 "Up to 209GW of solar PV to be installed in 2021, BloombergNEF forecasts", Liam Stoker, *PVTech*, 23 February, 2021. https://www.pv-tech.org/up-to-209gw-of-solar-pv-to-be-installed-in-2021-bloombergnef-forecasts/

7 While this report was published in July, 2022, the installation total for 2021 is not yet fully tallied.

8 "Solar – 10 Predictions for 2022", *BloombergNEF*, https://about.bnef.com/blog/solar-10-predictions-for-2022/.

9 "View from the Solar Industry: We Don't Need COP26 to Shine, But What Should We Worry About?", Jenny Chase, *Joule*, 2022. https://doi.org/10.1016/j.joule.2022.01.013

10 "BNEF: Net zero could require 455GW of new solar capacity each year by 2030, with 20TW installed by 2050", Liam Stoker, *PVTech*, 21 July, 2021. https://www.pv-tech.org/bnef-net-zero-could-require-455gw-of-new-solar-capacity-each-year-by-2030-with-20tw-installed-by-2050/

only a 15% annual growth rate, which the globe is presently exceeding (Figure 2). One implication of this exponential pace is that the vast majority of the installation will occur in the out years. The globe passed 1 TW of installed capacity early in 2022.[11] Thus 19 TW, or 95%, of the eventual 20 TW forecast in 2050 remain to be installed. Consequently, not only will much more solar be installed over the coming decades than we have seen thus far, but most of the manufacturing capacity for those PV modules has yet to be built. Countries that wish to compete to host this manufacturing capacity, particularly in the interest of ensuring domestic supply, have ample opportunity to do so.

Exploring the possibilities for what may happen beyond the right-hand side of Figure 2 over the next three decades is the primary goal of this series. Future reports will explore the possibility that the total installed PV capacity in 2050 could be many times larger than currently forecast. Because the rate of growth compounds over time, the differences between 15%, 20%, or 25% annual growth over a decade, or two, have profound implications for total solar power generating capacity around the globe. A back-of-the-envelope calculation that includes 20% annual growth continuing for another decade results in *annual* installations exceeding 1 TW. Part 1 of this series lays the foundation to consider whether these growth rates can continue, and, if so, at what pace.

There are three types of factors that point to long-term PV dominance: 1) scientific and technological, 2) economic (i.e., related to cost and price of producing and delivering electricity in the market), and 3) financial (related to project investment and borrowing, as distinguished from cost and price). The scientific and technical reality is that new generations of PV modules will continue to become more efficient over time, i.e., will produce more power from a given panel area. Those technological gains, combined with economies of scale and learning effects, will further drive down the cost per watt of new installations, thereby giving PV an ever greater market advantage over fossil fuels. In turn, this economic advantage of PV is driving changes in finance, which is most visible as a profound and sustained shift in investment away from fossil fuels and towards renewables.

> *Whereas the marginal cost of electricity production by PV and wind is approximately zero, to produce ongoing value at fossil-fueled electricity plants requires the constant incineration of capital.*

2.2 Closing the waste gap

There are two fundamental scientific and technological differences between fossil fuels and renewables. First, fossil-fueled power plants must, of course, be *fueled*. To derive ongoing value from infrastructure already built and paid for requires continual spending to mine, process, and transport combustible fuel that is then immediately destroyed. That fuel comes from a collection of individually finite sources, with the lowest cost resources exploited first, which when exhausted must be replaced with more expensive, new mines, where that exploration and development also requires ongoing spending. That is, fossil fuel electricity production at existing power plants requires unending expenditures on finding, acquiring, conditioning, and shipping ever more expensive fuel only to finally burn it at low efficiency.

That low efficiency highlights the second difference: fossil fuels are, of course, *combusted*. Combustion is an inherently inefficient thermodynamic process that converts the chemical energy stored in fossil fuels into useful work and waste heat. Internal combustion engines and boilers are typically no more than 30% efficient, while the most efficient combined cycle gas turbines top out at about 60%. Thus, of the energy in every kilogram of fossil fuel putatively delivered to a customer, between 40% and 70% goes up in smoke. Gregor Macdonald, a journalist and former energy trader, calls this inefficiency the “waste gap”.[12]

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11 “Humans have installed 1 terawatt of solar capacity, generated over 1 petawatt of solar electricity in 2021”, John Fitzgerald Weaver, *PV Magazine*, 14 March, 2022. https://pv-magazine-usa.com/2022/03/14/humans-install-1-terawatt-of-solar-capacity-generate-over-1-petawatt-of-solar-electricity-in-2021/

12 *Oil Fall*, Gregor Macdonald, Terrajoule Publishing, 2018. https://terrajoule.gumroad.com/l/OilFall

In contrast, an initial investment in renewable electricity capacity continues to produce ongoing value at near-zero cost. Sunlight and wind are free. The required maintenance at such installations is minimal. In other words, whereas the marginal cost of electricity production by PV and wind is approximately zero, to produce ongoing value at fossil-fueled electricity plants requires the constant application of labor, the constant incineration of assets and, therefore, the constant incineration of capital.

Moreover, when electricity is directly delivered to a customer, 90%–100% can be converted to useful work or heat. In other words, the waste gap for wind and solar is much smaller. As Macdonald puts it, "roughly half of the total fossil fuel consumed each year on the planet is lost to waste heat. Replacing combustion for the energy capturing devices of wind and solar, or storage devices like batteries, triggers a clawback of these losses."[13] The incentive to reduce the waste gap has enormous economic implications. To restate: the yearly energy budget for the planet could be halved by switching from combusting fossil fuels to direct electricity production and distribution and this would free up trillions of dollars, which otherwise would have been spent on fossil fuels, for other purposes.

13 "Worlds Collide", Gregor Macdonald, 15 November, 2021. https://gregor.substack.com/p/worlds-collide

3. Economic Inevitabilities

Long term exponential decreases in PV costs will have relentless and merciless impacts on fossil fuel use. There are two fossil fuel use cases to consider: 1) purchasing coal and gas as fuel for existing facilities and 2) investment in new fossil-fueled electricity production. The *unsubsidized* LCOE of new-build PV has already fallen below the marginal cost of operating coal and combined-cycle gas generation for half of the Earth's population.[14],[15],[16] That is, in those markets new-build PV now costs less than buying coal and gas to use as fuel for existing facilities. In the U.S., compared to installing new PV, 91% of existing coal and combined coal-gas capacity operated at a loss in 2020.[17] The Energy Information Agency (EIA) forecasts that from 2022 onwards, new renewables in the U.S. will displace both the share of natural gas in electricity production and the absolute volume of gas combusted to produce electricity.[18] Similarly, in Europe, new renewable electricity have already reduced natural gas use, even before renewable installation plans were accelerated by war.[19]

For new-build, fossil-fueled generation capacity the news is even worse. According to BloombergNEF, "Renewables [are] the cheapest source of new bulk power in countries comprising two-thirds of the world population and ninety percent of electricity generation", even accounting for temporary cost increases for raw materials driven by inflation and war.[20] The capital costs for new medium- and large-scale PV installations are now as much as seven-fold lower than for new coal- or gas-burning facilities.[21] While the long term mean cost difference is not yet uniform around the globe, and while in some markets the solar advantage is still facilitated by long-term Purchase Power Agreements (PPAs), the inexorable drop in PV costs, and the fundamental nature of the combustion waste gap, will inevitably put fossil-fueled power generation out of business.

3.1 The scalability advantage of solar PV

PV is not the only renewable energy source that now costs less than fossil fuels. Wind turbines will play an important role in the displacement of fossil fuels. And both solar and wind power performance continue to benefit from exponential technological and economic trends. But solar power has important scaling advantages over wind power, and it is likely that far more solar, in far more places, will be installed in the coming decades than wind. Solar power already accounts for more cumulative worldwide generating capacity than does wind; in 2019 solar installations accounted for half of new generating capacity from all sources, twice as much as wind; and solar installations are growing more than twice as fast as wind.[22],[23] One contribution to this disparity is that wind turbines must be large in order to achieve both physical and economic efficiency, which leads to a smaller number of installations of very large, very expensive turbines. While the vast majority of wind farms in the U.S. have a generation capacity larger than

14 "Building New Renewables Is Cheaper Than Burning Fossil Fuels", Will Mathis, *Bloomberg*, 23 June, 2021. https://www.bloomberg.com/news/articles/2021-06-23/building-new-renewables-cheaper-than-running-fossil-fuel-plants
15 As of May, 2022, the price differential has expanded due to price increases for fossil fuels resulting from various supply constraints. The differential will likely return to follow the long term trends as the pandemic abates, conflict is resolved, and supply chains recover; the price advantage of renewables is here to stay.
16 Evans, 2020.
17 p. 41-42, *Renewable Power Generation Costs in 2020*, International Renewable Energy Agency, Abu Dhabi, 2021.
18 Short-Term Energy Outlook, U.S. Energy Information Agency, January, 2022. https://www.eia.gov/outlooks/steo/
19 "Europe's Renewables Are Crowding Out Gas as Coal Phase-Out Slows", Todd Gillespie, *Bloomberg*, 31 January, 2022. https://www.bloomberg.com/news/articles/2022-01-31/europe-s-renewables-are-crowding-out-gas-as-coal-phase-out-slows
20 "Cost of New Renewables Temporarily Rises as Inflation Starts to Bite", *BloombergNEF*, 30 June. 2022.https://about.bnef.com/blog/cost-of-new-renewables-temporarily-rises-as-inflation-starts-to-bite/
21 pg. 7, Larzard, 2021.
22 "Renewable Power Will Soon Come Out on Top", Nathaniel Bullard, *Bloomberg*, 11 June, 2020. https://www.bloomberg.com/news/articles/2020-06-11/solar-and-wind-power-top-growth-in-renewable-energy-worldwide
23 "Global Trends in Renewable Energy Investment 2020", BNEF, UNEP & Frankfurt School of Finance & Management. https://www.fs-unep-centre.org/wp-content/uploads/2020/06/GTR_2020.pdf

100 MW, most PV installations are less than 5 MW, each built at correspondingly lower expense.[24],[25] U.S. small-scale solar generating capacity has grown at greater than 19% annually since 2014.[26],[27]

The PV market is generally segmented by size into three bins. Rooftop solar includes residential and commercial installations of 1–100 kW on new or existing structures. Community scale solar installed on small plots of land is in the range of 50–200 kW and may serve the role of distributed power generation in areas with little or no grid connectivity. Utility scale solar is typically located away from urban areas, may be built with a nameplate generation capacity of 1 GW, and directly supplies a power grid.

Each of these installations, regardless of size, is composed of different numbers of very similar PV modules, with some variation depending on the manufacturer, which demonstrates the inherent flexibility of PV as a power generation technology. A PV module manufacturing plant with a nameplate capacity of 1 GW produces approximately 2.5 million modules annually, depending on the module power rating. PV thus also benefits from economies of scale and learning effects that derive from producing vast quantities of identical items. An individual PV installation could be composed of 1 module or 1 million modules.

The fundamental scalability of PV enables new generating capacity to be installed physically close to demand, for example on residential rooftops, without needing additional investment in the transmission lines, step-up and step-down transformers, and grid connections necessary for large electricity generation facilities, all of which is accomplished while requiring neither fuel supply nor significant maintenance. PV is unique among power generating technologies in this collection of attributes. The combination of economic advantage and installation flexibility implies that new PV is likely to replace existing fossil-fueled generating capacity at an increasing rate, which will have long term impacts on electricity distribution via the grid.

3.2 Distributed solar contributes to grid stability

Renewable energy skeptics frequently argue that an increasing reliance on variable wind and solar generation will *necessarily* result in grid instability. In reality, the German electricity grid became more stable between 2006 and 2020 while the share of renewable electricity generation grew from 6% to 50% (Figure 3).[28],[29] Over that same period, the absolute amount of electricity generated from nuclear and fossil-fueled power fell by 50% and 60%, respectively.[30] The anti-correlation of renewable capacity and grid instability across an economy and a grid the size of Germany's stands as sufficient to refute the stability skeptics. Yet the case is stronger; the increase in grid stability has been causatively attributed to 1) the vast majority of PV installations in Germany being at the community scale or smaller, and 2) those distributed installations accounting for more than half the total PV generating capacity in the country.[31],[32] At a minimum, one can conclude that renewable capacity of at least 50% is compatible with increasing grid stability, even before widespread battery deployment, if system administrators choose to pursue these combined goals. There

24 See “Construction cost data for electric generators installed in 2019: Wind generators installed in 2019 by plant size: Number of plants”. https://www.eia.gov/electricity/generatorcosts/

25 See “Construction cost data for electric generators installed in 2019: Solar PV generators installed in 2019 by total added capacity at plant: Number of plants”. https://www.eia.gov/electricity/generatorcosts/

26 ibid.

27 U.S. EIA, “Electric Power Monthly: Estimated Net Summer Solar Photovoltaic Capacity From Small Scale Facilities by Sector.” https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=table_6_01_b

28 “Power interruptions in 2019”, German Federal Network Agency, 22 October, 2019. https://www.bundesnetzagentur.de/SharedDocs/Pressemitteilungen/DE/2020/20201022_SAIDIStrom.html?nn=265778

29 “Key figures for electricity supply interruptions”, German Federal Network Agency. https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/Versorgungssicherheit/Versorgungsunterbrechungen/Auswertung_Strom/start.html

30 “In Defense of the Energiewende”, Nick Tsafos, 24 August, 2020. https://www.csis.org/analysis/defense-energiewende; and https://twitter.com/ntsafos/status/1478010911143219201

31 p. 30, “Recent Facts about Photovoltaics in Germany”, Harry Wirth, Fraunhofer ISE, 15 May, 2021. https://www.ise.fraunhofer.de/en/publications/studies/recent-facts-about-pv-in-germany.html

32 p.18, “Photovoltaics Report”, Fraunhofer Institute for Solar Energy Systems, ISE, 27 July, 2021. https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

is no reason to expect this result to be localized to Germany. Consequently, given the combined economic benefits of lower electricity prices and fewer interruptions, grid stability concerns around the world may *accelerate* rather than retard PV adoption. The grid stability benefits of distributed generation may become recognized as a means to reduce spending on infrastructure maintenance and upgrades, an advantage that improves the value proposition of rooftop and community solar.

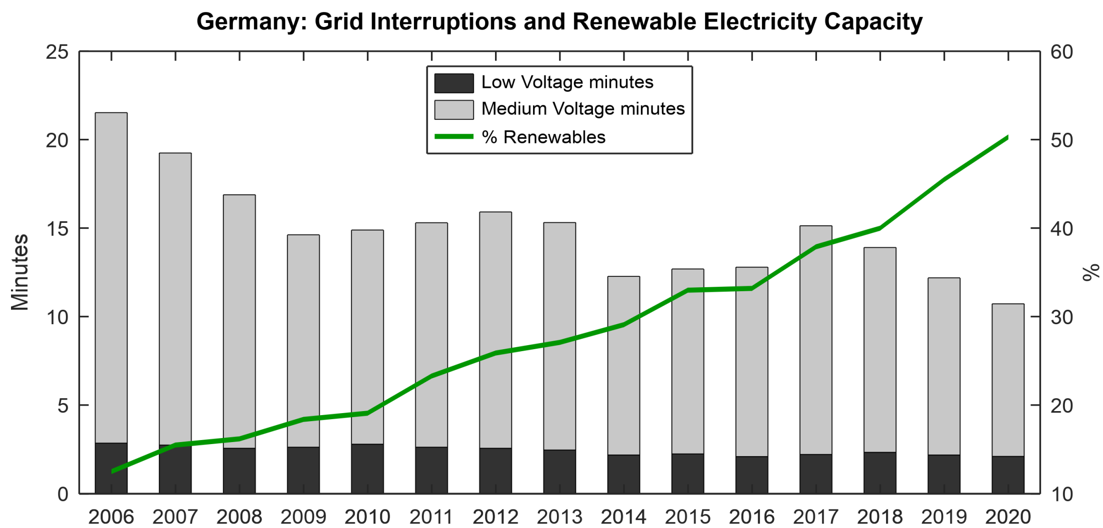

Figure 3: German national grid interruptions since 2006 and share Renewable Electricity Production (Source: German Federal Network Agency and Fraunhofer ISE).

3.3 The combination of new solar and battery storage are predicted to soon cost less than buying coal and gas as fuel

The deployment of power storage technologies such as batteries, which further improve grid stability, will continue to extend the economic advantage of renewables. BloombergNEF forecasts that storage will increase 20-fold by 2030, and 55% of that capacity will be used primarily to temporally shift energy produced from solar and wind to meet peak demand.[33] Exponential economics underlie battery deployment, just as with solar and wind installations; the average cost of battery storage has fallen by 90% over the last decade, and is forecast to further decrease at least another 50% by 2030.[34] By 2025, NextEra, a large investor-owned utility in the U.S., expects the cost of projects that include both new PV and new battery storage will fall below the marginal cost of operating fossil-fueled generation, i.e., less than the cost of buying coal and gas to fuel existing plants.[35] At that crossover point, the economic case for continuing to burn fossil fuels will largely vanish, so long as sufficient local wind, solar, storage, and distribution capacity has been installed to displace fossil fuel capacity. It is frequently argued that gas is a bridge fuel, but instead natural gas is a bridge to nowhere.

It is frequently argued that gas is a bridge fuel, but instead natural gas is a bridge to nowhere.

33 "Global Energy Storage Market Set to Hit One Terawatt-Hour by 2030", *BloombergNEF*. 15 November, 2021. https://about.bnef.com/blog/global-energy-storage-market-set-to-hit-one-terawatt-hour-by-2030/
34 "Battery Price Declines Slow Down in Latest Pricing Survey", James Frith, *Bloomberg*, 30 November, 2021. https://www.bloomberg.com/news/articles/2021-11-30/battery-price-declines-slow-down-in-latest-pricing-survey
35 "Clean energy group NextEra surpasses ExxonMobil in market cap", Gregory Meyer, *The Financial Times*, 2 October, 2020. https://www.ft.com/content/39a70458-d4d1-4a6e-aca6-1d5670bade11

To be sure, dealing with variation in wind and solar generation will require the development of short- and long-term energy storage. However, as explored below, even with exponential growth it will be many years until sufficient renewable capacity is deployed around the world to enable completely turning off fossil-fueled electricity generating stations. That date, which could be as distant as twenty years from now, provides a large window to develop and deploy long-term storage. Moreover, although expensive when compared to new renewables, existing nuclear power plants could easily fill the role of smoothing out electricity supplies to complement wind and solar, even while new nuclear plants are outcompeted economically by the combination of renewables and storage.

In summary, new-build PV already costs less than operating existing coal or gas powered generation in most cases. And due to technological trends, PV will inevitably cost less that fossil fuels in every case except that small number in which solar is physically impractical or is outcompeted by wind. As a consequence of the cost advantage and Capital Efficiency of PV, the shift now under way of capital from fossil fuels to PV will accelerate. Beyond the massive quantities of capital supposedly destined for ESG investments, there has been a fundamental structural change in the financing of energy projects that indicates that the electrification transition has already taken off.

> *Grid stability concerns around the world will accelerate rather than retard PV adoption. As soon as 2025, the cost of projects that include both new PV and new battery storage are forecast to fall below the marginal cost of operating fossil-fueled generation, i.e., less than the cost of buying coal and gas to fuel existing plants.*
>
> *Under these conditions, utilities will make more money by immediately shutting down fossil fuel plants and installing PV and batteries; customers, regulators, and, presumably, shareholders, are likely to demand that this transition proceed as rapidly as possible.*

4. Finance Inevitabilities

When evaluating the investment potential of a new market, or how a new business might grow over the next five to ten years, it useful to ask an oversimplified question: "What would bankers do?" That is, if the decision to invest were determined by financial considerations alone, solely risk and return, where would the money go? In the case of deciding between financing new fossil fuel power generating capacity or new renewable capacity, bankers have already made their choice.

4.1 Long term trends favor investments in renewables from here on out

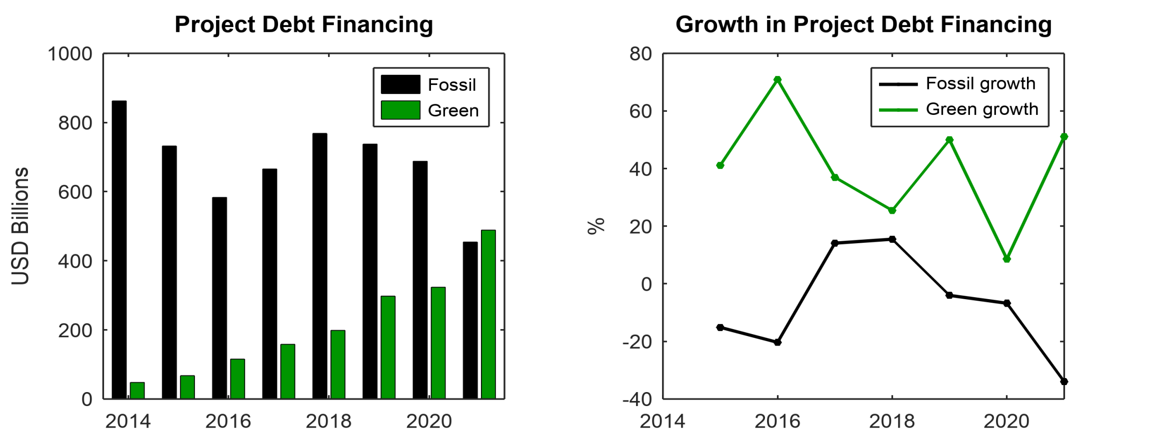

Figure 4: Left: The absolute amount of debt financing for fossil fuel projects and green projects (Source: Bloomberg. Data is available only from 2014). Right: The corresponding annual growth of fossil fuel and green project debt financing (Source: Planetary Technologies).

Just as the technical and economic factors for renewables described above have reached a crossover point compared to fossil fuels, so have financial factors shifted. As of the middle of 2021, debt finance for green projects surpassed debt finance for the fossil fuel industry for the first time (Figure 4).[36] Concomitantly, in 2021, for the first time banks earned more fees from green debt than from fossil fuel debt.[37] This is not a one-off payday. The average annual growth rate of fossil fuel project debt finance since 2014 is -8.7%, plunging by a projected -34% in 2021, the largest annual drop thus far; in only two of those years was there positive growth. In contrast, the corresponding average annual growth rate for green projects is 39%, accelerating to a projected 51% in 2021.[38] The shift in debt finance is but one example of trends that favor investments in renewables over fossil fuels from here on out.

The choice by bankers is particularly stark when comparing the borrowing costs and expected returns for solar power projects compared to fossil fuels. The cost of capital for fossil fuel projects is now 4–7X higher than for solar, a gap that continues to grow (Figure 5).[39] This spread reflects the larger risk premium demanded by investors for fossil fuel projects, and consequently requires that those projects generate a higher return simply to justify financing. To be sure, money will still be lent for fossil fuel extraction and combustion, but that borrowing is increasingly dear.

36 "Banks Always Backed Fossil Fuel Over Green Projects—Until This Year", Tim Quinson and Mathieu Benhamou, *Bloomberg*, 19 May, 2021. https://www.bloomberg.com/graphics/2021-wall-street-banks-ranked-green-projects-fossil-fuels/
37 "Bank Fees for Green Debt Surpass Fossil-Fuel Financing", Tim Quinson, *Bloomberg*, 5 January, 2021. https://www.bloomberg.com/news/newsletters/2022-01-05/bank-fees-for-green-debt-surpass-fossil-fuel-financing
38 This calculation uses the geometric mean of the annual growth rates.
39 pg. 11, *Carbonomics: The green engine of economic recovery*, M Della Vigna, et al., The Goldman Sachs Group, 16 June 2020. https://www.goldmansachs.com/insights/pages/gs-research/carbonomics-green-engine-of-economic-recovery-f/report.pdf

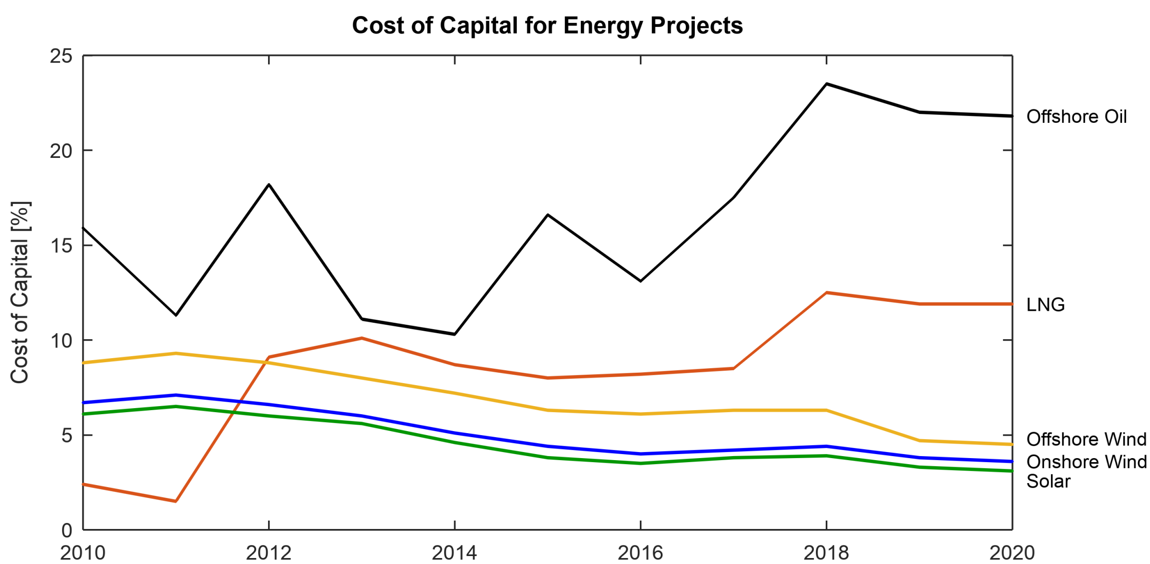

Figure 5: The cost of capital for fossil-fueled energy projects has been rising for a decade and is now 4–7X higher than the cost of capital for solar power projects (Source: Goldman Sachs).

The spread in the cost of capital is, of course, also affecting the relative amount of investment in the two broad categories. As of 2021, total spending on renewables projects for the first time equaled spending on new or existing oil and gas projects.[40] This watershed event is best understood as the first trickle of a building torrent. The phenomenon extends beyond debt to equity; institutional investors interested in participating in oil and gas projects have become scarce. In a revealing anecdote, one broker recently recently interviewed by *The Financial Times* noted that, among his 400 institutional clients, only one is still willing to invest in fossil fuels.[41] Large asset managers, such as Blackstone and Apollo Global Management, have sworn off new investments in fossil fuels and are specifically targeting future funds at the "energy transition".[42] Nevertheless, while fossil fuels are still burned some banks will make capital available for new fossil fuel investment.[43] But it is not clear how large the demand is for that capital. Even amid war-related supply disruptions, oil producers and oilfield services companies are not planning to increase investment in production, and instead are returning cash to investors.[44],[45] Any putative war-related increases in investment in fossil fuel production and distribution are, with virtual certainty, temporary and will eventually be revealed as a fluctuation away from the long-term downward trend.

The crossover to renewables is supported by a steady improvement in the long-term return on capital for PV, which has now reached parity with oil and gas projects.[46] Beyond this basic financial metric, Lazard calculates that the

40 "The slow death of Big Oil", The Editorial Board, *The Financial Times*, 17 September, 2020. https://www.ft.com/content/c343b958-63f4-44a4-9485-130d7740a843
41 "'Greenflation' threatens to derail climate change action", Ruchir Sharma, *The Financial Times*, 1 August, 2021. https://www.ft.com/content/49c19d8f-c3c3-4450-b869-50c7126076ee
42 "Blackstone Swears Off Oil-Patch Investing as Private Equity's Retreat Widens", Dawn Lim and Sabrina Willmer, *Bloomberg*, 22 February, 2022. https://www.bloomberg.com/news/articles/2022-02-22/blackstone-swears-off-oil-patch-investing-as-private-equity-s-retreat-widens
43 "Finance Industry's Climate Promises Leave Plenty of Room for Oil and Gas", Eric Roston, *Bloomberg*, 21 March, 2022. https://www.bloomberg.com/news/articles/2022-03-22/climate-change-finance-industry-oil-and-gas-policies-fall-short
44 "ESG Haters Think Climate Investors Are Controlling Everything. If Only", Kate Mackenzie, *Bloomberg*, 27 May, 2022. https://www.bloomberg.com/news/articles/2022-05-27/esg-haters-think-climate-investors-are-controlling-energy-markets
45 "Big Oil Spends on Investors, Not Output, Prolonging Crude Crunch", Kevin Crowley and Laura Hurst, *Bloomberg*, 7 May, 2022. https://www.bloomberg.com/news/articles/2022-05-07/big-oil-spends-on-investors-not-output-prolonging-crude-crunch
46 "Will the coronavirus kill the oil industry and help save the climate?", Damian Carrington, Jillian Ambrose and Matthew Taylor, *The Guardian*, 1 April, 2020. https://www.theguardian.com/environment/2020/apr/01/the-fossil-fuel-industry-is-broken-will-a-cleaner-climate-be-the-result

Levelized Cost of Energy of PV is impacted less by increases in the cost of capital (in particular the costs of equity and debt) than the LCOE of gas or coal.[47] Consequently, any increase in interest rates should have a smaller negative impact on solar installation than on any other power generation sector. It is also probable that rising interest rates will *accelerate* solar deployment, because the relative cost of power from new PV will decrease compared to every other operating electricity source. Adding all these factors together, strictly as a strategic financial play calculated on a spreadsheet, PV is simply a better, lower risk investment than any fossil fuel project today.

> *Any increase in interest rates will have a smaller negative impact on solar installation than on any other power generation sector. It is also probable that rising interest rates will accelerate solar deployment, because the relative cost of power from new PV will decrease compared to every other operating electricity source.*
>
> *Evaluated strictly as a financial opportunity, solar PV is a higher returning, lower risk investment than any fossil fuel project today.*

4.2 Renewable electricity outcompetes fossil fuels economically in spot markets and provides a structural competitive advantage over combustion

Dollars previously spent on fossil-fueled electricity generation are shifting *en masse* toward renewables, and in particular to PV. As of 2019, annual installation of new renewable electricity generation had risen to more than three times that of fossil fuel powered generation; as evidence of the pace of the transition, renewables grew nearly three-fold, to 77% of total installations, in only eight years.[48] By 2020, renewables accounted for 100% of net new generation capacity globally.[49] Given the combination of accelerating displacement with the impending economic advantage of combined renewables and storage, it is entirely plausible that no significant new net fossil-fueled electricity generating capacity will be added globally after approximately 2025. Furthermore, it is unlikely that replacement fossil installations built after that date will even be economically viable to commission and operate. Uncertainty in the timing of the end of new fossil capacity is primarily attributable to a combination of state-level policy preferences, the long timelines for constructing and commissioning fossil fuel projects currently in development, and the disruption of fuel supplies by war. Regardless, assuming the technological, economic, and financial trends described above continue apace, most organizations that continue to build gas- or coal-fired power plants after 2025 will not be making decisions based on energy economics or on purported calculations related to grid stability. To put that another way, continued investment in fossil fuels, whether by public or private entities, is investment in inefficient energy production, and therefore is investment in uncompetitive energy production. Continued investment in fossil fuels will actively destroy a country's ability to compete economically in the future.

Ultimately, a dollar, yuan, or euro spent on fossil fuels delivers substantially less useful energy to the end user than the same amount spent on renewable energy. Producers recognize this disadvantage. Energy companies have begun to ascribe more value to long term renewables contracts with lower, but predictable, annual returns than to fossil fuel projects that produce fluctuating revenues and that require ongoing high capital expenditures even during periods with low prices.[50] Paying the energy efficiency penalties inherent in fossil fuel mining and combustion made economic sense for centuries when there were few competitive alternatives. Now, however, renewable electricity both 1) outcompetes fossil fuels economically in spot markets and 2) provides a structural competitive advantage over combustion. States that rapidly adopt renewables will enable more capital-efficient economic activity, thereby freeing

47 pg. 6, Lazard, 2020.
48 See figs 17 and 18, pg 29, *Global Trends in Renewable Energy Investment 2020*.
49 “Technology Drives a Power Transition”, Nathaniel Bullard, *Bloomberg*, 2 December, 2021.https://www.bloomberg.com/news/articles/2021-12-02/technology-drives-a-power-transition
50 “Historical analogy may help with renewables investment”, Sir Mark Moody-Stuart, *The Financial Times*, 12 February, 2020. https://www.ft.com/content/3ed22574-4ce5-11ea-95a0-43d18ec715f5

up capital for other investments, and will thus have a greater competitive edge in global markets than those that continue to burn fossil fuels. Nevertheless, many countries have no choice but to proceed down the path of inefficiency until there exists sufficient annual renewables manufacturing and deployment capacity to supplant fossil fuels.

> *A dollar, yuan, or euro spent on fossil fuels delivers substantially less useful energy to the end user than the same amount spent on renewable energy.*
>
> *Continued investment in fossil fuels, whether by public or private entities, is investment in inefficient energy production, and therefore is investment in uncompetitive energy production.*

5. Geopolitical inevitabilities

Any discussion of the future of global electricity production must grapple with the ground truth that coal and gas will be burned for many years to come. China and India, in particular, can realistically do nothing else but burn coal in the short term in order to guarantee electricity supplies and avoid compromising their economies. In 2020, coal provided 62% of electricity production in China and 72% in India.[51] And yet in both countries PV increasingly outcompetes coal. In China, new, subsidy-free PV is now at or below cost parity with coal for more than 78% of grid power demand, with the rest of the grid expected to reach that threshold by 2023.[52] Across all of India, the LCOE of PV fell below that of coal in 2018, and PV costs across all installation scales are consistently below even those of China.[53],[54] Of immediate concern for India, the argument for shifting to renewables is being amplified by coal shortages that are threatening to cause "structural shortfalls in power supply".[55] Despite the cost advantage of PV over coal, both countries face the additional dilemma of employment dependence on coal mining and coal plant construction.[56],[57],[58],[59] That dependence will complicate the transition from coal to PV.

Both China and India constitute large electricity markets that cannot be shifted away from fossil fuels overnight. While wind and solar are the fastest growing sources of new electricity in China, coal and gas are each still growing and almost certainly will continue to do so until renewables can be installed fast enough to generate every new watt needed to power the economy.[60] While China has a target to build 1.2 TW of new renewable capacity by 2030, purportedly in the service of reaching peak carbon emissions, the government also recently reaffirmed the need to continue burning coal.[61] However, the resulting capital inefficiency and higher energy costs constitute a limitation on productivity that can only be tolerated for a limited number of years. Given the global economic penalty imposed by continuing to generate power from coal at uncompetitive costs, the scale of these markets serves to emphasize that the only uncertainty is how quickly, not whether, fossil fuels will be replaced by renewables.

China and India have economies that are dependent on competing in global markets at global prices. It is unlikely that these governments will remain sanguine for long about the structurally higher energy costs inherent in burning fossil fuels. This suggests that official plans for the renewables transition, however aggressive they may appear today, will be accelerated in order to maximize competitive advantage. Indeed, China's actual announced renewable deployment plans will result in the country reaching 1.2 TW of capacity by 2026 compared to the government target of 2030.[62] The country is on track to double PV installations in 2022 over 2021, and could account for nearly half of total global PV installations in 2022.[63] The resulting competitive advantage may serve as a forcing function to

51 "14 Million Tons a Day Show Why China and India Won't Quit Coal", David Stringer and Rajesh Kumar Singh, *Bloomberg*, 15 November, 2021. https://www.bloomberg.com/news/articles/2021-11-15/14-million-tons-a-day-show-why-china-and-india-won-t-quit-coal

52 "Combined solar power and storage as cost-competitive and grid-compatible supply for China's future carbon-neutral electricity system", Xi *et al.*, *PNAS*, 2021, Vol. 118, No. 42.

53 "Can Solar Power Compete With Coal? In India, It's Gaining Ground", Phred Dvorak, *The Wall Street Journal*, 12 February, 2020. https://www.wsj.com/articles/solar-power-is-beginning-to-eclipse-fossil-fuels-11581964338

54 *Renewable Power Generation Costs in 2020*, International Renewable Energy Agency, 2021, Abu Dhabi.

55 "India's Coal Crisis May Spur Shift to Clean Energy, ReNew Says", Rajesh Kumar Singh and Josh Saul, *Bloomberg*, 29 April, 2022. https://www.bloomberg.com/news/articles/2022-04-29/india-s-coal-crisis-may-spur-shift-to-clean-energy-renew-says

56 "India's Last-Minute Coal Defense at COP26 Hid Role of China, U.S.", Jess Shankleman and Akshat Rathi, *Bloomberg*, 13 November, 2021. https://www.bloomberg.com/news/articles/2021-11-13/india-s-last-minute-coal-defense-at-cop26-hid-role-of-china-u-s

57 "In Tougher Times, China Falls Back on Coal", Stephanie Yang, *The Wall Street Journal*, 23 December, 2019. https://www.wsj.com/articles/in-tougher-times-china-falls-back-on-coal-11577115096

58 Dvorak, 2020.

59 "India's coal demand likely to grow in absolute terms, phasing out difficult", Neha Arora, *Reuters*, 17 November, 2021. https://www.reuters.com/world/india/indias-coal-demand-likely-grow-absolute-terms-phasing-out-difficult-2021-11-17/

60 see "Global Electricity Dashboard: China", EMBER, https://ember-climate.org/data/global-electricity/

61 "China aims to build 450 GW of solar, wind power on Gobi desert", *Reuters*, 5 March, 2022. https://www.reuters.com/world/china/china-aims-build-450-gw-solar-wind-power-gobi-desert-2022-03-05/

62 "What do China's gigantic wind and solar bases mean for its climate goals?", Lauri Myllyvirta and Xing Zhang, *Carbon Brief*, 5 March, 2022. https://www.carbonbrief.org/analysis-what-do-chinas-gigantic-wind-and-solar-bases-mean-for-its-climate-goals

63 "China Is on Track to Double Its Solar Panels From Last Year's Record", *Bloomberg News*, 30 May, 2022. https://www.bloomberg.com/news/articles/2022-05-30/china-set-to-double-last-year-s-record-solar-panel-installations

accelerate renewables deployment in countries that deem themselves to be manufacturing competitors to China in global markets, and who thus require competitive electricity production infrastructure. Ultimately, the pace of replacement of fossil fuels by renewables will be set by a combination of domestic policy and the availability of financing, with a maximum pace limited by manufacturing capacity and development of infrastructure that enables electricity production and distribution.

This raises a point that appears to be frequently misunderstood by many journalists and investors; the vast majority of the dollars that will be spent on renewables *would have been spent on energy in any case and will simply be redirected toward more efficient supply*. That is, the large sums that will be invested in renewable power, and that are all too frequently portrayed as “extra” spending, will in fact be spent on renewables *instead of* fossil power. This transition can already be seen in the emerging dominance of renewables in debt financing, total investment, and most obviously, in the fraction of new annual generation capacity. Crucially, such investment will largely come from private capital rather than from governments, because markets will seek the lowest cost electricity, and because private capital is generally far more nimble than public capital in such re-allocations. Corporate demand for clean energy is an example of this trend, having grown at a CAGR of 40% over the last decade to reach over 31 GW in 2021.[64] Public policies such as tax credits, or direct government investment in manufacturing and deployment of solar and wind, or instruments such as loan guarantees and green infrastructure bonds, could further accelerate the flow of private capital into renewables.

> *The large sums that will be invested in renewable power, and that are all too frequently portrayed as “extra” spending, will in fact be spent on renewables* ***instead of*** *fossil power.*

64 “Growing Corporate Presence in Power Markets Will Boost Clean Energy”, Nathaniel Bullard, *Bloomberg*, 3 February, 2022. https://www.bloomberg.com/news/articles/2022-02-03/the-growing-corporate-presence-in-global-power-markets

6. Sunfight at the PV Corral

The future course of PV installation around the world is best understood through evaluating the recent past, and in particular the impact of the rapid decrease in PV costs on the displacement of fossil fuels. There are three distinct relative price Eras to consider, as illustrated in Figure 6.

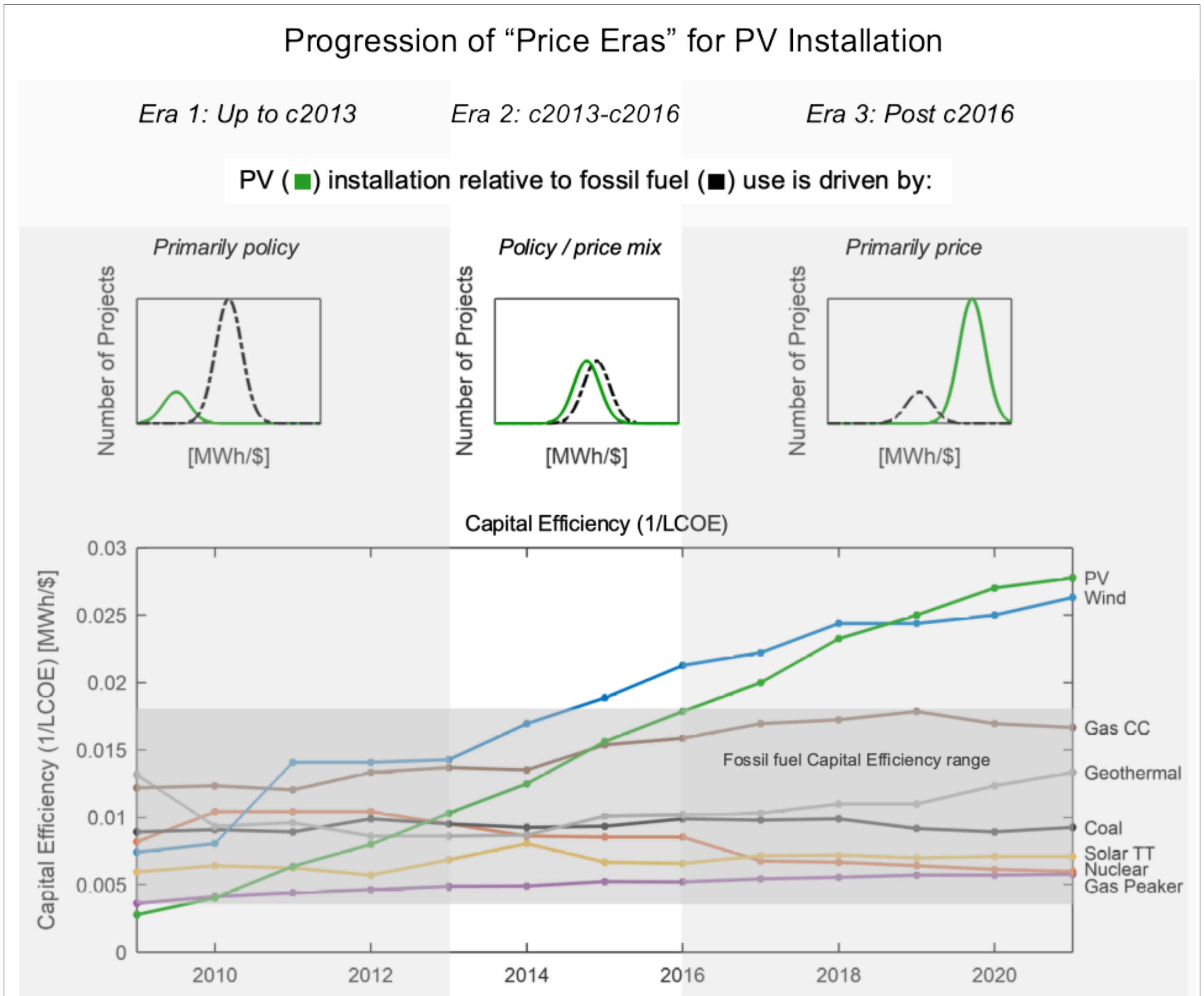

Figure 6: At the top, a sketch illustrating the relative number of new PV installations and fossil fuel projects as the relative Capital Efficiency has shifted since 2009. In Era 1, PV installations were driven primarily by policy. In Era 2, PV installations were driven by a mix of policy and price. In Era 3, new PV is less expensive than operating fossil fuel plants and installation is driven by price. Bottom: Capital Efficiency (1/LCOE), repeated from Figure 1.

In Era 1, the vast majority of PV installations produced less electricity per dollar than those burning coal. The global weighted average Capital Efficiency for utility scale PV reached approximate parity with coal for the first time only in

2013, and with gas for the first time in 2016.[65] During Era 1, large scale PV installations were driven by subsidies or other policy measures. In Era 2, the "approximate parity" time period, from 2013 up through approximately 2016, it could still be argued that a rational economic actor evaluating new electricity production could choose fossil fuel combustion based on Capital Efficiency. However, from 2016 onwards it has become increasingly difficult for a rational economic actor to decide in favor of fossil fuels over renewables. In Era 3, new renewables are clearly more Capital Efficient than fossil fuel combustion. Given the economic and financial trends described throughout this report, it is apparent that most energy project developers, and their financiers, are now behaving rationally and deciding to install renewables, primarily PV. The incentives in Era 3 are the converse of those in Era 1; going forward, any new fossil fuel combustion capacity installed will be driven by subsidies and policy measures, and will arguably reduce economic competitiveness. The continued roll-out of electricity storage globally will further accentuate the economic advantage of renewable electricity by enabling time-shifting of supply and thereby enabling elimination of expensive fossil fuel peaking capacity. In geographies in which installing new wind and PV today costs less than the marginal cost of coal and gas as fuel, continuing to operate the existing combustion fleet already impairs economic competitiveness.

6.1 The waste gap constitutes an investment gap that impairs long-term competitiveness

As a case in point, consider the United States. In 2019, U.S. electricity generating plants spent $21B on coal and $34B on gas as fuel.[66] Due to the inherent efficiency limitation of combustion, at best only half the energy in this fuel was converted to electricity and delivered to customers, with the rest constituting the "waste gap" and lost as heat. Assume for a moment that U.S. utility spending on fuel was the same in 2021 as in 2019 and that electricity consumption was unchanged. Because the LCOE of wind and solar, which are about equivalent today, have each fallen to be ~33% that of coal and ~60% that of gas (see Figure 1, inset, or Lazard, pg. 8), the same amount of electricity could in principle have been delivered to customers using renewables for only $31B, or a savings of 43%.[67] Therefore, U.S. utilities could have spent that $31B on equivalent renewable electricity and then spent an additional $24B on new renewable generation capacity—or on any other investment, including electricity storage—at no additional cost to customers or investors. To reiterate this point, the transition from fossil fuels to renewables will free up massive amounts of capital that can be invested in more lucrative and more beneficial projects. Thus, the waste gap also constitutes an investment gap. That gap exists regardless of the volume of U.S. domestic fossil fuel energy production, because there are ever fewer locations in which mining and combustion is a more capital-efficient means to produce either work or heat than renewable electricity. The investment gap is a significant economic cost, a self-imposed financial penalty that applies to every year in which the U.S. chooses to burn fossil fuels rather than install renewables, and ultimately degrades the country's long term global competitiveness. The same calculation applies to any nation, or any polity of any size, that chooses to continue burning fossil fuels in any application in which electricity could instead be provided more competitively with renewables.

> *The investment gap comprises a significant economic cost, a self-imposed financial penalty that applies to every year in which the U.S. chooses to burn fossil fuels rather than install renewables, and ultimately degrades the country's long term global competitiveness.*

65 pg. 17, IRENA, 2020.
66 "Electric Power Sector Energy Expenditure Estimates, 2019", U.S. Energy Information Agency, https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_sum/html/sum_ex_eu.html&sid=US
67 The final levelized energy cost, using renewables rather than coal and gas, would be .33 x ($21B) + .60 x ($34B) = $31B.

6.2 There is more than adequate capital available to deploy as much renewable power generation as we choose to

One oversimplified observation that follows from the above analysis is that the size of the pool of capital available annually to build new renewable capacity is, in principle, at least as large as that spent annually for coal and gas as fuel for heating, and electricity production. The reality, of course, is that the actual pool of capital available today is smaller; no country or region will be able to shift all spending from fossil fuels to renewables overnight. Nevertheless, this narrative of the waste and investment gap applies globally. The gap amounts to a significant economic pressure that countries must respond to, and in short order, lest they suffer the consequences of underinvestment and structural inefficiency. To reiterate a theme that arises throughout this report, the capital shift from fossil fuels to renewables is being driven by the simple fact that every dollar, yuan, or euro spent on delivering a unit of energy to an end user is more efficiently deployed in renewables than in fossil fuels. This differential will grow in the decades to come.

> *The capital shift from fossil fuels to renewables is being driven by the simple fact that every dollar, yuan, or euro spent on delivering a unit of energy to an end user is more efficiently deployed in renewables than in fossil fuels.*

6.3 Using renewable power to manufacture PV modules and wind turbines will decouple the future of energy production from its past

Technological improvements, as well as economies of scale, will continue to bring down the cost of renewables. Moreover, as renewables are increasingly manufactured using energy that is itself renewably produced, supply chain dependencies on fossil energy prices will gradually be eliminated, along with the price fluctuations that accompany fossil fuel market turmoil. A recently announced investment in China in a renewably powered facility that will refine silicon, produce PV cells, and manufacture PV modules will set the pace.[68] This a necessary and inevitable step towards decoupling—divorcing, even—the future of energy production from its past. To the extent that the needed energy can be provided by the sun, whether via photons, winds, or water, the manufacturing of renewable energy components can be sited wherever it is economically and logistically advantageous, and no longer must be shackled to the material flows of fossil fuel for thermal power generation or to the price fluctuations inherent in centralized energy supplies.

Governments and markets alike are discovering that the existing system is fragile and expensive. Fossil fuel price spikes caused by pandemic-related supply chain imbalances, or created through the actions of traders or others who seek profit in price movement, have now been amplified by war. Subsequent increases in energy prices that feed through into increased materials prices for new wind and solar installations will incentivize investments that decouple materials prices from traditional energy sources, and will thereby enable renewables costs to fall even lower. Among the likely targets for investment will be technological advances that further improve the capital and energy efficiency of wind and solar. The electrification transition will take time, and under prior circumstances might have been the work of several decades. But now the transition will also be driven by security concerns.

6.4 Pandemics and conflicts are lenses that will focus our attention on the sun

In this time of global market uncertainty, created first by a global pandemic and now by war in Europe, renewable energy is being hailed by national leaders as “freedom energy” and as being safer and better for national security than dependence on fossil fuels.[69],[70] Sudden geopolitical change has brought energy policy revelations and re-evaluations around the world. Jinko Solar, a large supplier of solar cells and modules, directly attributes significant

68 “China’s Risen Plans $7 Billion Solar Factory Run On Clean Energy”, *Bloomberg News*, 27 December, 2021. https://www.bloomberg.com/news/articles/2021-12-28/china-s-risen-plans-7-billion-solar-factory-run-on-clean-energy

expected growth in 2022 to the war, and forecasts what may amount to an increase of more than 35% in installations this year (compare this to recent growth in Figure 2).[71] Germany, in particular, is now considering accelerating its goal of achieving 100% renewable energy from 2050 to 2035.[72] Adopting this plan would triple the rate of solar and wind expansion in the country, in which case Germany itself would increase total global PV installation rate by roughly 2% annually. How many other countries will similarly increase their targets for PV installation? Understanding constraints on the rate of renewable capacity growth gets at the heart of the question motivating this report, which is critical to both energy independence around the globe and achieving the goal of Net Zero emissions: how quickly can we deploy renewable energy?

According to one quite credible projection, annual PV installation growth rates could fall by half over the next decade.[73] That magnitude of deceleration would put a serious crimp in efforts by any nation to achieve energy independence and to reduce carbon emissions. Yet it is perplexing that this slowing is proposed to occur just at the time when PV is thoroughly outcompeting the energy and capital efficiency of fossil fuels. It seems a more likely outcome that the combined and increasing economic benefits of solar will lead to an acceleration of installations, thereby providing the competitive advantages of local and low-cost electricity production to any nation that chooses to embrace this future.

69 "German envoy to raise energy security, climate on US visit", *AP*, 28 February, 2022. https://abcnews.go.com/International/wireStory/german-envoy-raise-energy-security-climate-us-visit-83164516
70 "U.S. Is Learning That Renewable Energy Is 'Safer': Whitehouse", Eric Roston, *Bloomberg*, 1 March, 2022. https://www.bloomberg.com/news/articles/2022-03-01/u-s-is-learning-that-renewable-energy-is-safer-whitehouse
71 "Russia's War Will Boost Solar Demand This Year, China Giant Says", *Bloomberg News*, 28 April, 2022. https://www.bloomberg.com/news/articles/2022-04-28/russia-s-war-will-boost-solar-demand-this-year-china-giant-says
72 "Germany Brings Forward Goal of 100% Renewable Power to 2035", Arne Delfs and Vanessa Dezem, *Bloomberg*, 28 February, 2022. https://www.bloomberg.com/news/articles/2022-02-28/germany-brings-forward-goal-of-100-renewable-energy-to-2035
73 Chase, 2022.

7. Conclusion

What, then, is the plausible future of solar power? Part 1 of this series has explored the economic and financial constraints on solar power installation over the coming decades. We are now in an era in which every dollar spent on new PV displaces higher cost fossil-fueled electricity production. From this vantage point, it appears likely that there will be as much capital available as can be utilized to build and deploy new renewables around the globe. The practical constraints on the amount of new PV that capital can buy and install include 1) the availability of new solar modules, that is, the combination of the availability of raw materials and of module manufacturing capacity, 2) the availability of installation hardware such as mounting systems, and 3) other factors such as land acquisition, regulation and permitting, and grid connections.

At a more abstract level, there may be a concern among some analysts and commentators that growth rates greater than 20% cannot be maintained simply because it is difficult to imagine that a large quantity can continue to rapidly grow. What are the appropriate considerations for determining the short-term and long-term trajectories for installation? The growth of global IT infrastructure and computational resources, and in particular data centers, serve as an example of a capital- and energy-intensive industry that has been accelerating for decades. Part 2 of this series will focus on a quantitative exploration of reasonable limits for total PV installation at a global scale and how quickly we might bump up against those limits.

Acknowledgments

The goal of this Research Report is to compile and summarize a collection of facts and trends that together illustrate that the global energy economy is already undergoing a fundamental and irreversible shift from fossil fuels to renewables. I would like to call attention to the data sources used herein, and to acknowledge those who have compiled that data. For this analysis, I have relied on data from organizations such as IRENA, *Bloomberg*, Bloomberg New Energy Finance (BloombergNEF), *The Financial Times*, Lazard, Carbon Brief, and *The Economist;* I am grateful for their efforts because I am well aware of how much time and effort goes into collecting and then representing data in a clear and concise manner. Beyond the raw data, I would particularly commend the analyses of Gregor MacDonald, Mark Lewis, and Jenny Chase. Finally, I would encourage readers to pay close attention to the summaries and syntheses of *Bloomberg's* Nat Bullard, who has clearly been thinking along the same lines as I have. Many thanks to Ben Rankin and Rik Wehbring for thoughtful questions. As always, I would like to thank Rik Wehbring for assistance in wrangling the Octave code used to generate quantitative models and figures for this report.

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