THE SHAPE AND PACE OF CHANGE IN THE ELECTRICITY TRANSITION:

Sectoral dynamics and indicators of progress

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COALITION

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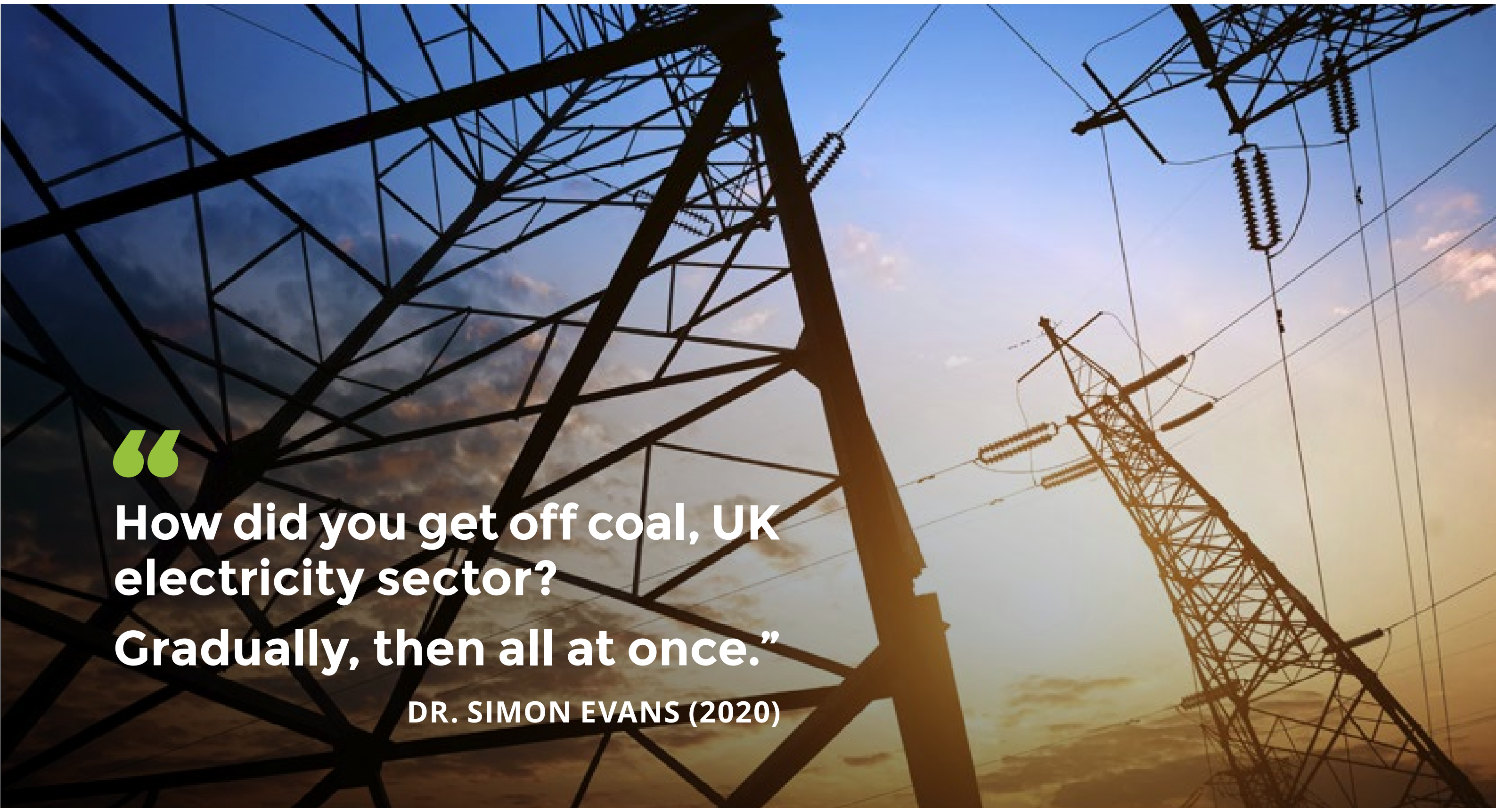
EXECUTIVE SUMMARY



> **How did you get off coal, UK electricity sector?**
>
> **Gradually, then all at once."**
>
> **DR. SIMON EVANS (2020)**

Change is not linear. Time and again, industries, policymakers, and commentators have been surprised by the pace of change that can erupt in markets, technologies, and societies. This report outlines the potential dynamics of the transition to net-zero emissions; explains the general principles, characteristics, and common drivers of growth of emerging technologies; and explores progress against metrics of transition in electricity generation.

Given that rapid technological progress and diffusion of zero-carbon technologies are critical to reduce emissions at the pace and scale required, this report looks at the deployment levels and rates of change needed to achieve global climate goals, assuming the widely observed "S-curve" and pace of change.

The electricity sector has to lead the global transition required to avoid dangerous climate change. Meeting the goal of limiting warming to 1.5°C, as set out in the Paris Agreement,[1] requires global power sector CO_2 emissions to reach net zero before 2050, with most studies showing that solar and wind are likely to become dominant sources of zero-carbon power. Many assessments of deployment levels to date are very pessimistic, extrapolating linear growth and looking at the absolute contribution from renewable energy sources, which, though growing, is still limited. This report probes deeper and anchors its analysis in the more commonly observed nonlinear dynamics of technological transition, comparing the trends since 2010 with the pace of transition required.

The results may surprise, and bring clarity to where progress is being made and where and how it needs to be pushed faster. A rapid transition is underway and appears now unstoppable, though its pace and depth will depend on policy. But inconsistency with dynamic indicators for fossil fuel-based generation points to a high risk of stranded fossil fuel generation assets irrespective of future policy decisions.

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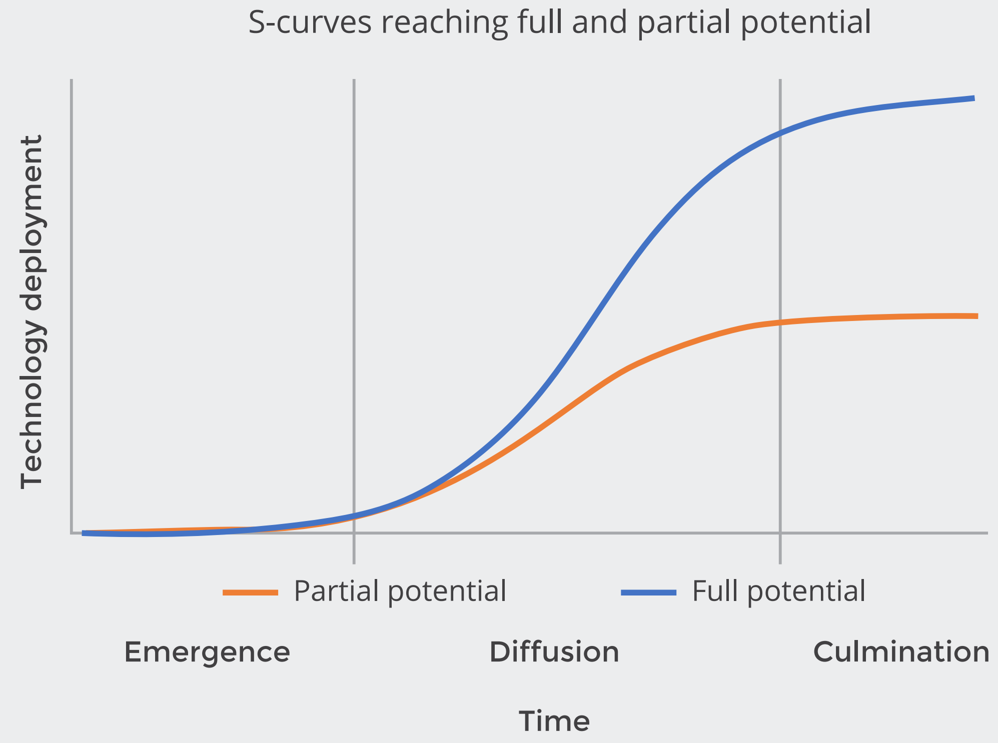
[1] Namely: "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C." (UN, 2015).

PROCESS AND METRICS OF TRANSITION

Major transitions require new technologies and practices to emerge, improve, and displace incumbents. This tends to occur with an S-curve dynamic, characterized by an early emergent phase in which growth appears small, but growth then gathers magnitude as new technologies become established and enter a phase of widespread diffusion characterized by exponential rates of growth. This is followed by a final phase when the pace of diffusion slows as the new technology stabilizes and culminates. The level at which growth flattens may match the full potential of the technology, or may fall short of this if growth becomes constrained and begins to decline prematurely due to other factors (Figure ES.1).

Figure ES.1: The S-curve



Historic examples of such S-curve dynamics include mobile communication technologies, jet engines, and successive steel-making technologies.

We identify three groups of indicators to assess progress of technological emergence and diffusion relative to this expected trajectory, and the evolution or impact of a variety of factors that influence this dynamic and are likely to continue to do so in the coming years. The three groups are:

- physical indicators related to the technology itself: of emissions and of deployment and use of low-carbon technologies;
- economic indicators of technology cost and finance; and
- systemic indicators relevant to sustain and extend the transition focusing on enabling technologies, infrastructure, and other conditions.

These indicators help us assess the current progress relative to what the best science tells us is required, and can inform decision-making by leaders across the public and private sectors working to remove barriers and accelerate progress. Table ES.1 presents an abridged summary focused on physical and economic indicators (drawn from a fuller set of indicators presented in our conclusions) and compares the observed indicators to benchmarks required for a Paris-consistent decarbonization of the power system, defined as median values drawn from the Intergovernmental Panel on Climate Change (IPCC) database of 1.5°C-consistent scenarios.

Table ES.1: Summary of indicators and trends.

System element	Indicator	Current (2019) status /decadal trend (2010-2019)	Paris-consistent?
CO_2 emissions and technology deployment			
Power system	Total CO_2 emissions	+10%	🟥
	CO_2 intensity (per kWh)	-12%	🟩
Wind	Generation growth rate	17%/year average growth	🟩
Solar	Generation growth rate	41%/year average growth	🟩
Wind and solar PV	Combined share of total generation	Increase from 2% to 8%	🟩
Unabated fossil fuels	Share of total generation	5.2 percentage point decline	🟨
Electricity demand	Demand growth substantially outpacing non-fossil fuel growth and mostly not displacing other carbon-intensive energy		🟥
Costs and finance			
Onshore wind	Global weighted average cost (auctions/PPAs)	-28%	🟩
Offshore wind	Levelized cost of energy	-29%	🟨
Solar PV	Global weighted average cost (auctions/PPAs)	-69%	🟩
All renewables	Generation investment –share of renewables	~65%	🟨
Batteries	Global weighted average cost	-87%	🟩

PHYSICAL INDICATORS: CO_2 EMISSIONS, CO_2 INTENSITY, AND TECHNOLOGY DEPLOYMENT

Overall CO_2 and fossil fuel indicators have been off track … mostly. Global CO_2 emissions from power generation rose 11% from 2010 to 2018, before falling by 1% in 2019 (i.e., *before* the impact of COVID-19, hereafter, Covid). Fossil fuel generation increased in absolute terms before contracting slightly in 2019 (and sharply under the impact of Covid), but the *share* of fossil fuel generation was declining as non-fossil sources grew faster. Consequently (with the fossil fuel balance also shifting toward gas, which is cleaner), the *CO_2-intensity* ($C0_2$ per unit of electricity) of global electricity generation has declined since 2010. Averaging 1.4%/year to 2019, *the rate of intensity improvement slightly exceeds that required for a long-term transition to net zero before 2050 driven by S-curve-shaped growth of renewables, but falls short of the 2030 benchmarks*, which would inhibit electricity's timely contribution to decarbonizing other sectors (e.g., transport). However, the trend of declining CO_2 intensity has sharply accelerated with Covid.

… whilst the growth of wind generation is plausibly on track and the pace of solar photovoltaics (PV) expansion has exceeded the needs of Paris-consistent trajectories. Most studies, and the evidence to date, now suggest the electricity transition will be dominated by the growth of wind and solar PV. Both these sources are now moving beyond "emergence" into the early stages of widespread global diffusion, demonstrating exponential growth rates. *Our S-curve scenarios show that recent trends in the growth in generation from these sources are well within the range required to achieve key benchmarks for growth to net-zero goals, with solar PV substantially surpassing these requirements*. The combination of wind and solar growth has been on track for the benchmark indicators for 2050, and consistent with the 2030 benchmark averaged across scenarios, though behind that required for more rapid or renewables-only decarbonization scenarios (Figure ES.2; Box 1).

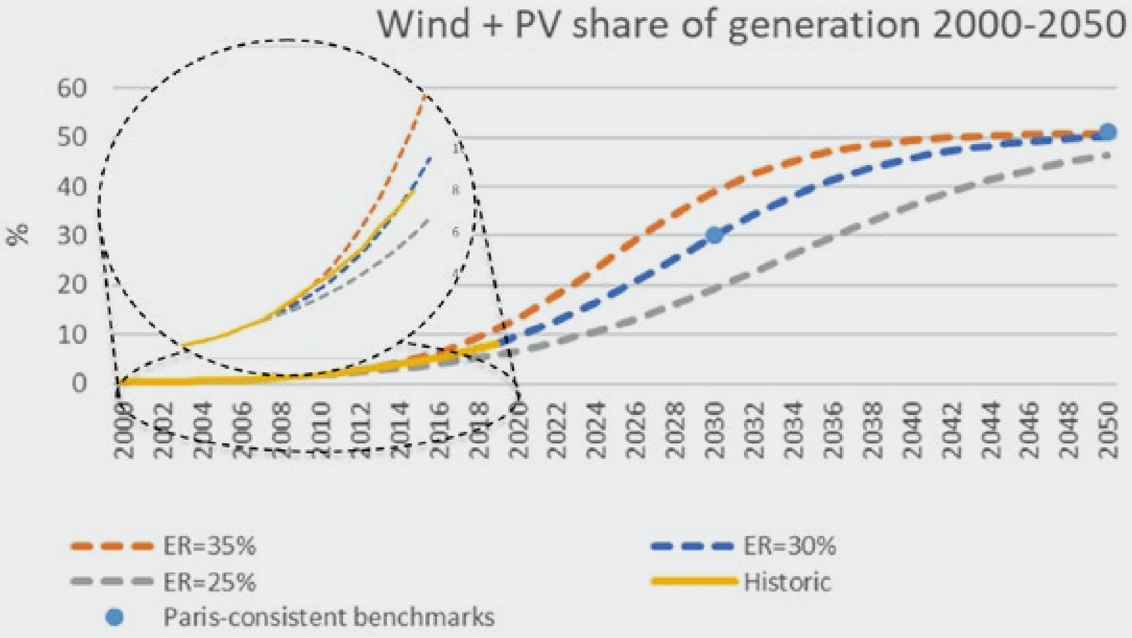


Figure ES.2: Wind and solar PV's historic share of total electricity generation, compared to S-curve projections toward 2050 Paris-consistent benchmarks calculated from the median values of "1.5 low overshoot" and "below 1.5" scenarios from the IIASA 1.5 Degree scenario database (Huppmann et al., 2018). Historic values for 2000-2019 calculated based on IRENA (2020a), EIA (2020), and BP (2020).

Demand growth has been a dominant challenge. A prime reason for the discrepancy between the messages of CO_2 trends and those of renewables trajectories is that – at least until Covid – the volume of *electricity demand growth was outpacing that of renewables (in absolute terms); nor has most of that growth been displacing more carbon-intensive end uses* like traditional cars. Both these dimensions need to change before electrification can be considered as a positive indicator of progress.

ECONOMIC INDICATORS – TECHNOLOGY COSTS AND FINANCING

The key renewables and related technologies have all gotten cheaper. Declining installation costs, alongside declining O&M and financing costs and increasing capacity factors, have led to rapidly falling energy costs in onshore and offshore wind and in solar PV, especially over the past ten years. *Cost reductions in solar PV and batteries have been dramatic, and transform the prospects*, e.g., for wide use of PV for day-to-evening energy. The cost of offshore wind has also tumbled more recently.

… and are widely competitive against new fossil fuel generation, and in some cases, with existing fossil fuel plants. The typical overall costs of electricity for all three technology types are now firmly within the range of new fossil fuel generation in most regions, and sometimes cheaper than operating existing stations. Information from energy auctions suggests continuing cost reductions toward being *competitive with the cheapest new fossil fuel plants, and displacing a growing share of existing coal generation.*

An investment tipping point has been crossed. With the falling costs of renewables, redirecting investment away from fossil fuels is already a sound business proposition, and will become further entrenched especially where markets are open to long-term contracts. Limited evidence comparing the performance of investment portfolios based on renewables and fossil fuels, respectively, indicates that *renewable power portfolios have given better returns, with less volatility, in several geographies,* and the share of global generation investment in renewables was 65% in 2019, suggesting that an economic tipping point has indeed been reached – but that share needs to grow further.

SUSTAINING AND EXTENDING THE TRANSITION

The near-term prospects for continued growth in renewable power look extremely positive. If recent percentage growth rates of wind and solar are sustained and extended in an S-curve dynamic, the levels of deployment found in Paris-consistent scenarios would be reached. However, various factors could erode growth rates more quickly, leading to slower growth and tail-off well below their full potential, like the lower curve in Figure ES.1.

Renewables remain very diverse. Incentive and regulatory structures vary. *In many regions, deployment has been driven more by private sector investment; but entrenched practices particularly with centralized utilities (including state-owned enterprises) create obstacles to renewables deployment.* Also, operating power systems with much higher shares of variable renewables will require complementary technologies, improved infrastructure, and appropriate policies. The plummeting cost of batteries and smart control systems helps, but longer-term storage options are also needed, and *appropriate market structures and incentives to encourage the deployment and use of these complementary technologies remain largely absent.* Publicly backed strategic investment in complementary technologies and infrastructure can also help to drive the reconfiguration of existing systems to enhance renewables deployment.

The impact of rising demand for electricity, our final indicator, is in principle double-edged. Continuing electrification of energy in most net-zero scenarios implies higher demand as electricity replaces fossil fuel combustion in engines, heating, and industry. If such demand growth is at least matched by growth in renewables supply, then emissions would decrease, as already observed in 2019 and accelerated by the impact of Covid to date.

Implications

Overall, our analysis points to a fundamental clash with risk of extensive stranded assets. The “red-green” divergence between the fossil fuel and renewables indicators – combined with the 35% of generation investment that still flows into non-renewable (mostly fossil) generation – suggests that the rapid growth of renewables is not being factored in by incumbent industries. The load factors for fossil fuel generation cannot be sustained: not only are they incompatible with avoiding dangerous climate change, but they are inconsistent with the observed dynamic growth of renewables. Not for the first time, it seems that incumbent industries are failing to acknowledge the dynamics of disruptive change.

Our overall conclusion though is conditionally positive. *The breakthroughs in solar, wind, and batteries have created unstoppable momentum toward growing market share, at a pace which is consistent with the renewable share trends observed in Paris-consistent scenarios, and power sector investment in fossil fuels is being rapidly eclipsed.* However, serious obstacles remain which could slow the pace of transition and prevent realization of the full potential, whilst resumed growth in electricity demand would risk outstripping the growth of renewables for long enough to render the Paris targets unreachable. High ambition still requires strong and broad-based policy action.

SECTION 1: INTRODUCTION

1.1 AIMS AND CONTEXT

The Paris Agreement, signed in 2015 by 197 countries, declares the global community's response to the threat of climate change as "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UN, 2015).

Meeting this challenge requires major social and technological transformations to reduce greenhouse gas (GHG) emissions dramatically across all sectors of the economy. Emissions of the major greenhouse gas by volume, carbon dioxide (CO_2), would need to be net zero by around 2050 and before then in the power sector.

How do the world's current social and economic systems, and the rate at which they are changing, measure up to this challenge? Is the world on track to meet the goals of the Paris Agreement? In this report, we consider these questions with respect to just one sector, but one of the most important – electricity generation. We look closely at the shape and pace of change, and the rates of growth and diffusion of key technologies, to examine whether the rate of change in this sector can be said to be Paris-consistent.

1.2 THE POWER SECTOR

The electricity generation – or "power" – sector currently accounts for 41% of global energy-related CO_2 emissions (IEA, 2020a). Decarbonizing this sector is therefore critical to reaching the goal of net-zero CO_2 emissions by 2050. Moreover, zero-carbon electricity is important to unlock decarbonization in other sectors through the increased "electrification" of energy services – for example, the adoption of electric vehicles in the transport sector, or the increased use of heat pumps in buildings.

Table 1 compares the CO_2 emissions intensity (average emissions per unit (kWh) of electricity generated) and the share of renewables in the current global power system, with relevant benchmarks for a 2050 Paris-consistent power system. The benchmarks are derived from three sources. The first is Climate Works Foundation et al.'s Climate Ambition Benchmarks (Climate Works Foundation et al., 2019). The second is New Climate Institute and Climate Analytics' Climate Action Tracker of Paris Agreement Compatible Sectoral Benchmarks (CAT, 2020). The third is a calculation of the median value of Paris-consistent scenarios from the database of scenarios that supported the IPCC's Special Report on Global Warming of 1.5°C (Huppmann et al., 2018), maintained by the International Institute for Applied Systems Analysis (IIASA). Further explanation of our process for selecting Paris-consistent scenarios from this database – hereafter, "relevant" (for this report) scenarios – is given in the Technical Annex.

	2019 system	**Climate Ambition Benchmarks**[2]	**Climate Action Tracker**[3]	**Median of relevant Paris-consistent scenarios**[4]
Power sector CO_2 intensity	463 gCO_2/kWh	**2050:** 0 CO_2/kWh	**2030:** 87.5 CO_2/kWh **2050:** <0 gCO_2/kWh	**2030:** 125 gCO_2/kWh **2050:** -7.5 gCO_2/kWh
Share of renewable or zero-carbon sources in electricity generation	26% renewables (wind and solar combined 8%)	**2030:** 65% renewables **2050:** 100% (zero carbon)	**2030:** 55-90% renewables **2050:** 98-100% renewables	**2030:** 54% renewables (wind and solar combined 30%) **2050:** 77% renewables (wind and solar combined 51%)

Table 1: Comparison of 2019 power system characteristics with selected benchmarks.

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[2] Climate Works Foundation et al. (2019)

[3] CAT (2020)

[4] Huppmann et al. (2018)

The table indicates that a Paris-consistent power system must at a minimum reach net-zero CO_2 emissions by 2050. However, because of the relative wealth of technological options for decarbonizing the power sector, and its importance in helping to decarbonize other sectors, earlier is preferable. Of the relevant scenarios, 29% reach net-zero power sector emissions by 2040, and 51% of them do so by 2045.[5]

Achieving this ambition will require substantial contributions from renewable power sources. Across the relevant scenarios, renewables commonly account for over three-quarters of power generation by 2050 (median: 77%), of which about two-thirds (51%) is from wind and solar photovoltaics (PV). Using an alternate approach, the Climate Action Tracker (CAT) benchmark demands close to 100% renewable power generation in 2050, as it largely discounts the potential for other sources, such as fossil fuels with carbon capture and storage (CCS) and nuclear, to meaningfully contribute.

1.3 THE NATURE OF TRANSITIONS: CHANGE IS NOT LINEAR

A comparison of contemporary characteristics of the global power system with Paris-consistent sector benchmarks for 2050 prompts the question: is the power sector on track to be Paris-consistent?

The relatively small share of generation from renewables today may easily give the impression that we are far off course. This impression would remain if one were to project in a straight line even the recent trends in the share of renewables in global power generation to 2050. Figure 1 shows that with such a linear projection, the resulting share of generation from renewables in 2050 would still be far from the Paris-consistent CAT and CAB benchmarks.

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[5] This is an estimate because some models report in ten-year, not five-year, increments. In such cases a linear interpolation was made between the 2040 and 2050 emissions value in order to approximate whether the emissions pathway implies zero emissions by 2045. This estimate of the percentage of scenarios with zero power sector emissions by 2045 includes those scenarios for which a linear interpolation gives zero or a negative figure in 2045.

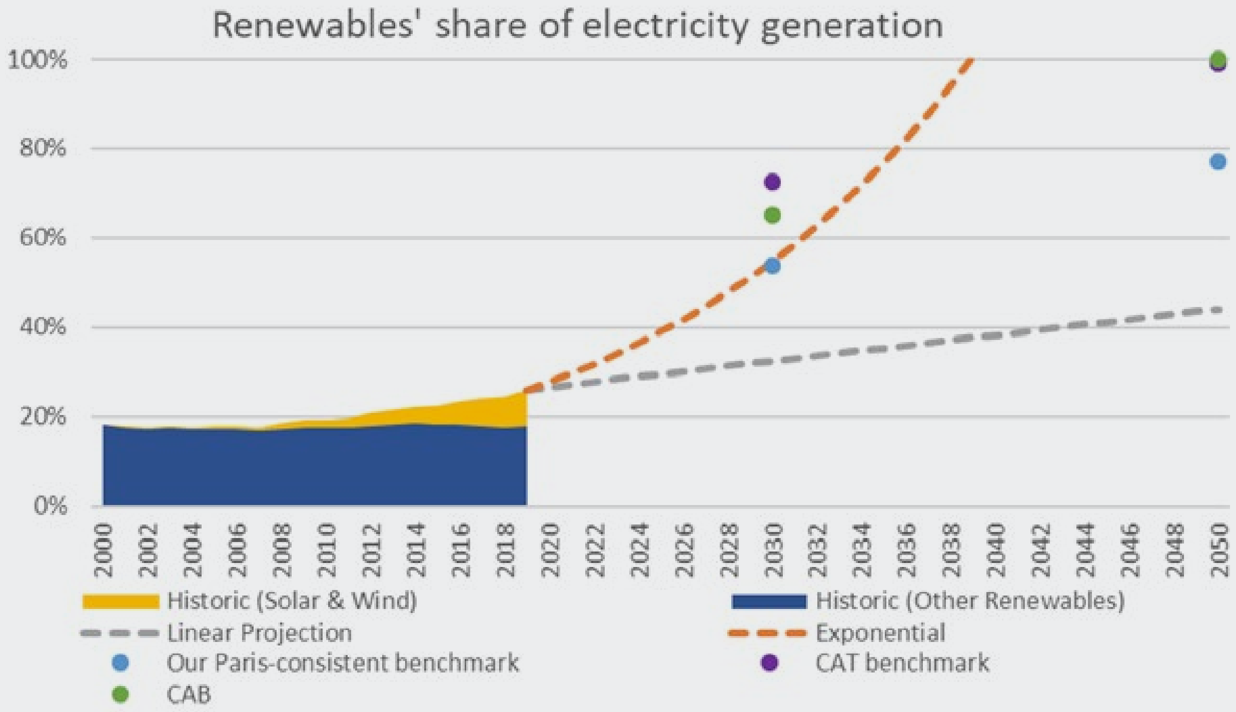

Figure 1: Comparison of linear extrapolation of historic trend in growth of renewables' share of electricity generation (2008-2019 average rate), with exponential growth (7% annual increase), and with 2030 and 2050 benchmarks derived from Climate Action Tracker (CAT, 2020), Climate Ambition Benchmarks (CAB) (Climate Works Foundation et al., 2019), and "our Paris-consistent benchmark," based on the median of relevant scenarios from Huppmann et al. (2018).

However, the dynamics of technological transitions are not so simple. Very often, the adoption of a new technology may grow very slowly for a number of years before becoming increasingly rapid. The inverse is often true for the technologies which are displaced, so that they are removed from the system "gradually, then all at once," as in the case of coal power in the UK (Evans, 2020).

If a technology grows at a constant (percentage) rate of increase year-on-year, exponential growth results. The trend in the share of renewables in power generation shown in Figure 1 combines a largely stable share of the most established renewable technologies – principally hydro – with rapid, exponential growth in wind and solar, as charted later in this report. In the early stages of exponential growth, the absolute contribution is small relative to the overall market, but as market share grows, each annual increase becomes correspondingly more dramatic.

Figure 1 also illustrates the implication if the contribution of all renewables together were to grow exponentially at 7%/year on average from now on – more than yet seen in total, but far slower than the growth observed in the wind and solar components. By 2040, the system would be completely decarbonized. This is the old story of exponential growth, often acknowledged in theory but hugely underestimated in practice.[6]

Many factors affect the rate of growth, and how long exponential growth can be sustained. Cost-competitiveness is an obvious but nonetheless important example. If a new technology is more expensive than the incumbent for the same type and quality of service, adoption beyond a small niche is unlikely; whereas if it is able to deliver at a lower cost, a stable rate of growth may persist for much longer, with the technology breaking through into new and larger markets.

Wider, systemic factors are also important. For example, some technologies exhibit "network effects" in which increased adoption generates benefits for the wider system. The attractiveness of such technologies may be limited while there are few adopters, resulting in slow growth; but as the number of users increases, their attractiveness is transformed and growth can be rapid. Network effects are often exhibited in telecommunications systems and technologies (Doganoglu and Grzybowski, 2007). In other cases the full functionality of a technology may be dependent on the existence of an underlying infrastructure – physical as well as social and institutional. Examples include automated teller machines (ATMs), the adoption of which took off rapidly once supporting IT systems and infrastructure were constructed (Watson et al., 2019), and motor vehicles, which benefited from the construction of paved roads throughout the twentieth century (Nakicenovic, 1986).

However, exponential growth cannot continue indefinitely. The ultimate limit to growth is market saturation – the point when all potential demands for a technology have been satisfied. But well before this, numerous factors often lead to the rate of growth progressively declining, tailing off as saturation begins to appear on the horizon. For renewable technologies, suitable sites may become increasingly difficult to find. In some places the pace of development of supporting physical, institutional, and social infrastructure may suffer its own constraints and throttle further deployment. In some instances the incumbent technology may still retain advantages (or not yet have reached the end of its life). Investment in new supply chain capacity may begin to decline as the remaining market share to be captured begins to dwindle, or other emerging technologies begin to compete.

The adoption of a technology is then characterized by phases of acceleration and deceleration. Plotting technology adoption against time in light of this produces an S-curve (also known as a logistic substitution curve), as illustrated in Figure 2, with an "emergent" phase of low overall deployment, giving way to a "diffusion" phase where sustained annual growth rates give rise to an exponential adoption curve. This slows down to linear growth during the main diffusion stage as limiting factors such as those described above begin to exert their influence, before subsiding in the final "culmination" phase as market saturation is approached. Such a dynamic has been demonstrated in a wide range of contexts. Historic examples – alongside incumbent electricity-generating technologies – include mobile communication technologies (Schwieterman and Fischer, 2017), jet engines, and successive steel-making technologies (Dattee, 2007).

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[6] There are many classic examples of exponential growth. Perhaps the most famous historical story is that of wheat (or rice) grains on a chessboard –sometimes attributed to the inventor of chess: when asked by his King what he would like as reward, he asked for one grain on the first square, two on the second, four on the third, and doubling successively. The story goes that the king asked "is that all?", before eventually realising that the entire global supply would be exhausted long before the request could be met. More prosaic examples abound, including the growth of lily pads on a pond which seem to do very little for many weeks, before apparently suddenly covering the pond in a few days.

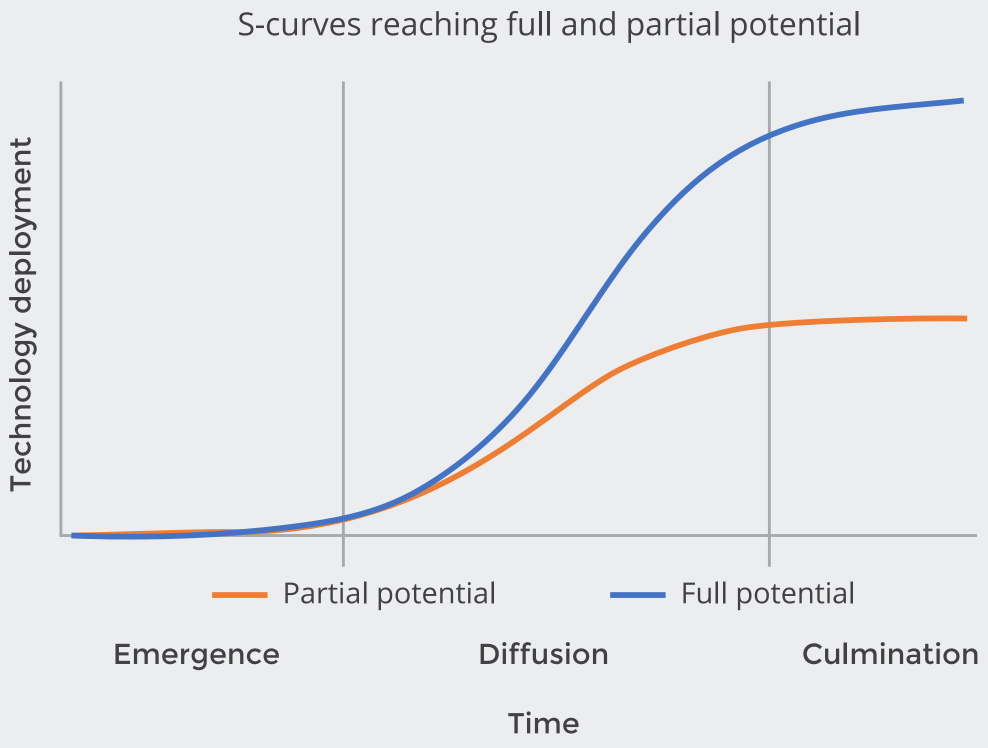

Figure 2: The S-curve and its three phases

Figure 2 illustrates two curves, one in which various constraints combine to progressively slow the rate of growth, but the full market potential of the technology is reached in the culmination phase, and one in which constraints manifest to slow growth prematurely and prevent the technology from reaching its full potential.

So, if technological transitions typically follow an S-curve dynamic, what are the implications for assessing progress in power sector decarbonization, and future prospects?

First, it means that understanding the likely shape and pace of change between these two points is crucial to any evaluation of progress. Using simple straight-line extrapolation from recent trends to assess progress excludes consideration of these dynamics, and could result in a misleading and undue pessimism.

Second, it draws attention to the factors that may sustain the adoption of decarbonizing technologies such that exponential growth rates are maintained for as long as possible, alongside factors that could cause these rates to decline prematurely: what progress is in turn being made with these elements, and how possible constraints may be eased.

1.4 OUR APPROACH

In this report, we use S-curve dynamics as a framework for assessing whether the power sector is on track to be Paris-consistent by 2050.

We start in Section 2 by examining recent power sector trends in CO_2 emissions, the deployment of and generation from key renewable technologies, and the decline in fossil fuels. We consider what effect the assumption that such trends represent the early stages of an S-curve transition has in determining whether or not the sector is on track to be Paris-consistent by 2050, with reference to key benchmarks (see Box 1 on page 10).

We then consider the key driving and constraining factors that could affect the continuation of an S-curve-shaped trajectory by accelerating, sustaining, or decelerating technology adoption. In Section 3 we examine the costs of key technologies as a crucial factor for accelerating deployment through the diffusion phase. In Section 4 we focus on wider systemic and contextual factors which, if not addressed, might prematurely constrain growth and result in diffusion levelling out some way below its potential. Section 5 draws conclusions.

Box 1: Benchmarks as reference points for wind and solar trajectories

Benchmarks provide a reference point against which to judge progress on various metrics. Our primary benchmarks are derived from the IPCC's database of relevant 1.5°C-compatible trajectories available in the literature; the 2050 benchmarks, the median value from the scenarios in the database, anchor the S-curve trajectory from 2010 for each metric (see Technical Annex). The 2030 benchmarks illustrate how the computed S-curve trajectory compares against the median value for 2030.

There are other benchmarks in the literature (Table 1). A recent Climate Action Tracker report (CAT, 2020) presents benchmarks for overall decarbonization, and in our analysis we present those which correspond to our electricity-focused categories. Their values diverge particularly for wind and solar energy, because the CAT benchmarks focus only on scenarios with 100% renewables for electricity by 2050.

There are many ways of decarbonizing power generation. National conditions, views, and preferences vary. The majority of the Paris-consistent scenarios in the IPCC database have over half of all electricity by 2050 generated from solar and wind, and about three-quarters from renewables overall, but still with important contributions from nuclear and/or fossil fuels with CCS.

The CAT scenarios assume that nuclear is largely phased out by 2050 and CCS remains insignificant. They reflect a particular view of likely, or desirable, choices in power generation and thus form a useful complementary reference point, but we base our Paris-consistent benchmarks on relevant 1.5°C-compatible scenarios from the IPCC's database, which reflect a diverse set of potential future developments and generation options.

SECTION 2: CO_2 EMISSIONS & TECHNOLOGY DEPLOYMENT

This section considers physical dimensions of the electricity sector – its CO_2 emissions and its technology profile. We compare recent trends with the early stages of illustrative S-curve trajectories that reach Paris-consistent benchmarks in 2050, and assess whether, and under what conditions, these indicators may be considered on track.

Our benchmarks are based on the median values in 2050 of relevant scenarios from the database assembled by Huppmann et al. (2018) (see Technical Annex for full method). In Table 1, benchmarks derived in this way were reported for CO_2 intensity and share of electricity produced by renewables. In this section we use the same approach to derive additional benchmarks on total CO_2 emissions, installed capacity and generation for wind and solar technologies, the share of electricity generated from wind and solar, and total generation from unabated fossil fuels (i.e., without CCS), with 2050 benchmarks defining the end point for S-curve dynamics starting in 2010. We also present 2030 benchmark values using this method, and values from the Climate Action Tracker where available, to allow comparison.

We focus on wind and solar PV, since these are the most dynamic technologies and are critical in all the relevant scenarios – contributing more than half of power supplies by 2050 in the median case – with the remainder a varied mix of other renewables, nuclear, and fossil fuels with CCS.

For each indicator we present trends from 2000 to 2019, and plot S-curves starting from 2010 and to culminate at the 2050 benchmark levels, so that recent trends may be compared with these projections. For the purposes of this report, we therefore assume that the benchmark values represent the maximum potential market share for wind and solar technologies in 2050.

The shapes of the S-curves are defined by three parameters:

- the **starting point** – this is normally taken to be the 2010 historic value;
- the **saturation point** – set at the level of the 2050 benchmark; and
- the **emergence annual growth rate** – the maximum annual growth rate as technologies begin to emerge, and which gradually reduces over time.[7]

In the case of CO_2 emissions and unabated fossil fuel technologies, we plot "inverse" S-curves reflecting a somewhat simplified dynamic of the decline of incumbent fossil fuel technologies (with further explanation provided below).

[7] The maximum annual growth rate is that experienced by a technology at the very first stages of growth, but which declines slowly over time to produce S-curve penetration. By the time a technology moves from emergence to diffusion, the annual growth rate will typically have reduced by only a small degree. For example, in Figure 6 (Section 2.3), annual growth in the S-curve with a 30% ER reduces from 29.9% in 2011 to 28.4% in 2021. It is also worth noting that in practice, for some years, annual growth rates may be much higher than this "maximum" rate. This highlights the fact that transitions are complex, with S-curves describing a general shape of transition rather than a narrow pathway from which there is no deviation.

2.1 TOTAL CO_2 EMISSIONS AND CO_2 INTENSITY OF THE POWER SECTOR

	Climate Action Tracker	**Paris-consistent Benchmark**
CO_2 emissions	-	**2030:** 4,171 Mt/year **2050:** -622 Mt/year -
CO_2 intensity	**2030:** 87.5 gCO_2/kWh **2050:** <0 gCO_2/kWh	**2030:** 125 gCO_2/kWh **2050:** -7.5 gCO_2/kWh

The trend in CO_2 emissions from power generation since 2010 is not Paris-consistent, but the trend in CO_2 intensity is moving in the right direction, and close to being on track for an S-curve-based trajectory consistent with the 2050 benchmarks. However, more rapid changes would be required to achieve the 2030 benchmarks, consistent with using electricity to decarbonize other sectors.

In the relevant scenarios, annual CO_2 emissions from electricity generation are typically zero or negative before 2050[8]; just over half of them achieve net-zero emissions by 2045 (see note 5).

Figure 3 shows CO_2 emissions from global power generation for 2000-2019, and projections to the 2050 benchmark for 2010-2050, whilst Figure 4 presents the corresponding values for CO_2 intensity. In both figures, linear and (inverse) S-curve trajectories from 2010 are presented, for illustrative purposes. The S-curve trajectories can be thought of as reflecting what would happen to incumbent technologies,[9] and their associated emissions, if they are displaced one-for-one by new zero-carbon technologies based on S-curves with combined emergence growth rates of 20%/year.

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[8] Power sector emissions lower than zero would require "negative emissions" technologies, such as power stations with carbon capture and storage (CCS) fuelled with biomass.

[9] Under a simplified assumption of consistent CO_2 intensities.

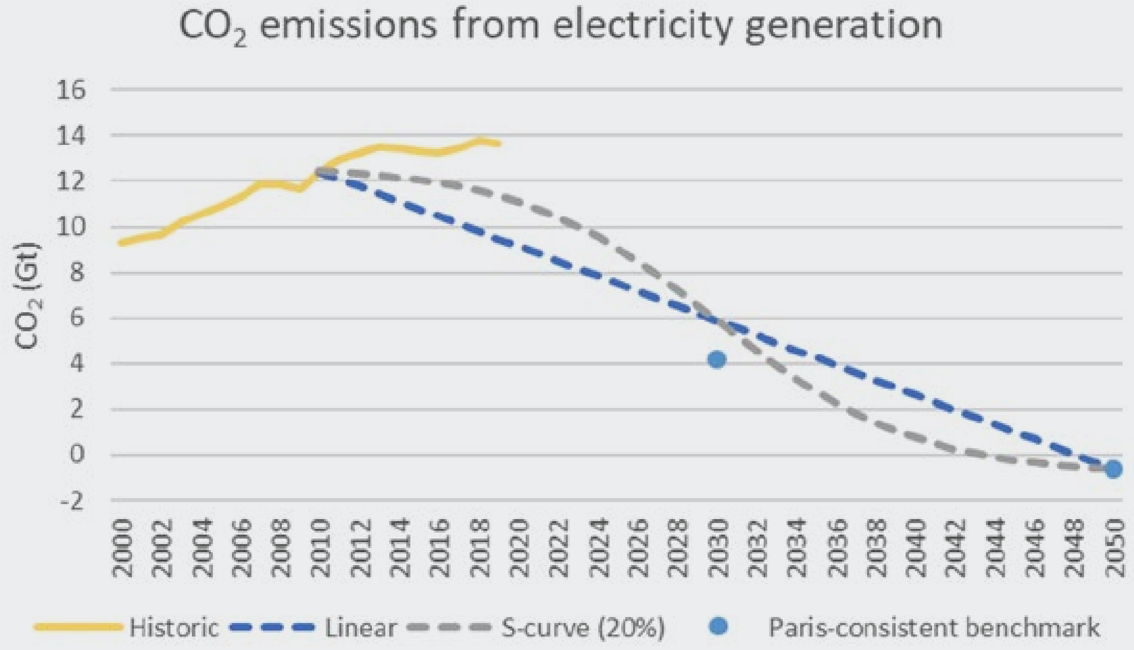

Figure 3: Historic (2000-2019) and projected (2010-2050) CO2 emissions from global electricity generation. Historic emissions data from IEA (2020a).

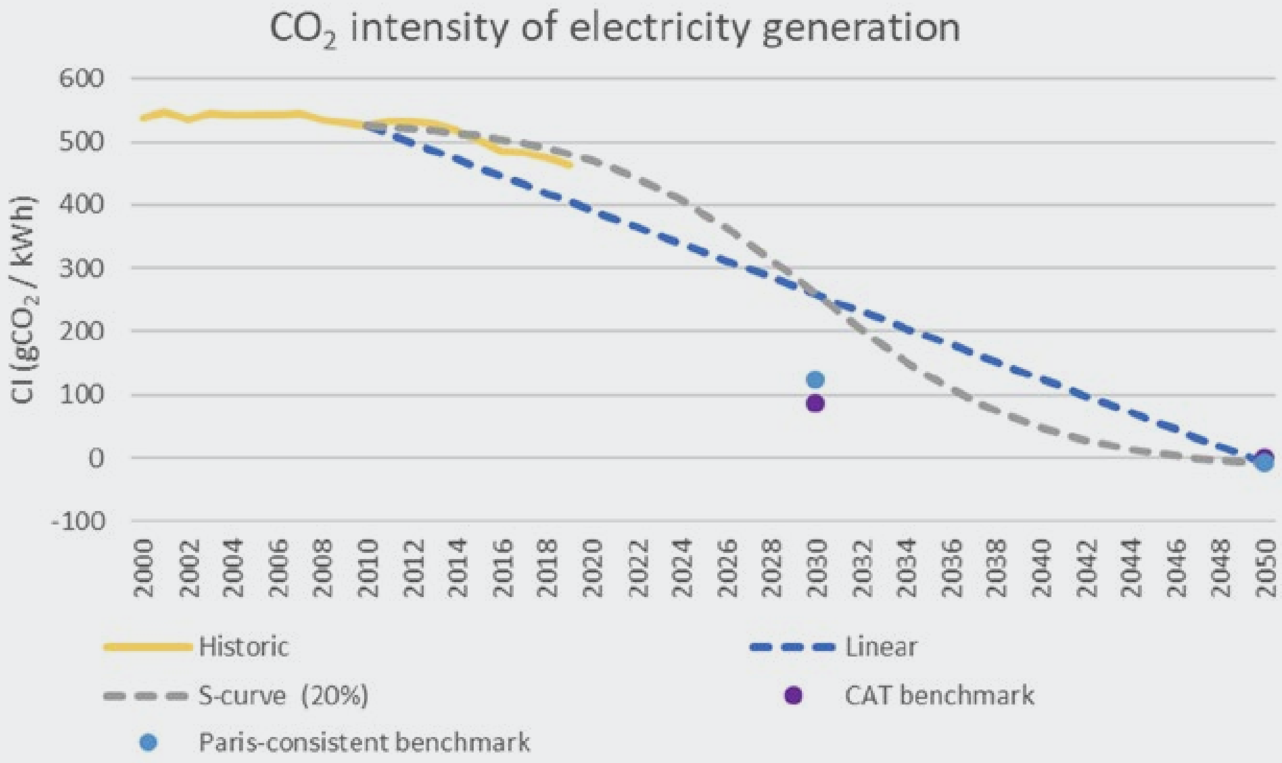

Figure 4: Historic (2000-2019) and projected (2010-2050) CO2 intensity of global electricity generation. Historic data for 2000-2009 from IEA (2018), and for 2010-2019 from IEA (2020a).

Figure 3 illustrates that power sector CO_2 emissions were broadly rising until 2018. Although they then fell by around 1% in 2019, this overall trend diverges sharply from that required to meet the 2050 benchmark (under either projection). By contrast, Figure 4 illustrates that although the CO_2 intensity of global power generation was fairly static over 2000-2010, it began falling thereafter, and fell by 2.6% in 2019. This trend reflects the fact that although coal-fired generation grew at an average of 1.4% per year over 2010-2019, this growth was less strong than gas-fired and non-fossil generation, which grew at annual averages of 3.0% and 3.8% respectively over this period (IEA, 2020a; BP, 2020).

The rate of decrease in CO_2 intensity is not aligned with the linear interpolation, but it is fairly well matched to the inverse S-curve trajectory. However, this “aggregate electricity” S-curve projection in itself falls short of the 2030 benchmarks, achieving these levels only in the mid-2030s. This suggests that if electrification is to support wider global decarbonization, power sector decarbonization during the 2020s would have to be more rapid than indicated by this S-curve.

In practice, the shapes of these particular S-curves are necessarily more complex than for those charting the adoption of a new technology. Fossil fuel generation technologies have highly varied specific CO_2 emissions, particularly between coal and natural gas plants but also between individual plants with different efficiencies and different specific fuels (e.g., lignite vs. anthracite). The shape of the curve would therefore depend on the profile of the specific plants displaced over time.

The opposing trends apparent in these two indicators summarize the positive and negative sides of the story being played out in the global power sector. Although growth in generation from highly CO_2-intensive fossil fuels (particularly coal) is being outpaced by that of less CO_2-intensive fossil fuels (particularly natural gas) and zero-carbon sources (particularly renewables), thus reducing CO_2 intensity, the increase in fossil fuel generation continued the long-term (overall) trend of increasing total annual CO_2 emissions at least until 2018. Changing this overall trend will depend on zero-carbon technologies not only adding to fossil-fueled generation but rapidly displacing it. In turn, this will hinge on the combination of high rates of annual growth in the zero-carbon technologies, and on changes in electricity demand. We focus on zero-carbon technologies in this section, and consider the complex role of electricity demand in Section 4.

2.2 TOTAL CAPACITY AND GENERATION FROM WIND

	Paris-consistent Benchmark
Wind capacity	**2030:** 2,380 GW **2050:** 6,437 GW
Wind generation	**2030:** 6,758 TWh/year **2050:** 17,112 TWh/year

Wind capacity increased by 15% per year on average over 2010-2019, with electricity generated from wind increasing by 17% per year on average. The rate of increase in *generation* is on a Paris-consistent trajectory, but the recent slowdown in *capacity* growth is not.

Figure 5 compares global installed capacity of (onshore and offshore) wind (2000-2019, left-hand panel), and electricity generated from wind (2000-2019, right-hand panel), with S-curve trajectories starting from 2010, and approaching the relevant Paris-consistent benchmark values in 2050. Callout bubbles focus on the years 2000-2020.

Global installed capacity of wind grew at an average annual rate of 21% over 2000-2019, but at 15% over 2010-2019. As illustrated by the callout in the left-hand panel of Figure 5, when compared against projected S-curves with emergence annual growth rates of 15%, 20%, and 25%, the trend since 2010 is toward the least rapid of these projected deployment curves, which despite running close to the 2030 Paris-consistent benchmark only reaches around 90% of the benchmark value in 2050.

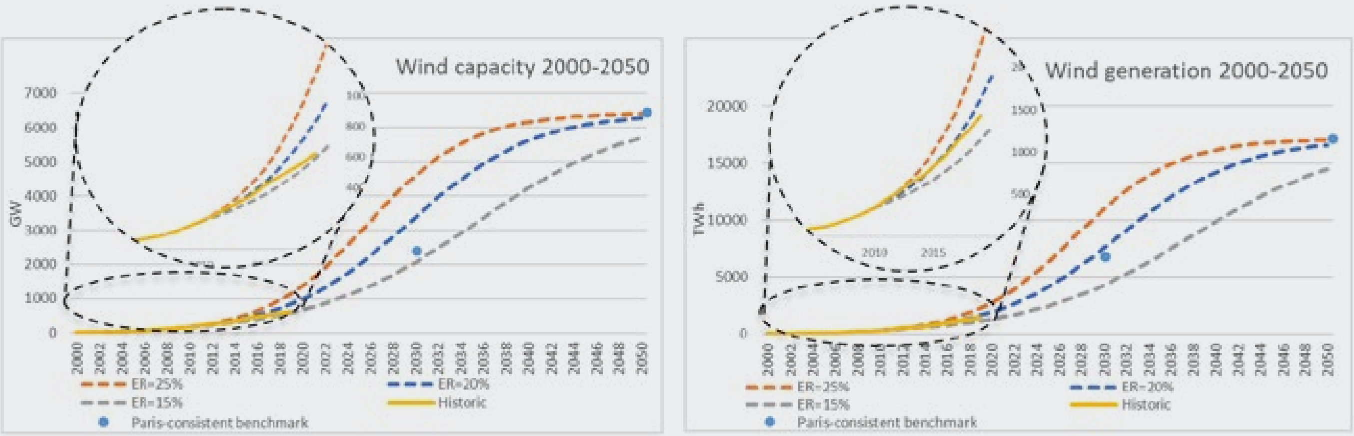

Figure 5: Wind installed capacity and generation. Historic values for 2000-2019, from IRENA (2020a) and BP (2020). S-curve projections start from 2010 values. Saturation point of S-curves set at relevant 2050 Paris-consistent benchmark. Left-hand panel shows capacity, right-hand panel shows generation. Callouts focus on 2000-2020.

Electricity generated from wind increased more rapidly than capacity, at an average annual rate of 22% over 2000-2019 (and 17%/year since 2010). This is largely due to increasing capacity factors – in other words, more electricity (kWh) can be generated from a single unit (kW) of installed capacity due to technological improvements (e.g., taller towers and longer blade lengths) that can capture more energy from a given wind resource, more of the time (IRENA, 2020b). Compared with S-curves with emergence annual growth rates in the range of 15-25%, the trend since 2010 followed a central path, which places it on track to achieve the 2050 (and the intermediate 2030) Paris-consistent benchmark.

As it is the electricity generated, and not the capacity itself, that is of primary interest, the growth in generation is the more salient indicator. However, the importance of increasing capacity factors in placing the trajectory of generation from wind on track, whilst capacity lags behind, points to the need to combine improved performance with a continued or accelerated pace of capacity growth to meet the Paris-consistent generation benchmark by 2050 (discussed further in Section 3.1).

2.3 TOTAL CAPACITY AND GENERATION FROM SOLAR PV

	Paris-consistent Benchmark
Solar PV capacity	**2030:** 1,377 GW **2050:** 4,826 GW
Solar PV generation	**2030:** 2,320 TWh/year **2050:** 9,934 TWh/year

Solar PV capacity increased by 34% per year, and electricity generated from solar PV by 41% per year, on average over 2010-2019. The rate of increase in both generation and capacity is higher than that required for a Paris-consistent trajectory.

Figure 6 compares global installed capacity of solar PV (left-hand panel), and electricity generated from solar PV (right-hand panel), for 2000-2019 with S-curve trajectories starting from 2010, and approaching Paris-consistent benchmarks in 2050. Callout bubbles focus on the years 2000-2020. Because solar PV has seen much more rapid growth than wind – a pattern continued in Paris-consistent scenarios – Figure 6 illustrates faster emergence rates than for wind (of 25%, 30%, and 35%/year).

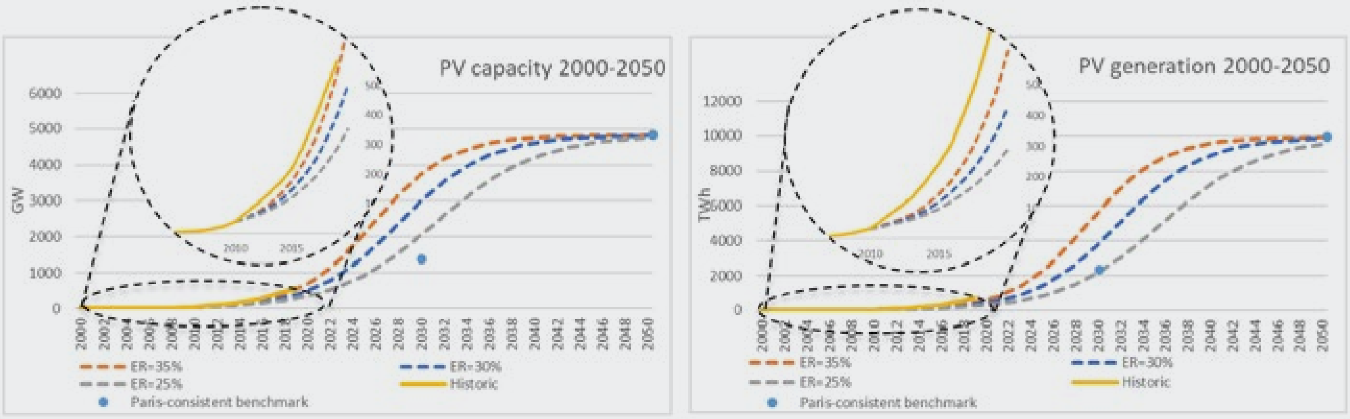

Figure 6: Solar PV installed capacity and generation. Historic values from 2000-2019, from IRENA (2020a). S-curve projections start from 2010 values. Saturation point of S-curves set at relevant 2050 Paris-consistent benchmark. Left-hand panel shows capacity, right-hand panel shows generation. Callouts focus on 2000-2020.

Global installed capacity of solar PV grew at an average annual rate of 41% over 2000-2019, but at 34% over 2010-2019. Electricity generated from solar PV increased at average annual rates of 43% and 41% over these timeframes, respectively. As illustrated by Figure 6, the trends experienced since 2010 are ahead of even the most rapid of the S-curve ranges presented (all of which, in the case of installed capacity, well exceed the 2030 benchmark), particularly for generation. As with wind, trends in generation outpacing those in installed capacity reflect increasing capacity factors (IRENA, 2020b) (discussed further in Section 3.1).

2.4 SHARE OF TOTAL GENERATION FROM WIND AND SOLAR PV

	Climate Action Tracker	Paris-consistent Benchmark
Share of total generation from wind and solar PV	**2030:** 30-65% **2050:** 73-75%	**2030:** 30% **2050:** 51%

The combined global share of electricity generation from wind and solar PV rose from 2% in 2010 to 8% in 2019. This rate of increase is on track to meet the Paris-consistent benchmarks in 2050 under an S-curve trajectory, and an intermediate benchmark for 2030.

In 2019, while all renewables accounted for 26% of electricity generated (with the majority from hydropower), the combined share of electricity provided by wind and solar PV was 8% (BP, 2020). Although this share is relatively small, it is rapidly increasing. Figure 7 combines the data on power generation from wind and solar PV presented in Figures 5 and 6, and plots them against three S-curve trajectories at the emergence annual growth rates used for Figure 6, above (25%, 30%, and 35%).

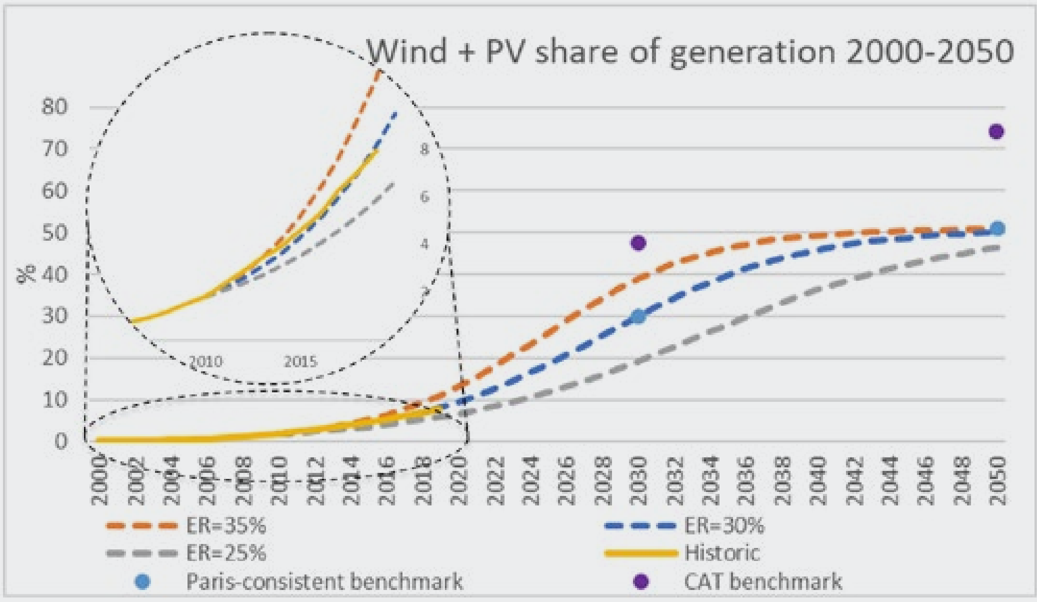

Figure 7: Wind and solar PV's historic share of total electricity generation, compared with S-curve projections toward 2050 Paris-consistent benchmarks. Historic values for 2000-2019 calculated based on IRENA (2020a), EIA (2020), and BP (2020). CAT benchmarks are the midpoint of ranges.

Recent trends are following the trajectory plotted by an S-curve with a 30% emergence annual growth rate. Continuing this trend as indicated would meet not only our 2050 Paris-consistent benchmark, but that for 2030 as well. However, it falls well short of the CAT benchmarks for renewables-only scenarios,[10] and if the rate of growth slows and the trend begins to follow a trajectory closer to a 25% emergence annual growth rate, generation in 2050 would be around 5% short of our own benchmark.

As this is a combined benchmark for wind and solar PV, if growth in one technology suffers, the other may compensate. If impediments to onshore wind grow, the remarkable progress in offshore (Section 3) might compensate, and/or so might solar PV if the current spectacular growth rates can be sustained. Of course, alongside this benchmark, meeting those for CO_2 emissions and CO_2 intensities (Section 2.1) requires a growing contribution from other zero- or negative-carbon sources as well (e.g., other renewables, nuclear, and/or fossil fuel or biomass generation equipped with CCS). If any such sources were to be severely limited (as is assumed by the CAT benchmarks), the contribution from wind and solar PV – in particular – would have to be significantly higher.

[10] The CAT benchmarks focus on total renewable electricity. To calculate the value used in Figure 7, we use the midpoint of the benchmark range presented by CAT, and assume that all renewables other than wind and solar contribute 25% of global electricity generation, in both 2030 and 2050, compared with the current 19%. Global hydropower generation grew from 3,445 TWh/year in 2010 to 4,333 TWh/year in 2019, a compound growth in absolute generation of 2.5%/year, exceeding the rate of growth in global power demand. Projections suggest continuing growth of hydro generation, but falling short of 3%/year to 2030, as capacity additions are slowing (IEA, 2020c).

2.5 TOTAL GENERATION FROM UNABATED FOSSIL FUELS

	Paris-consistent Benchmark
Share of total generation from unabated fossil fuels	**2030:** <26% **2050:** <1.5%

Total fossil fuel generation continued to expand every year over 2010-2018, though more slowly than total power demand, leading to a decline in its share of power generation. Coal generation declined in 2019, with sharper reductions for both coal and gas expected for 2020 following the impact of COVID-19. Sustaining accelerated decline, particularly of coal, is essential in the coming years, if the Paris goals are to be met.

Figure 8 presents illustrative inverse S-curves for the decline of unabated fossil fuel generation required for Paris consistency, based on the projections in Figure 7, and supplementary assumptions (see Note 11 for details).

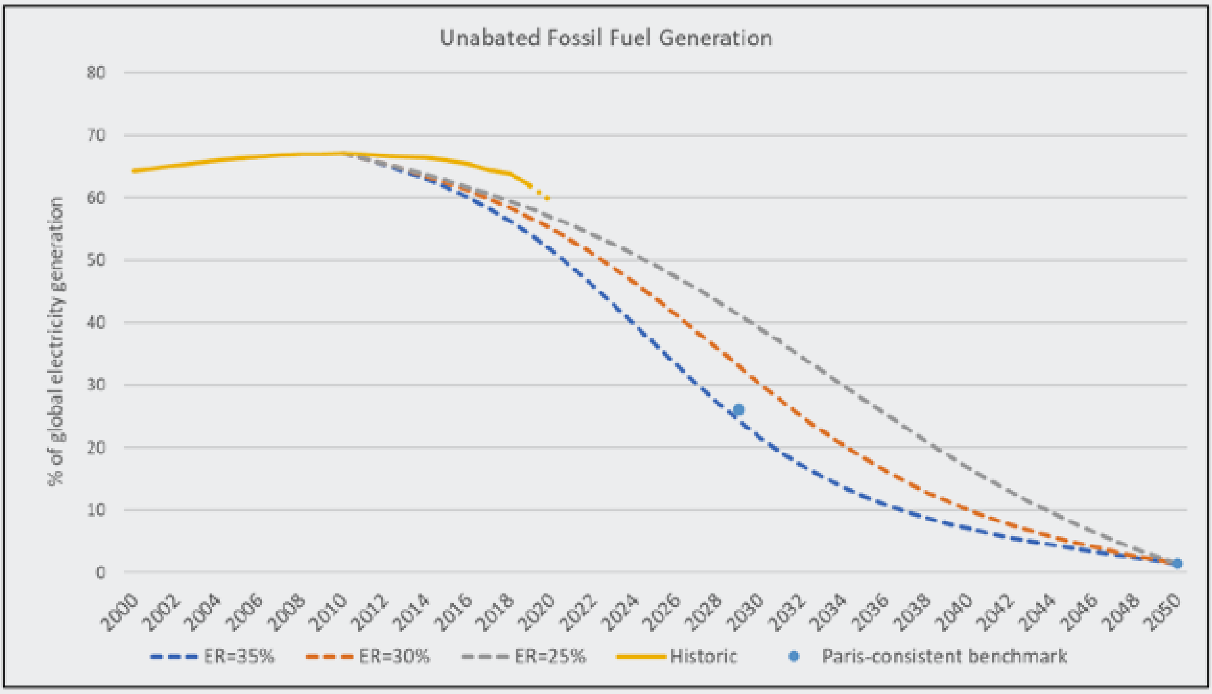

Figure 8: Trend in overall fossil fuel generation, compared with S-curve projections toward 2050 Paris-consistent benchmarks.[11]

The share of unabated fossil fuels began to decline in 2011, although until 2018 this decline was relatively slow, and well behind the pace required for Paris consistency, as indicated by the illustrative inverse S-curves in Figure 8. Despite the decline in *share* of total generation, generation from both coal and gas continued to increase at 1.4% and 3.0% per year on average, respectively, over 2010-2019 – but with electricity demand growing faster in absolute terms. Given the deep emission reductions implied by the Paris goals – and the long-lived nature of electricity-generation assets – any increase in unabated fossil fuel generation is contrary to Paris-consistent power sector scenarios, even if the majority of new demand is satisfied by growth in non-fossil fuel sources.

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[11] The median value of fossil fuel generation in 2050 in the relevant scenarios is 1.45% of global electricity generation, which presumably reflects models capturing special limited circumstances which constrain alternatives and CCS (power sector emissions overall are negative due to assumed contribution of some negative emission technologies, notably biomass with CCS). The "inverse" S-curves presented here are constructed first by subtracting from 100% both the 1.45% of remaining unabated fossil fuel generation and the combined share of generation from wind and solar PV under the three trajectories in Figure 7 for 2050, to produce the remainders that should be satisfied by all other sources (all other renewables, nuclear, and fossil fuel with CCS) in that year. We then assume these other sources increase as a share of generation linearly from 2010 (from 31%, to 48-52%). For the years 2011-2049, projected generation from wind, solar, and all other sources are subtracted from 100%, with the remainder used to generate the curves presented.

While fossil fuel trends to 2018 were far off course for Paris goals, coal-fired generation fell by 3% in 2019, and another sharp drop is expected in 2020 as a result of the Covid crisis. In June 2020, the IEA estimated a 5% decline in annual electricity consumption in 2020, which is driving/will drive larger reduction in fossil fuels because renewables are still growing and generate preferentially due to very low running costs. They estimated 2020 gas generation would decline by 7% – and coal (which is also displaced by cheaper gas) by 10% (IEA, 2020b).

This accelerated decline of unabated fossil fuels will reduce their share of total generation below 60% in 2020 (as illustrated by Figure 8). This acceleration must be sustained, and even enhanced, if the 2050 benchmark (and particularly the 2030 benchmark) is to be achieved, and total CO_2 emissions from the sector are to enter terminal decline (Figure 3). However, the extent of the possible post-Covid bounce-back remains to be seen, and will depend heavily on electricity demand. The medium- to long-term implications are also far from certain.

Most significantly, Figure 8 points to the rapid decline in unabated fossil fuels implied over the next decade by the growth of wind and solar PV, particularly if it is accompanied by a post-Covid recovery, which keeps electricity demand growth down whilst sustaining low-carbon investment.

Consequently, any continued construction of fossil fuel plants is at high risk of being stranded by the wind and solar revolution. If the Paris goals are to be achieved, post-Covid investment must shift dramatically away from fossil fuels and toward renewables and enhancing energy efficiency, with an eye also to the ability of power systems to absorb high levels of variable renewables. Section 3 looks at indicators relating to costs, finance, and investment; Section 4 then considers other dimensions, including the role of supporting technologies and electricity demand.

SECTION 3: COSTS & FINANCE

Section 2 presented indicators that recent trends in the physical characteristics of the global power sector are or are not track to be consistent with the goals of the Paris Agreement by 2050, if S-curve dynamics are appropriately considered. It found that despite adverse trends in CO_2 emissions overall, the pace of growth in deployment and generation from key low-carbon technologies is largely on track to meet 2050 Paris-consistent benchmarks. Can and will this be sustained?

Cost is an important factor affecting the dynamics of a technology transition. If a new technology is more expensive than a competitor that provides the same service, it will not diffuse widely unless it receives continued, targeted policy support (e.g., deployment subsidies), which is hard to sustain as adoption increases. If, however, the cost of a new technology falls to a level comparable to that of its competitors, widespread diffusion is far more likely to be sustained at pace. The role of public policy is then more to reduce and remove obstacles and potentially provide some transitional support for entry into new markets, particularly where the societal costs of CO_2 emissions are not appropriately incorporated into the costs of fossil fuel-based incumbents.

To indicate comparative costs, this section uses the levelized cost of electricity (LCOE). This is calculated as “the ratio of lifetime costs to lifetime electricity generation, both of which are discounted back to a common year using a discount rate that reflects the average cost of capital” (IRENA, 2020b). Accordingly, the LCOE is affected by factors including the initial investment costs, interest rates on money borrowed to finance the project (the cost of capital), operation and maintenance (O&M) costs, and the capacity factor of the technology, which determines how much electricity is generated for each unit of capacity installed.

3.1 COST OF ELECTRICITY FROM WIND AND SOLAR PV

The costs of generating electricity from onshore wind, offshore wind, and solar PV have fallen substantially in recent years, and are competitive with new fossil fuel capacity in most cases. Prices in recent auctions suggest that onshore wind and solar PV may soon be cheaper than even the cheapest fossil fuel generators in a growing number of countries, sustaining rapid diffusion if markets are open and impediments removed.

Figure 9 presents estimates of the global range of LCOE for onshore wind, offshore wind, and solar PV annually since 2010. Grey boxes show the range between the 5th and 95th percentiles, and the grey line shows the global weighted average. Alongside historic LCOE values, future estimates derived from auctions and power purchase agreements (PPAs) are shown in blue, again with boxes indicating the 5th-95th percentile range and the blue line the global weighted average. LCOE data extends to 2019, whereas the auction/PPA data can extend beyond this, based on information from auctions and agreements already settled for future years.[12] For comparison, Figure 9 also presents estimates of the global range of LCOEs for new fossil-based electricity generation.[13]

The cost of generating from of all three renewable technologies has fallen significantly over the past decade, and all three now have weighted-average costs well within the estimated range of costs of generation from new fossil fuel capacity. In fact, in 2019, 56% of all new utility-scale renewable generation capacity provided electricity at a lower cost than the cheapest new fossil-based option (IRENA, 2020b).

The dramatic fall in costs of solar PV since 2010 has been driven by multiple factors: declining module costs due to mass production, reducing O&M costs, increasing deployment in areas of high solar resource, and low financing costs (IRENA, 2020b), discussed further in Section 3.2, below. Onshore wind was already often cost-competitive with fossil fuels in 2010, but costs have continued to decline due to improvements in turbine design and manufacturing, increasing competitiveness of global supply chains, and an increasing range of turbine designs optimized for different operating conditions (IRENA, 2019).

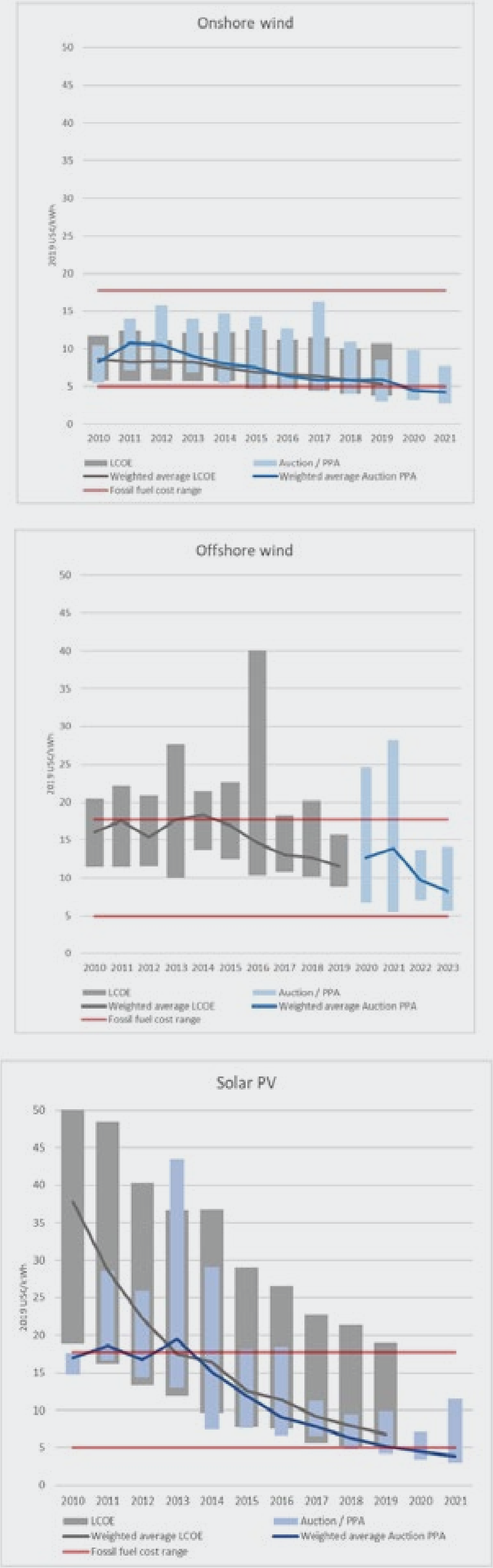

Figure 9: IRENA estimates of levelized cost of energy (grey) and cost data revealed by auctions and power purchase agreements (blue – see note 12) for onshore wind, offshore wind, and solar PV. Boxes show 5th to 95th percentile range. Lines show weighted averages. IRENA estimates of high and low range of new fossil fuel power generation shown in red. Data from IRENA (2020b).

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[12] Power Purchase Agreements (PPAs) are private contracts with generators setting the agreed price of electricity supplies, potentially several years ahead. Auctions tend to be government-convened competitive processes for long-term contracts. Consequently, both provide market-based indications of the cost at which generators are willing to sell power in future years from renewables under construction.

[13] The lower bound of $0.05/kWh represents new, coal-fired capacity in coal-producing regions in China.

Offshore wind is a less mature technology than onshore wind and solar PV. In the early years of its deployment, costs did not fall quickly (Greenacre et al., 2010). However, Figure 9 indicates clear and sustained weighted-average cost reductions from 2015 onward. According to IRENA, this “step-change in competitiveness has been driven by the industry achieving critical mass, along with innovations in wind turbine technology, installation, and logistics; economies of scale in O&M (from larger turbines and offshore wind farm clustering); and improved capacity factors from higher hub heights, better wind resources (despite increasing costs in deeper waters offshore), and larger rotor diameters” (IRENA, 2020b).

Costs are expected to continue declining as these industries continue to evolve and expand. Economies of scale in installation size, supply chains, and manufacturing, together with continuing technology advances and reducing costs of capital (discussed in Section 3.2), are projected to further reduce investment costs. Higher wind turbines, technology and operational refinement, and new techniques to identify optimal installation sites and configurations will likely continue to increase capacity factors,[14] further reducing LCOEs. Table 2 presents IRENA’s projections for LCOE ranges for 2030 and 2050, for all three technologies.

Table 2: Projected LCOE ranges. Source: IRENA, 2019a; 2019b.

LCOE Range (US¢/kWh) (5th-95th Percentile)						
	Onshore Wind		**Offshore Wind**		**Solar PV**	
	High	Low	High	Low	High	Low
2030	5	3	9	5	8	2
2050	3	2	7	3	5	1.4

Continuing cost reductions are evidenced by the estimates of LCOE derived from future auction and PPA prices presented in Figure 9, the weighted average for which dips below the lower bound of generation costs for new fossil-based capacity for solar PV and onshore wind, and close to it for offshore wind.

Indeed, the weighted average values for 2021 would mean new solar PV and onshore wind projects have lower generating costs than over half and a third, respectively, of *existing* global coal-fired installations (IRENA, 2020b). Once this threshold is breached, new renewable installations may grow at a rate faster than demand for all new generation capacity, and increasingly displace existing fossil-based capacity. This enhances space to maintain high annual growth rates for renewables into the future (Sections 2.2-2.4), and would accelerate the decline in unabated fossil-based generation (Section 2.5) and, consequently, CO_2 emissions from power generation (Section 2.1).

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[14] For onshore wind, the 5th-95th percentile range for capacity factors in 2030 is projected at 30-55%, and at 32-58% for 2050. For offshore wind, the corresponding values are 36-58% for 2030 and 43-60% for 2050 (IRENA, 2019b).

3.2 COST OF CAPITAL FOR INVESTMENT IN RENEWABLES

There is evidence that the falling technology costs, and lower risks, of renewables is reducing the cost of capital, which in turn reduces the levelized cost of electricity (LCOE).

Figure 9 also allows a comparison, in the case of onshore wind and solar PV, of IRENA's LCOE estimates with revealed auction and PPA data for the same years. In the case of solar PV, the revealed auction and PPA price is generally lower than the estimated LCOE value. One explanation may be the difference between the assumed and actual weighted-average cost of capital (WACC) – the combined cost of debt and equity used to finance the project. Renewables typically have high upfront investment costs and very low operating costs (Ameli et al., 2017), which amplifies the importance of financing costs. Indeed, for solar PV, aside from location, the WACC has been found to have the greatest impact on LCOE – with a nominal increase from 2% to 10% doubling the resulting LCOE estimate (Vartiainen et al., 2020).

Data on the cost of capital in different parts of the world for these technologies is limited. As a result, the LCOE values given in Figure 9 reflect a blanket assumption of a 7.5% WACC in OECD countries and China, and 10% for the rest of the world (IRENA, 2020b). The fact that auction and other contract prices have in recent years been at the low end of LCOE estimates – and that forward-contracted prices are still lower – suggests that the cost of capital can be substantially lower than the IRENA assumptions. This aligns with analysis by Ameli et al. (2017), who estimated WACCs for both green and renewable energy, and the power sector as a whole, for a range of OECD countries and emerging markets, for 2015-2016 (Table 3).

Table 3: WACCs across countries and sectors, based on 2015-2016 data. Source: Ameli et al. (2017).

WACC	Germany	France	Greece	Italy	UK	US	Japan	China	Emerging markets
Green and renewable energy	3.41%	3.90%	8.03%	5.06%	4.39%	5.14%		6.56%	8.16%
Power	3.22%	3.69%	7.59%	4.77%	4.27%	4.37%	1.82%	6.04%	6.31%

Table 3 shows that financing costs in many regions were already in 2015-2016 lower than the generalized IRENA assumptions – below 7.5% in several key OECD countries and China, and well below 10% in emerging markets, 4-5 years ago. IRENA also report "anecdotal evidence … that WACC expectations have fallen significantly … in recent years, as the extremely low-risk nature of developing solar PV projects is increasingly being correctly priced into cost-of-capital rates for both debt and equity" (IRENA, 2020b).

However, substantial differences in financing costs between different countries clearly remain – with WACCs in emerging markets more than double those in Germany and France. Measures to reduce financing costs for green and renewable energy in emerging markets may be an important route to accelerating investment and deployment in these markets, as discussed in Section 4.

Table 3 also illustrates the relatively small difference in the WACC between green/renewable energy and the wider power sector – including fossil fuels, a traditionally safe, well understood investment. This difference is likely to have reduced further since 2015-2016.

3.3 INVESTMENT RETURNS

A final economic indicator, of high relevance to potential investors in the power sector, is the return on investment portfolios. This forms a broader market indicator than the WACC.

The general presumption has been that fossil fuel investments generate higher returns. However, an in-depth study by Plantinga and Scholtens (2020) finds no significant difference in risk and return from fossil-free investment portfolios compared to unrestricted portfolios: specifically, drawing on performance data from almost seven thousand companies over the past forty years, they find that "the investment performance of portfolios that exclude fossil fuel production companies does not significantly differ in terms of risk and return from unrestricted portfolios. This finding holds even under market conditions that would benefit the fossil fuel industry."

Focusing more on recent data specific to the power sector, Donovan et al. (2020) find that when reviewing hypothetical investment portfolios across the US, the UK, and Germany/France, over 5-10 years, renewable power portfolios generally delivered even higher returns (with less volatility) than fossil fuel-based portfolios. They also found that this remains true for US portfolios between January and April 2020 in the context of the Covid crisis, and that the renewable power portfolio even outperformed the S&P 500 index.

Such analysis remains a work in progress. However, it is particularly striking because, as just indicated, the cost of capital in renewables has declined as the industries have matured, whilst the risks to fossil fuels – and particularly, utilities heavily dependent on fossil fuels – have increased. A key tipping point will be when it becomes clear that renewables-dominated investments are less risky than their fossil fuel counterparts.

The fact that by 2019, capital spending in wind and solar PV formed almost two-thirds of total investment in power generation[15] (IEA 2020b, p. 25, Figure 1.4) – a share that is likely to be at least maintained, within a more than 10% reduction in total power generation investment estimated for 2020 – suggests that this tipping point may already have been reached.

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[15] Not including investments in electricity networks.

SECTION 4: SUSTAINING AND EXTENDING THE TRANSITION

Section 2 compared progress in key power sector indicators to illustrative S-curves which, if extended, would reach the relevant Paris-consistent benchmarks for 2050. Recent trends in solar and wind are comparable to the early stages of such S-curves, but rising electricity demand has more than offset their impact on total CO_2 emissions from the sector to date. Section 3 found that key renewable technologies are now cost-competitive with new fossil fuel capacity, and with a growing share even of existing fossil fuel generators, giving reasonable grounds to expect that the renewables trajectories discussed in Section 2 will continue.

Given this data, the direction of progress is now unstoppable, with huge implications for the sector. However whether this contributes enough to achieving the Paris targets overall still depends on three additional factors:

- Barrier removal with integration, to ensure that high levels of variable renewables can be achieved, in enough regions, to also meet 2030 benchmarks so that electrification can contribute to timely, economy-wide decarbonization.
- Strategic investments in continued innovation and infrastructure, to facilitate access to additional renewables and regional integration.
- Enhanced efficiency in electricity consumption to ensure that demand growth is associated with decarbonization, not the extension of carbon-intensive systems.

This section considers these challenges and opportunities.

4.1 ACCELERATING AND DEEPENING INTEGRATION OF VARIABLE RENEWABLES

Developing power systems with high shares of variable renewables is a challenge for which several solutions are available, including cost-effective battery storage. However, appropriate markets and incentives are required to extend and accelerate investment in renewables globally and ensure that complementary technologies and behaviors are appropriately rewarded.

A sustained rate of growth in the adoption of renewables risks being impeded by institutional and technical inflexibilities. Private investment in renewables has been crucial, but has historically often required out-of-market government-backed structures like feed-in tariffs or other long-term contracts. Some centralized generating systems still resist renewables because they undermine the interests of incumbents, including state-owned enterprises (Zhou et al., 2018). A recent survey in Southeast Asia finds that continued coal investments there largely reflect legacy habits and networks, often backed by state finance (Johnson, du Pont, and Guegen-Teil, 2020).

Competitive electricity markets as currently designed are poorly suited to a system dominated by variable generators. They place the main revenue risks on renewables rather than fossil fuels. High levels of renewables, which cost almost nothing to run, can crash the market price of power generation, and cannibalize their own revenue. More generally, operating power systems with high proportions of variable or inflexible low-carbon generation, which cannot simply begin generating to meet demand in real time, could be a growing challenge.

The 2050 Paris-consistent benchmark for the combined share of wind and solar PV in electricity generation is 51% (and 77% for all renewables), demonstrating the need for power systems to accommodate large volumes of variable power sources. If not addressed, rapid (and market-driven) renewables investment could be impeded, and maintaining a stable power system may limit the transition to a Paris-consistent power sector.

There is no clear limit on the proportion of variable generation any given system can accommodate – it depends on context. In some countries, such as Norway and Brazil, very high shares of renewable electricity are provided by hydroelectricity, which is much less variable than other renewables – although there is some important seasonal variation. Wind power and solar PV of course fluctuate more, and are subject to both diurnal and seasonal variability. Power systems dominated by greater shares of these variable renewables could face greater challenges with matching supply and demand. The highest combined share of wind and solar experienced so far is in Denmark, with just over 50%. This is enabled by strong interconnection with neighboring countries, a combined heat and power (CHP) capacity which has flexibility to shift between power and heat production (and appropriate market signals to incentivize this), integration of weather prediction within power system forecasting, and investment in microgrids and distributed storage (Marcacci, 2016). Much higher shares of variable renewables may be possible. Although the technical feasibility of such systems has not been demonstrated (Heard et al., 2017), it is likely that the intermittency challenge can be addressed through a range of complementary technologies and system designs.

Complementary generation. As noted, some flexibility could be provided by less variable renewable sources such as biomass and large hydro. However, it may also be possible to achieve high supply-side flexibility using nuclear and fossil fuels with growing shares of CCS. It is theoretically possible to run nuclear in a flexible mode (Jenkins et al., 2018); up to 40% of the French nuclear fleet already engages in some form of load following (Cany et al., 2018). Pre-combustion CCS, producing hydrogen from the reforming of fossil fuels, could provide flexible load-following output by switching between hydrogen and electricity production (Cloete and Hirth, 2020).

Short-term storage. Batteries could make a crucial contribution to the continued growth and integration of variable renewables, and are already starting to play a role. Batteries have experienced even more dramatic cost reductions than solar PV and wind – Figure 10 illustrates the 87% reduction in lithium-ion battery costs from 2010 to 2019, with projected costs for 2025 and 2030. This has been due to both technology improvements induced by R&D and to learning by doing and economies of scale as they are increasingly deployed – particularly in electric vehicles.

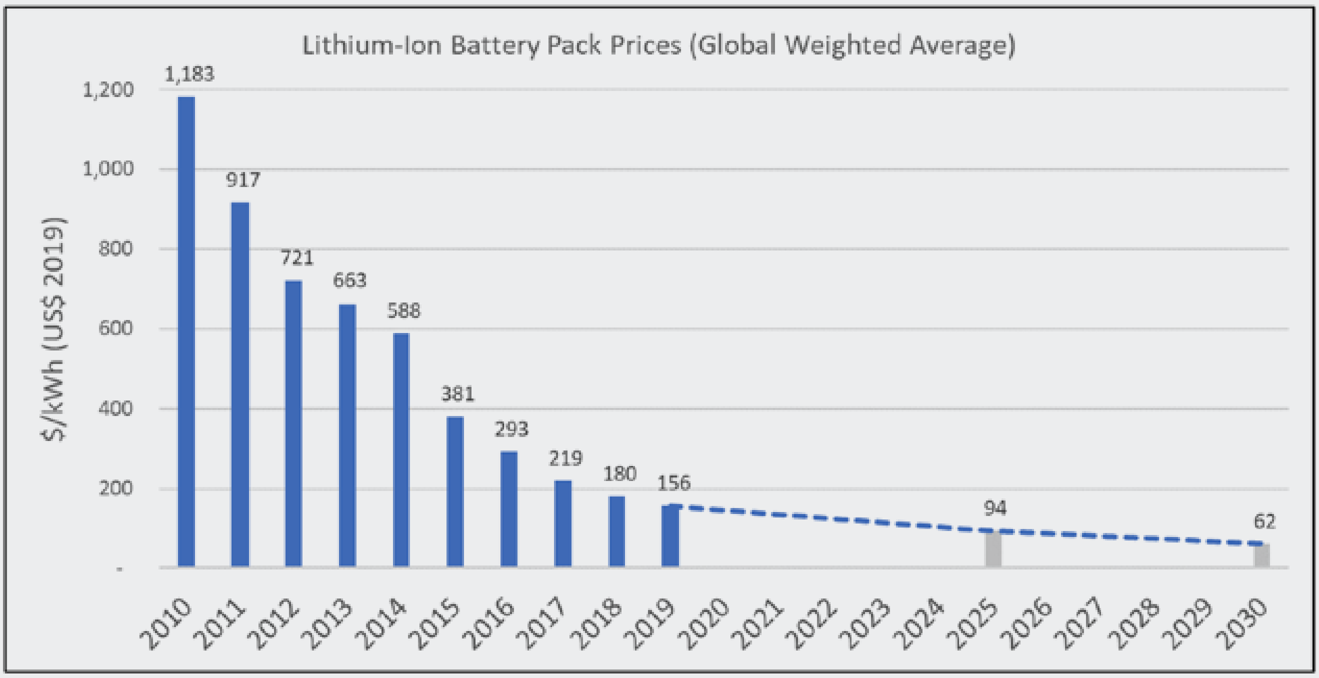


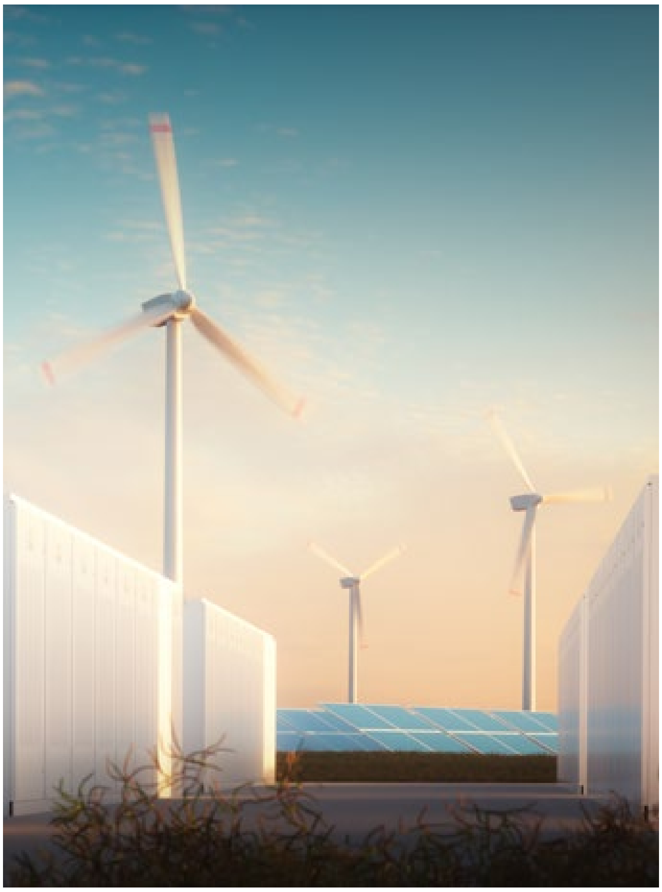
Figure 10: Lithium-ion battery pack prices (global weighted average) 2010-2030. Source: Bloomberg New Energy Finance.

However, batteries are already starting to be used for both grid stabilization and electricity storage at relative scale in some systems. In Germany, domestic and grid scale battery storage together is nearing 1 GW capacity (Parkin, 2019), with the combined LCOE of domestic PV-battery systems now lower than the average retail price of grid electricity (GTAI, 2019). Energy service companies such as Senec GMBh and Sonnen GMBh offer solar PV and battery systems as part of energy service packages, which also include benefits such as credits for exported energy, and can provide grid services through large-scale distributed storage (Senec, 2019; Sonnen, 2019). As cost reductions continue, the economic attractiveness for use in a range of systems and configurations will expand further. Electric vehicle batteries (both when in use in the vehicle itself, and once it has been replaced) may also be used for electricity storage, if appropriate market incentives and structures are in place.

Demand-side response and flexibility. Smart grids – systems in which components are able to respond to information signals to optimize system operation – could provide the technical architecture to support more widespread flexibility in demand (Rathor and Saxena, 2020; Connolly et al., 2016). For the domestic consumer, a key point of entry into this system is the smart meter; beyond simply providing real-time information on energy use, and potentially prices, the smart meter has more advanced functions that can allow consumers to shift demand away from periods when supply is more constrained or expensive (for example, due to low output of variable renewables). Integration with smart appliances can occur on an automatic (or semi-automatic) basis.

However, smart meter programs are currently more focused on simplifying meter-reading and providing real-time feedback to consumers. The use of smart meters and demand-side response as a means of seriously improving the system's ability to accommodate high proportions of variable renewables remains some way off, even amongst countries with relatively advanced smart meter programs (Shivakumar et al., 2018).

Interconnectors. Decentralized options can be complemented by multinational or even continent-wide interconnections to help balance supply and demand. This enables a wider base of possible supply, demand, and integration options. In practice, the specific configurations that develop are likely to look very different around the world as they evolve to fit local characteristics, and many systems are likely to adopt a range of solutions in combination (Bogdanov et al., 2019; Breyer et al., 2017; Jacobson et al., 2017).



The policy lacunae. Common to all of these potential solutions is the need for market structures and incentives to foster the effective integration of variable renewables into power systems, alongside these complementary options. This could include capacity payment schemes to reward occasionally used flexible generators or large-scale storage, or time-of-use pricing, that creates strong incentives for demand flexibility and arbitrage at multiple scales. New business models may also be created (or even required) to take full advantage of some options.

However, even if appropriate market structures and economic incentives are in place, some hurdles may remain. For example, domestic load-shifting also involves social and behavioral dynamics beyond economic optimization, with some energy using practices more amenable to shifting than others (Smale et al., 2017).

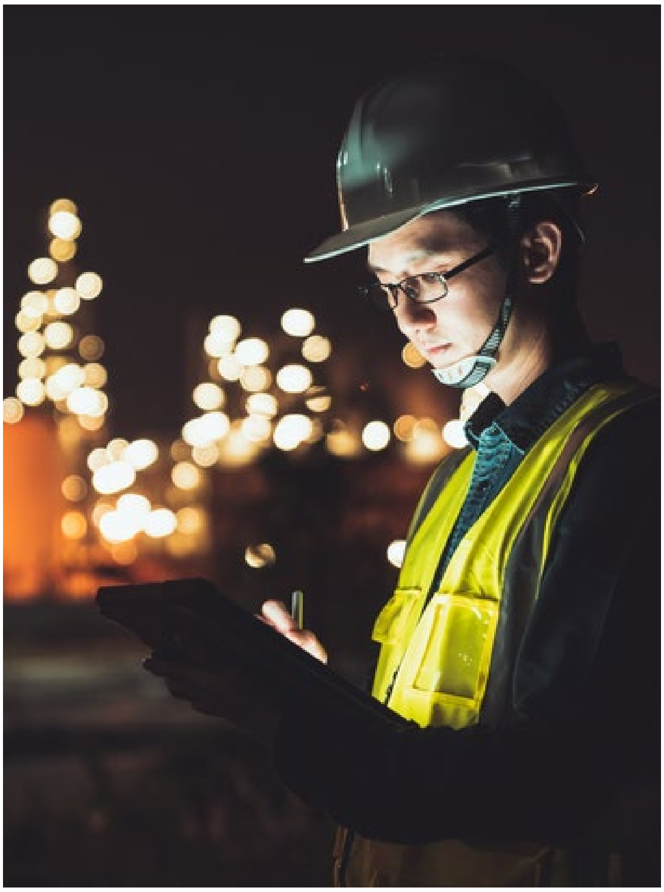
In a few power systems, high penetration of variable renewables – driven so far by feed-in tariffs and auctions, and managed partly through interconnections – has already been successfully accommodated, as noted. This, combined with the progress of batteries, load management, and transmission technologies, means the outlook is optimistic. However, progress in the deployment of renewables between countries remains very diverse, due in part to various institutional impediments. Adoption in low-income countries is often impeded by perceptions of high risks, limited access to or high costs of capital, and market structures generally remaining poorly aligned to the needs of renewables.

4.2 CAPITAL AND STRATEGIC INVESTMENT

Technological transitions demand disruption and reconfiguration of physical and societal systems and infrastructure. Strategic investment can support this reconfiguration.

Many developing countries have huge potential for renewables – particularly solar PV – but limited deployment to date, reflecting the greater challenges to investment and/or integration of renewables. This points to even greater opportunities and motivation for investment to support the transition. Section 3.2 discussed the importance of the cost of capital to the overall costs of renewables. Renewables are capital intensive – they entail high upfront costs. This impedes particularly potential adopters who are sensitive to upfront costs, have limited access to credit, or experience high interest rates (as often is the case in emerging markets, as illustrated by Table 3). This is often driven by a range of technical and regulatory barriers, even when targeted support is in place (Chirambo, 2016). In the Philippines, for example, Barroco and Herrera (2019) found that uncertainties related to the design of direct support policies for renewables reduced the availability of project finance, which in turn limited the participation of smaller and less well-capitalized investors.

Minimizing uncertainty in design of direct policy support would help reduce these risks and thus expand finances at lower rates. However, this would likely not extend access to capital or credit sufficiently to allow the poorest in society to benefit from investing in solar home systems, for example. The market potential for solar home systems for such households may increase if new business models, such as fee-for-service models, are available (Terrado et al., 2008), but this can increase risks for business (Friebe et al., 2013).



Thus, accelerating deployment in developing countries may require policy intervention that focuses not only on the product itself, but on incentivizing businesses to provide services, including maintenance and after-sales support as well as innovative financing services (Friebe et al., 2013). Support for Community Renewable Energy projects may also address barriers relating to a lack of local maintenance capability as well as generating local employment (Madriz-Vargas et al., 2018). In such contexts there may be great potential for a repeat of the "leapfrogging" paradigm demonstrated by the growth of mobile communications (Arndt et al., 2019). Strategic planning may in these cases be more about local energy networks than planning large-scale transmission infrastructure, to align with these micro-scale developments and maximize the potential of the decentralized energy future – somewhat like the jump to mobile phones.

Development and state-backed investment banks can play a crucial role in strategic investment, particularly in emerging economies, through the provision of direct investment helping to mobilize private finance, through a range of vehicles including grants, equity investments, concessional loans, credit lines, guarantees (in which the bank assumes some or all of the credit risk from a project), co-financing, and technical assistance to build local knowledge and capacity. In 2016, all Multilateral Development Banks (MDBs)[16] committed to align their financial flows with the goals of the Paris Agreement. Although progress is being made, this commitment is yet to be fully implemented, and many of the details remain vague (Fekete et al., 2020). However, to date, the largest single foreign energy investment initiative (China's Belt and Road program) remains poorly aligned (even to China's own domestic environmental standards) as it accepts host country standards, which in many recipient countries are not yet Paris aligned (Voituriez et al., 2019).

Technological transitions demand disruption and reconfiguration of systems and infrastructure. Conversely, infrastructures that were designed for previous technological systems can impede the transition, part of the wider problem of "lock-in". Long-term strategic investment that anticipates the needs of the future system can accelerate and extend the transition and reduce the risks of lock-in and stranded assets – not least by more clearly signaling future directions.

This could include investments or support for supply chain infrastructure, such as ports from which offshore renewable hubs can be built and serviced, and facilities for the manufacture of components and supporting technologies. Battery development and production has been announced as a "strategic imperative for Europe in the context of the clean energy transition" (EC, 2018).

Stronger grids can accommodate more renewables, and the dramatic recent fall in cost of offshore wind energy also highlights this need. Studies in northern Europe have suggested that meshed offshore grids can provide economic benefits and help support increased deployment of renewables relative to radial, or country-by-country, connections (Konstantelos et al., 2017), but practical progress has been slow.[17]

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[16] African Development Bank (AfDB), Asian Development Bank (ADB), Asian Infrastructure Investment Bank (AIIB), European Bank for Reconstruction and Development (EBRD), European Investment Bank (EIB), InterAmerican Development Bank (IADB), Islamic Development Bank (IsDB), New Development Bank, and the World Bank Group.

[17] The North Seas Countries' Offshore Grid Initiative aims to "establish a strategic and cooperative approach to improve current and future energy infrastructure development in the North Seas," seeking to "identify ways to facilitate coordinated development of a possible offshore network that maximizes the cost-effective use of renewable energy and infrastructure investments in the North Seas" (NSCOGI, 2014). However, progress toward such aims has been fitful, and legal and regulatory frameworks remain a barrier (Sunila et al., 2019).

4.3 ENERGY DEMAND – A DOUBLE-EDGED SWORD

The role of electricity demand in the sector's transition – and electricity's wider contribution to low-carbon and sustainable development – is not straightforward. Electricity makes crucially important contributions to almost all aspects of development – sanitation, irrigation, education, and industrialization. Moreover, almost all low-carbon scenarios involve further electrification, coupled with low-carbon generation, as a crucial basis upon which to decarbonize transport, heating, and swathes of industry. Rising electricity demand has many positive attributes.

At the same time, electricity demand rising faster than the expansion of low-carbon energy generation relies on fossil fuels, and increases CO_2 emissions from the sector (which are only offset if expanding electrification displaces more carbon-intensive fuels). Electricity demand as an indicator of progress thus involves two component assessments:

- *Demand relative to the growth of non-fossil electricity.* In the decade since 2010, electricity demand increased far more than the additional generation provided by non-fossil fuel sources, leaving room for fossil fuel sources to continue growing;
- *Cleaner supply of energy services?* The vision of electricity providing a clean substitute for fossil fuels – including reducing local air pollution from urban vehicles and heating – is starting to emerge, with as much growth of electric motorcycles as of electric cars. However, this type of demand growth – substituting for direct combustion – remains small compared with the overall drivers of electricity demand, which in most countries represent expansion of more traditional uses, and often with poor efficiency (in part due to continued subsidies for fossil fuel consumption).

Delivering the Paris goals would require electricity demand growth to be slower than the growth of low-carbon electricity, in absolute terms, and with growth in demand reflecting burgeoning electrification to replace end-use services currently satisfied by fossil fuels. At present, neither is the case.

Changing this would require consistently strong and supportive policy frameworks across a range of end-use sectors, operating on and within numerous different socio-technical contexts across the world – each with its own individual characteristics and dynamics. A subsequent report will focus on those dynamics and indicators within key elements of the global transport sector.

CONCLUSION

The electricity sector has a pivotal role to play in delivering the goals of the Paris Agreement. It has the most readily available zero-carbon technologies of any sector, and is expected to decarbonize earliest. It could also become a crucial source of low-carbon energy for more end uses as energy demands such as transportation and heat become electrified. This report presents indicators by which to assess progress and prospects, measured against the changes we would expect to have seen since 2010 and projected forward, under the assumption of S-curve transition dynamics.

For total CO_2 emissions, levels of fossil fuel generation, and the contribution of low-carbon sources, initial impressions indicate that we are far off track. Yet, the sector is clearly in the midst of radical change. Precedents indicate that in such circumstances, simple linear extrapolations of recent trends can be deeply misleading. Technological transitions are rarely linear, but are characterized by accelerations and decelerations that give rise to an S-curve dynamic of technological substitution. New entrants at first tend to grow exponentially, and then maintain growth at a pace which only slowly declines as incumbent systems are displaced. This study has sought to offer metrics appropriate to assess such dynamic transitions, grounded in S-curve dynamics.

Table 4 summarizes the full set of indicators reviewed in this report, the trends associated with them, and their consistency with the aims of the Paris Agreement. It provides grounds for optimism. Most significantly, recent growth rates in electricity generation from wind and solar PV, if extended on an S-curve basis, would meet Paris-consistent 2050 benchmarks.

To give a broader picture, we have grouped indicators into three categories and assigned each indicator a "traffic light" score to highlight areas of risk and of opportunity:

- The physical indicators underline a stark contrast: renewables are on a sharp growth trajectory which, if sustained, places us on the right track; however, because they have been late out of the starting gate, their growth to 2019 was still substantially outstripped by rising electricity demand, allowing the continued (though relatively much slower) growth of fossil fuels. The burning issue is whether the near-exponential growth of renewables can be sustained for long enough, and efficiency in the use of electricity accelerated, so as to begin to rapidly displace fossil fuels.
- The economic indicators are positive. Onshore wind and solar PV are already highly cost-competitive with new fossil fuel capacity, and will soon be able to outcompete a substantial share of the existing global coal-fired fleet – helping to displace this capacity and support a decline in CO_2 emissions. Investors are increasingly seeing the benefits of investing in renewables, as reflected in both the value and stability of renewable-based portfolios relative to those based on fossil fuels, and the level of returns they seek – further reducing the cost of installing and generating from renewable capacity.
- Integrating new technologies into the existing system may present challenges as the scale grows which, if not addressed, may slow the rate of growth prematurely and prevent technologies from reaching their full potential. The integration of variable renewables into a system that seeks to match supply and demand in real time is one such challenge. Numerous technical and other solutions are available which may be employed in various configurations to suit local system characteristics. However, deploying such solutions at scale requires appropriate market structures and incentive mechanisms, which remain largely absent. Strategic investment, particularly through development banks in emerging economies, may also help to drive the reconfiguration of existing systems to facilitate the greater deployment of renewables; build local knowledge, capacity, and supply chains; and help overcome remaining barriers of access to capital for the poorest in society, who may stand to benefit most through the deployment of low-cost renewable energy.
- Finally, the pace at which the growth in renewable energy can continue depends in the long term on the demand for electricity. Rapid electrification of end-use sectors is a key strategy to achieve the Paris goals, and although electrification has been steadily progressing for at least 50 years, its expansion into new sectors is slow. Another key pillar of decarbonization is a step-change in energy efficiency which, if achieved, may facilitate a rapid global transition to electrification. Achieving this requires consistently strong and supportive policy frameworks across a range of end-use sectors, operating on and within innumerably different socio-technical contexts across the world – each with its own individual characteristics and dynamics. Ensuring that such policy encourages, sustains, and extends the technological transitions in these sectors – in demand, as well as in generation – remains an urgent task if national and global decarbonization aims are to be achieved.

Table 4: Summary of indicators and trends.

System element	Indicator	Current (2019) status/decadal trend (2010-2019)	Paris-consistent?
CO_2 emissions and technology deployment			
Power system	Total CO_2 emissions	+10%	🟥
	CO_2 intensity	-12%	🟩
Wind	Total capacity	15% average annual growth	🟨
	Total generation	17% average annual growth	🟩
Solar PV	Total capacity	34% average annual growth	🟩
	Total generation	41% average annual growth	🟩
Wind and solar PV	Combined share of total generation	Increase from 2% to 8%	🟩
Coal	Total generation	1.4% average annual growth	🟥
Gas	Total generation	3.0% average annual growth	🟥
Unabated fossil fuels	Share of total generation	5.2 percentage point decline	🟨
Costs and finance			
Onshore wind	Global weighted average cost (auctions/PPAs)	-28%	🟩
Offshore wind	Levelized cost of energy	-29%	🟨
Solar PV	Global weighted average cost (auctions/PPAs)	-69%	🟩
Renewable finance and investment	Weighted average cost of capital	Reducing	🟨
	Share prices	Less volatile, higher returns relative to fossil fuel portfolios	🟩
	Generation investment – share of renewables	65%	🟨
Sustaining and extending the transition			
Technical integration of variable renewables	Battery storage declining sharply (-87%) to provide competitive firm day to night power Many additional technological and behavioral options available		🟩
Regulatory and funding alignment	Inadequate regulatory structures for market-based renewables investment, for extending efficient system balancing, or international financing for less developed countries		🟥
Strategic investments	Slow growth of large-scale enabling infrastructure, and development banks investing in emerging economies yet to fully align activities with Paris Agreement		🟨
Electricity demand	Absolute electricity demand growth substantially exceeding pace of non-fossil fuel growth, with new demand largely not displacing fossil fuels in end-use sectors		🟥

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TECHNICAL ANNEX

OUR APPROACH TO SETTING BENCHMARKS

The benchmarks used in this report are derived from the database of scenarios reported by Huppmann et al. (2018). The International Institute for Applied Systems Analysis (IIASA) has in recent years established a database of global energy-CO_2 scenarios – the *Scenario Explorer* database (Huppmann et al., 2018). These include numerous scenarios developed in the context of the IPCC's report on Global Warming of 1.5°C (IPCC, 2018), which assumed a remaining emissions budget of about 580 $GtCO_2$ (median) from 2018 onward, declining to net-zero global emissions by about mid-century (Rogelj et al., (2018) p. 105 and Table 2.2).

The scenarios are produced by a range of Integrated Assessment Models (IAMs) which provide a representation of global economic, energy, land use, and climate systems, and enable exploration of the impact of different technological shifts and societal changes on emissions.

The *Scenario Explorer* database (Huppmann et al., 2018) was used to identify scenarios consistent with climate change of 1.5°C or below. The categories "1.5C low overshoot" (n=44) and "Below 1.5C" (n=9) were selected. "Low overshoot" scenarios are those "limiting median warming to below 1.5°C in 2100 and with a 50–67% probability of temporarily overshooting that level earlier" (Rogelj et al. (2018) p.100, Table 2.1). "Below 1.5C" scenarios have 50–66% likelihood of keeping peak warming below 1.5°C for the entire 21st century (Rogelj et al. (2018) p.100, Table 2.1). Huppmann et al. also present a category called "1.5C high overshoot" (n=37) scenarios. In these scenarios the probability of temporarily overshooting 1.5°C is greater than 67%. In general, the greater the risk of overshoot, the greater the need for "negative emissions."

In Chapter 2 of the IPCC 1.5 Special Report, the term "1.5°C-consistent pathways" includes scenarios from all three (1.5C low overshoot, Below 1.5, and 1.5C high overshoot) categories (Rogelj et al. (2018) p. 100, Table 2.1). However, the Summary for Policy Makers of the IPCC 1.5 report (IPCC, 2018) focusses on pathways with "no or limited overshoot" – i.e., "below 1.5" and "low overshoot" categories.

In this report we select scenarios as "Paris-consistent" that we judge to be consistent with the goal of the Paris Agreement of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UN, 2015). We judge that scenarios falling within the categories of "Below 1.5°C" and "1.5°C low overshoot" are "Paris-consistent," and therefore "relevant" for the purposes of this report. We do not include the category of "1.5°C high overshoot" scenarios within our set of "Paris-consistent" scenarios.

Our 2050 benchmarks are mostly based on the median values of these "Paris-consistent" scenarios, for each indicator. (The exception is the benchmark on capacity – in this case the benchmark for generation is identified from the median generation value, and the capacity value for this particular scenario is provided.)

The approach of using the scenarios underpinning the IPCC's report on Global Warming of 1.5°C as the basis for establishing 2050 benchmarks is consistent with other approaches – for example, the Carbon Ambition Benchmarks produced by Climate Works Foundation, European Climate Foundation, and We Mean Business (Climate Works Foundation et al., 2019), which are also reported in Table 1. This report sets 100% zero-carbon technologies in power generation as the benchmark for 2050 globally, and in China, the EU, India, and the US. Climate Works Foundation et al. also set a highest plausible ambition benchmark of 65% of electricity generated from renewable sources in 2030 globally. This is based on the upper end of the interquartile range of 1.5°C-consistent scenarios with no or limited overshoot, as reported in IPCC (2018) – in other words the same set of scenarios as we use for our benchmarks. However, as noted, in this report we use median values.

The total number of scenarios in the Huppmann et al. database that fall within our definition of "Paris-consistent" is 53. However, due to differing reporting conventions of the models, the full set of 53 is not always available for every indicator.

OUR APPROACH TO GENERATING S-CURVES

S-curves are generated in Excel using the following formula:

$$Y = K / (1 + ((K - Y_0) / Y_0) * EXP(R * T))$$

Where:

K = stable value
Y_0 = initial value
R = intrinsic growth rate
T = year

For each S-curve, K, or the stable value, is set by the 2050 benchmark. The nature of the formula is such that the curves approach this value but never quite reach it.

Y_0, the initial value or starting point of the S-curve, is a historic value for the indicator in question, usually its value in 2010.

T is the year or time step along the x axis of the curve. Our S-curves extend from 2010 to 2050.

R is the intrinsic growth rate, which initially sets the trajectory on a path of exponential growth, but which gradually decays, causing growth to reduce toward zero, and the S-curve to level out as it approaches K. The intrinsic growth rate is derived from the curve's emergence growth rate using the Excel formula: LOG(*[emergence growth rate],*EXP(1)). It is the growth rates that are referred to when describing the curves.