TRUE NORTH
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Energy Transition Investment Framework
(Second edition)

The pace and scale of global renewable energy penetration by 2030 & 2050

Authors

Stan Miranda
Vasishta Dasari

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Authors

Stan Miranda
Founder, Chairman

- Partners Capital Chief Executive (2001-2020)
- Founder, CEO of the True North Institute
- Evolution Global Partners (Venture Capital)
- Bain & Company Director
- Harvard MBA

Vasishta Dasari
Principal

- Partners Capital
- Barclays
- London School of Economics, CFA Charterholder

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Charity think tank OpenMinds, international strategy consultants Bain & Company and Clean Air Task Force are among the valued sources of insight on the Energy Transition

OpenMinds

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CLEAN AIR TASK FORCE

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Contents

Executive Summary

	2022	2030	2050
Global Electricity Generation (TWh)	28,600	36,000	72,000
Renewables %	39%	50%	77%
Wind and Solar %	12%	25%	57%
CO2 Reduction Potential (Gt)	–	2.2	7.7

Source: 2022 data from Ember Global Electricity Review 2023. Forecasts based on Partners Capital assumptions and analysis.

One of the most critical assumptions in our, or anyone's, energy transition net-zero pathway is the extent to which renewable energy sources (in which we include wind, solar, hydro, nuclear and bioenergy) can supply our electricity needs going forward. Clearly, the ideal outcome is as near to 100% as possible. However, wind and solar are the primary drivers of growth in renewable electricity and these are both constrained by the intermittent nature of wind and sun, combined with the limits of battery storage duration. Furthermore, the pace of wind and solar buildout is constrained by the slow pace of transmission line buildout and connection to the grid.

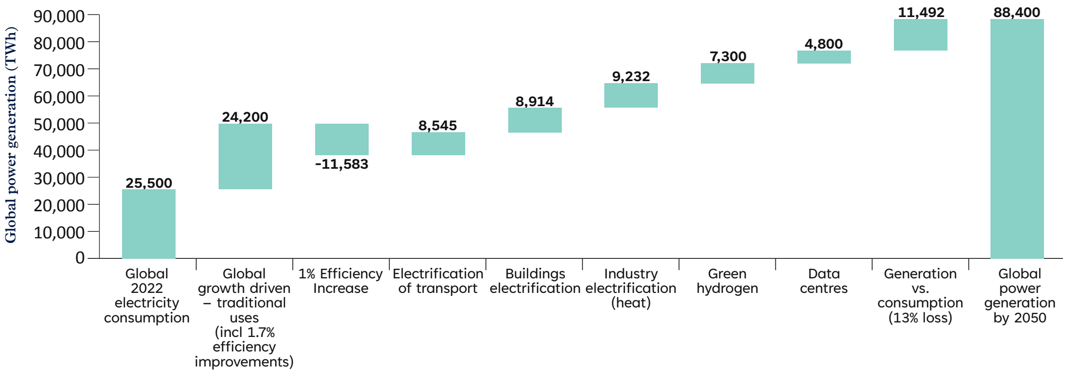
To the extent the answer is less than 100%, other solutions will be required including clean hydrogen, CCUS (carbon capture, utilisation and storage), nuclear, bioenergy and geothermal, all of which come with their own unique challenges. The correct answer to this question, in many ways, dictates the scale of the opportunity for alternative energy technologies. If renewables could get close to 100%, hydrogen and carbon capture would have no role to play in electricity generation. This construct underscores the importance of this question to any overall energy transition strategy.

The extent of renewables penetration depends on the growth of the overall demand for electricity – i.e., the more that electricity demand grows, the lower the penetration of renewables. As we have set out to electrify transport, buildings and industry, wind and solar may struggle to keep up with the demand created. While the power sector has made strong progress by increasing renewables generation capacity since 2000, global electricity demand has generally been rising, in absolute TWh terms, faster than clean power generation, with the recent shortfalls being met by fossil fuel-based generation. Renewables' share of global power generation has only grown from 36% in 2000 to 39% in 2022. Electricity demand is set to rise further, driven by electrifying transport, buildings and industry. Thus, we face the dual challenge of continuing to scale up power generation, and meeting all or most of this increased demand with renewables.

The main driver of electricity demand historically has been economic growth with an interesting dynamic between developed and developing economies. Developed economies typically improve the efficiency of electricity usage to the point of almost offsetting demand growth from a growing economy. In stark contrast, emerging and developing economies see significant electricity demand growth as large swaths of the population are pulled out of poverty, move to cities and buy cars and larger homes, driving industrial growth, all contributing to faster emissions growth than real economic growth.

We estimate that global electricity generation will rise from the current 28,660 TWh to 36,000 TWh by 2030 and 72,000 TWh by 2050, with a skew in the range of likely outcomes to the upside on these figures. Expert estimates average around 36,700 TWh by 2030 and 65,000 TWh by 2050. Our bottom-up estimates of global electricity generation needed by 2030 arrive at 44,000 TWh by 2030 and 88,000 TWh by 2050, 22% higher than our point estimate of 72,000 TWh. This 16,000 TWh difference is explained by our expected shortfalls in electrification relative to the best expert estimates we found for electricity required for transport, buildings, industry, green hydrogen and data centres which summed to 39,000 additional TWh by 2050. The 72,000 TWh 2050 estimate looks at historical electricity build out growth rates which averaged 2.8% p.a. and caps the potential growth rate at 3.5% p.a. which is 25% faster growth than we have witnessed historically. The "upside scenario" of 88,000 TWh in 2050, would require a 4.3% growth rate which is 54% faster than seen in the past.

Exhibit 1: We expect total electricity generation to exceed 88,000 TWh by 2050, but the constraints on expanding capacity will see something closer to 72,000 TWh of actual electricity generation



Source: Partners Capital analysis (Clean Hydrogen Investment Framework), BloombergNEF, Journal of Cloud Computing.

The key constraint on renewables penetration is not demand, but the rate at which we can build generation assets and transmission infrastructure. While wind and solar electricity generation has grown at an impressive pace in recent years (15% p.a. and 30% p.a. over last 10 years, respectively), we expect the pace of growth to moderate, while experts are forecasting accelerated growth. The primary obstacles today are i) building the required transmission lines to connect renewable generation to the grid, and ii) getting approval from grid operators to connect new generation to the grid (known as "interconnection"). Building new transmission infrastructure is a notoriously slow and complex process, and the scale of the challenge is enormous. The interconnection process, which worked fine for adding a small number of large conventional (e.g., natural gas-fired power plants) generation projects each year, is now ill-equipped to deal with the sheer volume of smaller wind and solar generation projects, resulting in clogged up interconnection queues and long waits for projects to come online. Dealing with intermittency, land use constraints and rising NIMBYism presents further obstacles.

Based on total electricity generation forecasts in 2030 of 36,000 TWh, we estimate c. 50% of all electricity generation will be derived from renewables in 2030, up from 39% today. This compares to expert forecasts, which range from 42% to 70%, most assuming a smaller denominator. Of the c.50% electricity generation that we predict to come from renewables in 2030, c.25% will be from wind and solar, up from 12% today.

Looking out to 2050, our analysis suggests 77% of the 72,000 TWh of electricity generation will be from renewables, which is also at the more conservative end of the 65% to 92% range of expert forecasts. Of the c.77% of electricity generation that we predict will be from renewables in

2050, c. 57% will be from wind and solar. So other low emission energy sources (essentially clean hydrogen and CCUS) and/or fossil fuels will have to fill the gap of 50% by 2030 and c. 23% in 2050. We do not see a likely scenario where more than 85% of all electricity is met by renewables by 2050.

Using our base case assumptions, we expect the growth of renewable electricity to be one of the greatest contributors to global decarbonisation, reducing two gigatons of carbon emissions by 2030 and nearly eight gigatons by 2050. This ignores the emission reduction from electrifying transport, industry and buildings which we account for separately in the global decarbonisation waterfall.

1. What has been the pace of renewables buildout to date?

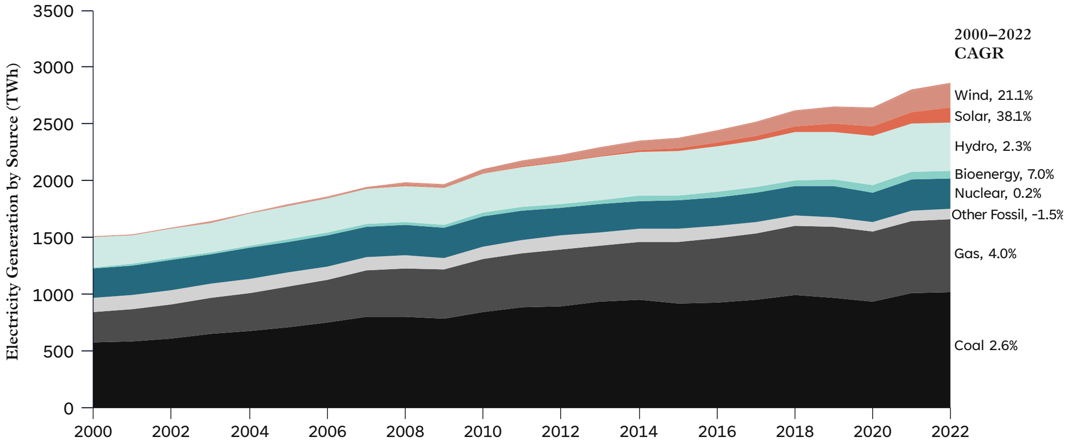
Since 2000, global electricity generation has almost doubled from 15,096 TWh to 28,661 TWh in 2022, growing at 2.8% p.a., which broadly aligns with annual average global GDP growth over that period. Renewables' share of global power generation (in which we include wind, solar, hydro, nuclear and bioenergy) has grown from 36% in 2000 to 39% in 2022. As you can see in Exhibit 2, total electricity generation from renewables has only grown at 3.2% p.a. since 2000, while wind and solar generation has grown from a low base in 2000 at a staggering pace of 22.5% p.a., far outpacing coal (2.5% p.a.) and natural gas (3.9% p.a.) over that same period. This impressive pace of growth has primarily been driven by the falling "levelized cost of electricity" (LCOE) from these sources. Between 2009 and 2023, the LCOE for solar and wind decreased by 84% and 66%, respectively.

Renewables growth 2000 to the present

The global energy industry has made unprecedented progress in building renewables generation capacity in recent years, as shown in Exhibit 2. Between 2001 and 2010, net solar capacity additions globally averaged 4 GW per year. In the following decade, driven primarily by the significant drop in costs of solar modules, that figure had increased to 71 GW per year, a step-up of almost 18x[1]. According to Ember, solar generation grew by 24% in 2022, making it the fastest-growing electricity source for 18 years in a row. Not far behind, wind generation grew by 17%[2] in 2022.

1 DNV Energy Transition Outlook 2023
2 Ember Global Electricity Review 2023

Exhibit 2: Global electricity generation has grown by 2.8% p.a. on average over the past 22 years with little impact from increased electrification of end-uses (e.g., electric vehicles, heat pumps, etc.)

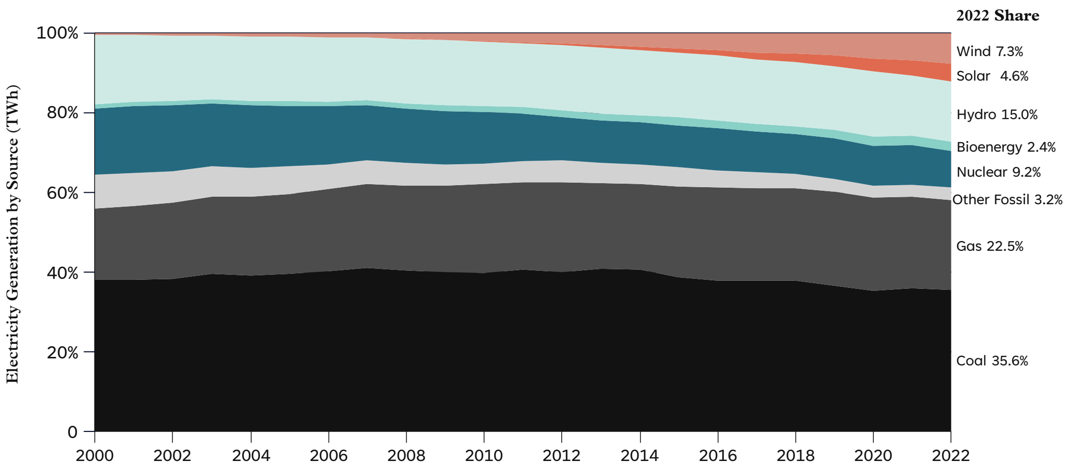


Source: Ember Global Electricity Review 2023

Despite this impressive pace of growth, renewables penetration of overall power generation has not increased meaningfully over the last two decades. As shown in Exhibit 3, renewables' share of global power generation (in which we include wind, solar, hydro, nuclear and bioenergy) has grown from 36% in 2000 to 39% in 2022. Hydro (15%) and nuclear (9%) comprised the majority of electricity generation from renewable sources in 2022, while wind and solar together comprised 12%[3].

The figures also vary widely by country and region as shown in Exhibit 4. Those countries with a higher level of renewables penetration typically benefit from ample supply of dispatchable (generation sources that can be turned on and off to meet variable demand) sources of renewable energy. Dispatchable renewable energy is primarily hydroelectric. Norway for example enjoys abundant sources of hydro (88% of electricity generation in 2022), which it has supplemented with a significant increase in wind generation capacity in recent years (10% of electricity generation in 2022)[4].

Exhibit 3: Renewables share of electricity generation has grown from 36% in 2000 to 39% of all power generation. Wind and Solar has grown from nothing to 12%.

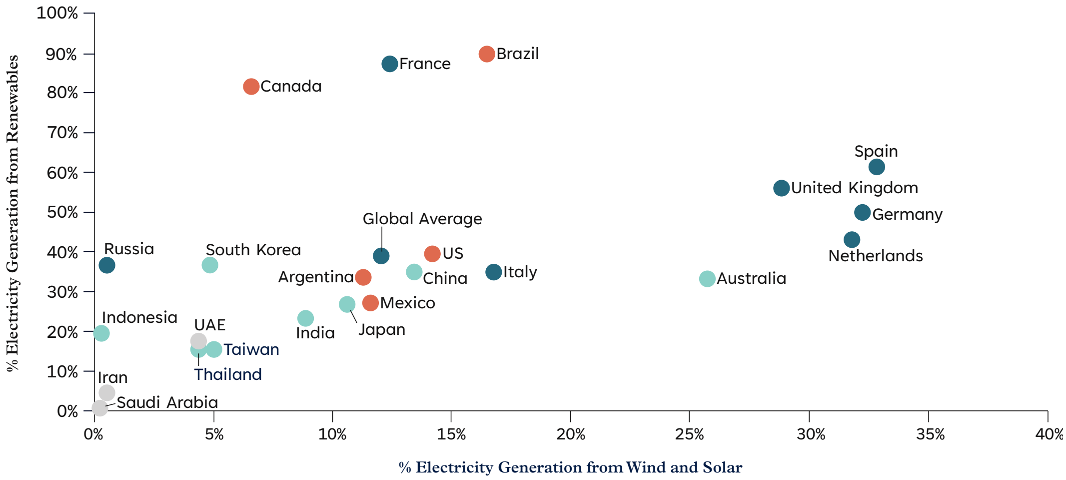


Source: Ember Global Electricity Review 2023

3 Ember Global Electricity Review 2023
4 Ember Global Electricity Review 2023

This global picture masks the dramatic variations in renewables penetration across countries which vary most due to climate (wind and solar), geography (hydro and geothermal) and political (nuclear) differences. Norway is nearly 100% renewables with over 88% supplied from hydroelectric power. Similarly, Brazil is 89% renewables from hydroelectric power. France is 87% renewables with 63% supplied from nuclear power. Spain, Germany and the Netherlands have the highest wind and solar penetration accounting for roughly 32% of all electricity generation.

Exhibit 4: Renewables share of electricity generation varies significantly by country

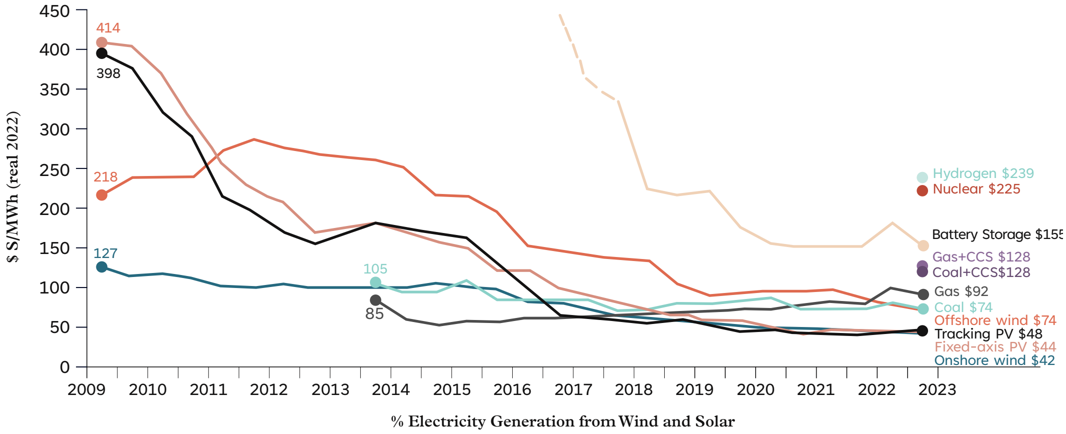


Source: Ember Global Electricity Review 2023

Cost of Wind and Solar Power

Over the past decade, the costs of renewables have dropped significantly across the world to the point where, today, solar and onshore wind are economically competitive with incumbent coal and gas generated electricity. Exhibit 5 shows the historical trajectory of costs for onshore wind and solar in the US over the last 14 years with the bulk of the cost reduction observed in the earlier years, while costs have flattened out more recently. Switching to renewable sources of power generation comes with the added benefit of providing energy security which is a heightened priority since Russia invaded the Ukraine over two years ago.

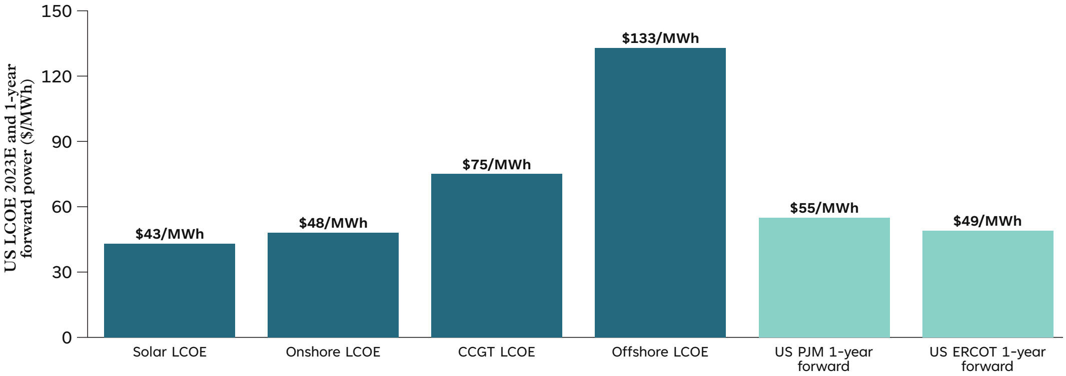
Exhibit 5: Global levelized cost of electricity benchmarks show that solar and onshore wind fell below the cost of coal and gas generated electricity in 2018. The cost of new-build offshore wind is now on par with coal and gas



Source: BloombergNEF June 2023

However, costs vary from these BloombergNEF global estimates in individual countries or regions within countries. Exhibit 6 shows the current US cost of offshore wind which remains uncompetitive with onshore wind, solar, gas and coal. The price of offshore wind installation can be up to 20% higher than that onshore. This is largely due to the lack of existing energy transmission infrastructure at sea, the extra materials required for safety purposes, and other technical challenges, including the maintenance of machinery out at sea. By the year 2038, it is projected that offshore wind power will be as affordable as fossil fuels in the US.

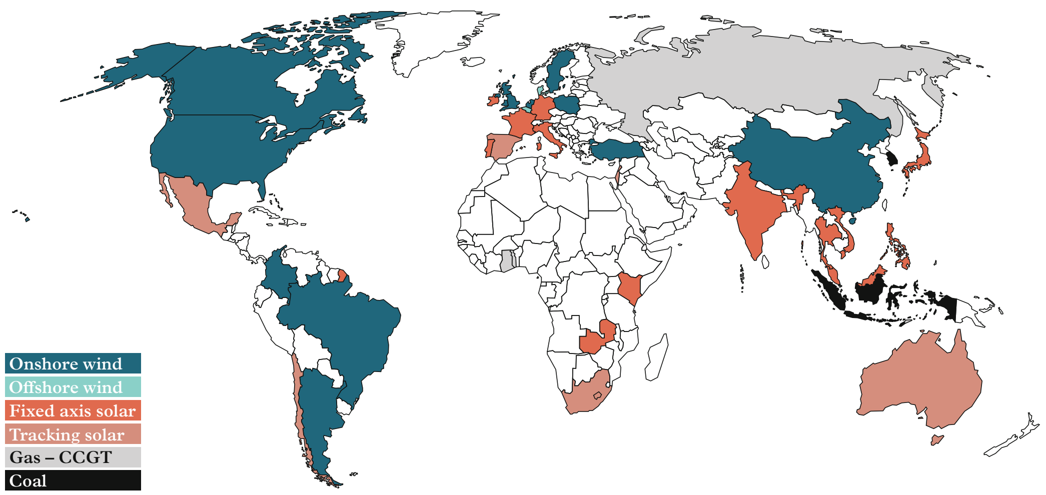
Exhibit 6: In the US, offshore wind is the standout from a cost perspective at 2.5x the forward price of electricity



Source: Goldman Sachs Global Investment Research, SNL

The cheapest renewable power projects in the first half of 2023 can be found in China, achieving an LCOE of $23/MWh for best-in-class onshore wind farms and $31/MWh for fixed-axis solar PV farms. While costs for onshore and offshore wind have recently risen outside China due to raw material and cost of capital increases, a highly competitive domestic wind turbine manufacturing market has led to continued price declines in China. Two years ago, China's offshore wind LCOE was $91/MWh, on par with global costs. Today, China's average offshore wind LCOE is $66/MWh, $21/MWh less than the average cost in the rest of the world.

Exhibit 7: Markets where new-build solar and/or wind are cheaper than new-build coal and gas-fired power as of June 2023



Source: BloombergNEF. Note: The map shows the technology with the lowest LCOE (or auction bid for recent delivery) for new-build plants in each market where BNEF has data. LCOEs exclude subsidies, tax credits and grid connection costs, and include a carbon price where applicable.

2. What are the key obstacles to continued renewables buildout?

We believe the pace of renewables buildout will likely moderate between now and 2030, rather than accelerate as most experts are forecasting, largely due to the slow pace of transmission buildout and permitting, managing the intermittency of renewables generation, the need for storage to manage this intermittency, NIMBYism objections from various stakeholders and land use competition. However, the biggest and most pressing issue in our view, is the need for transmission and the slow pace of permitting.

Before we dive into a better understanding of these obstacles, we need to introduce the "power generation load curve" which is vitally important context for understanding the greatest inherent obstacle to 100% renewables penetration. Electricity demand is variable and wind and solar power generation is variable and these variations generally work against each other. The variability of electricity is illustrated with the power generation load curve described below.

Power Generation Load Curve

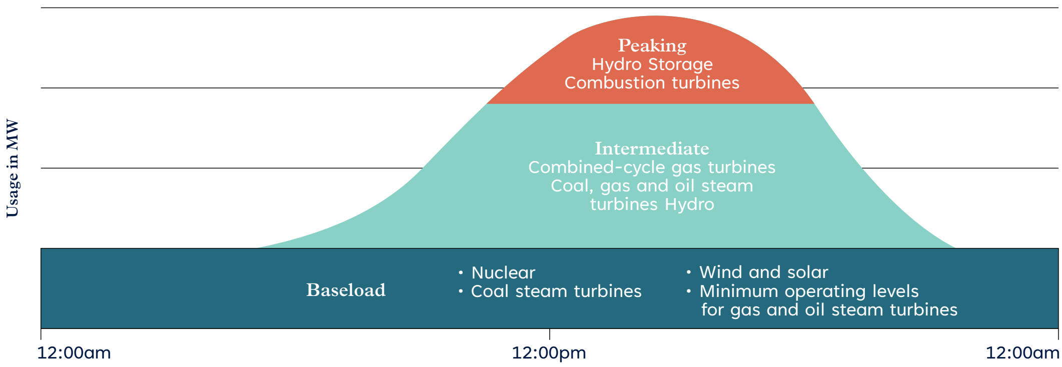
Electricity generation is often divided into three sources defined by ease of turning them on and off: **baseload**, which is generation run 24 hours of the day; **intermediate**, which is run from mid-morning until the evening; and **peaking**, which is run during the peak hours (often from late afternoon until early evening). Wind and solar do not fit into any of these three definitions due to the lack of reliable timing of supply (aka, intermittency).

Baseload generation is typically satisfied by nuclear units, high-efficiency coal and natural gas units and cogeneration units. Wind and solar generated electricity are generally not considered baseload sources of electricity, mainly due to their intermittent and variable nature. However, with improved battery storage systems and grid management, it is becoming more feasible to use wind and solar power in ways that can support baseload demand (accordingly, we show renewables in Exhibit 8 as baseload sources).

Intermediate generation is often provided by coal units ramped up from minimum loads, combined-cycle gas turbines, and hydropower. These are used because their operational flexibility allows them to be ramped up and down as loads rise and fall during the day and also because their variable costs are lower than other options. In some regions, wind or solar power also provides intermediate supply.

Peaking generation is most commonly provided by single-cycle gas turbines (also known as combustion turbines or peaking turbines), gas reciprocating engines, hydropower, pumped hydro, battery storage, and economic demand response (i.e., consumers cutting usage). Peaking units must have operational flexibility to be able to ramp up or down quickly in response to load changes and to be able to turn on and off as loads change.

Exhibit 8: The power generation load curve illustrated below shows that variable demand has to be met by variable sources of supply that can be cost-effectively turned on and off. Wind and solar are intermittent sources of baseload demand, nuclear is a continuous source of baseload demand.



Source: Enerdynamics

In a world where we are replacing fossil fuel generated electricity with renewables, our sources of variable supply are reduced to hydroelectric (including pumped hydro), storage batteries, fossil fuel (coal and gas plants) based generation with carbon capture and clean hydrogen. Wind and solar power can only satisfy peak capacity by chance or from storage batteries.

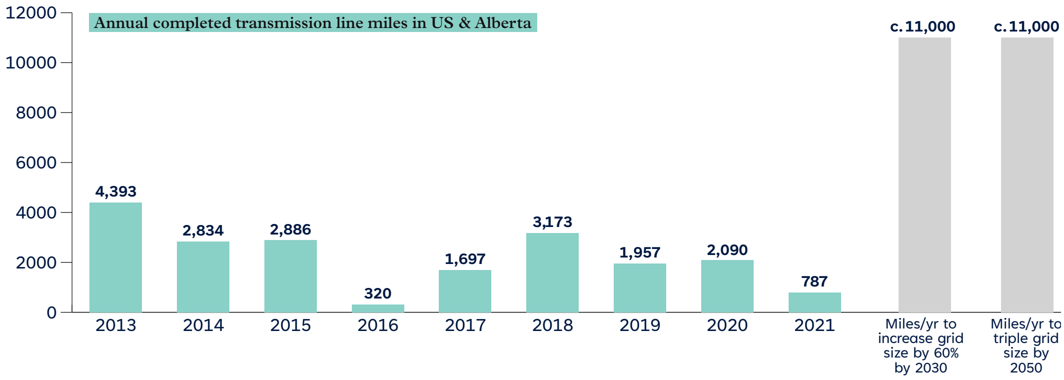
Before we worry about having so much wind and solar that it exceeds baseload demand, we need to get the wind and solar attached to the grid and we need more transmission infrastructure to get the power to the consumer.

Grid Connection and Transmission Infrastructure Bottlenecks

Below we describe the specific nature of the connection and transmission bottlenecks which are paramount to the pace and scale of renewables penetration. This would appear to be an immovable structural government bureaucracy obstacle across the developed world, only potentially mitigated with improvements in transmission infrastructure utilization via technological solutions which appear on our list of some of the most attractive investments in the energy transition space.

Renewable energy generation presents a unique challenge given that the best sites for wind and solar projects are not always close to existing transmission and/or the regions where the power is needed, requiring the buildout of new transmission infrastructure to access them. In the United States for example, the greatest potential wind energy resources are in the Midwest and along the two coasts, while the greatest solar energy resources are in the Southwest and in Florida. New transmission lines continue to be needed to carry the electricity from the areas where the renewable resources are most plentiful to distant usage markets. A US Department of Energy study found that transmission infrastructure will need to grow by 60% by 2030 and may need to triple by 2050 to meet the Biden administration's target of 100% emissions-free electricity generation in the US by 2035. This will require a massive step up in the pace of transmission buildout compared to history, as shown in Exhibit 9.

Exhibit 9: **The scale of transmission line buildout needs to increase from recent 2-3000 miles per year to c 11,000 miles per year**



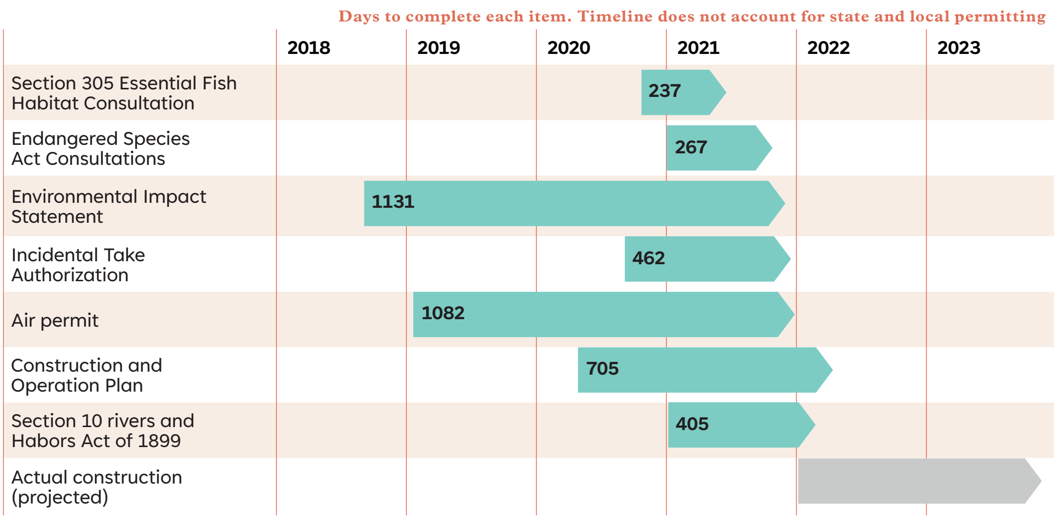
Source: S&P Global Data; EIA; DOE; Princeton, Net Zero America; NREL, Examining Supply Side Options to Achieve 100% Clean Electricity by 2035. Data shown here refers to transmission lines > 100kV

This discussion on transmission bottlenecks focusses on the US where we have the best data to illustrate the problem, but the issues faced are broadly consistent across most developed nations.

One of the reasons for the slow pace of transmission buildout in the US and elsewhere is the administrative bureaucracy involved in permitting. A renewable energy project must first procure several permits before it can be constructed. It also needs permission to connect to the grid (in effect, another permit) and it needs the physical transmission infrastructure to connect to the grid. Transmission, just like a wind or solar farm, requires its own set of permits.

The permitting process in the US today is hugely complex and time-consuming, with each individual project typically requiring a mix of local-, state- and federal-level permits before construction can begin. Exhibit 10 illustrates the federal permitting timeline for South Fork Wind, a 130MW offshore wind project off the coast of Rhode Island. To be clear, this is only the Federal permitting process and ignores local and state permits. Challenges from local communities and other stakeholders, who can voice concerns through public comment processes, litigation or advocacy, present additional bottlenecks and delays to the permitting process.

Exhibit 10: **South Fork Wind, a 130MW offshore wind project near Rhode Island, started its permitting journey in October 2018 and the project broke ground in February 2022**

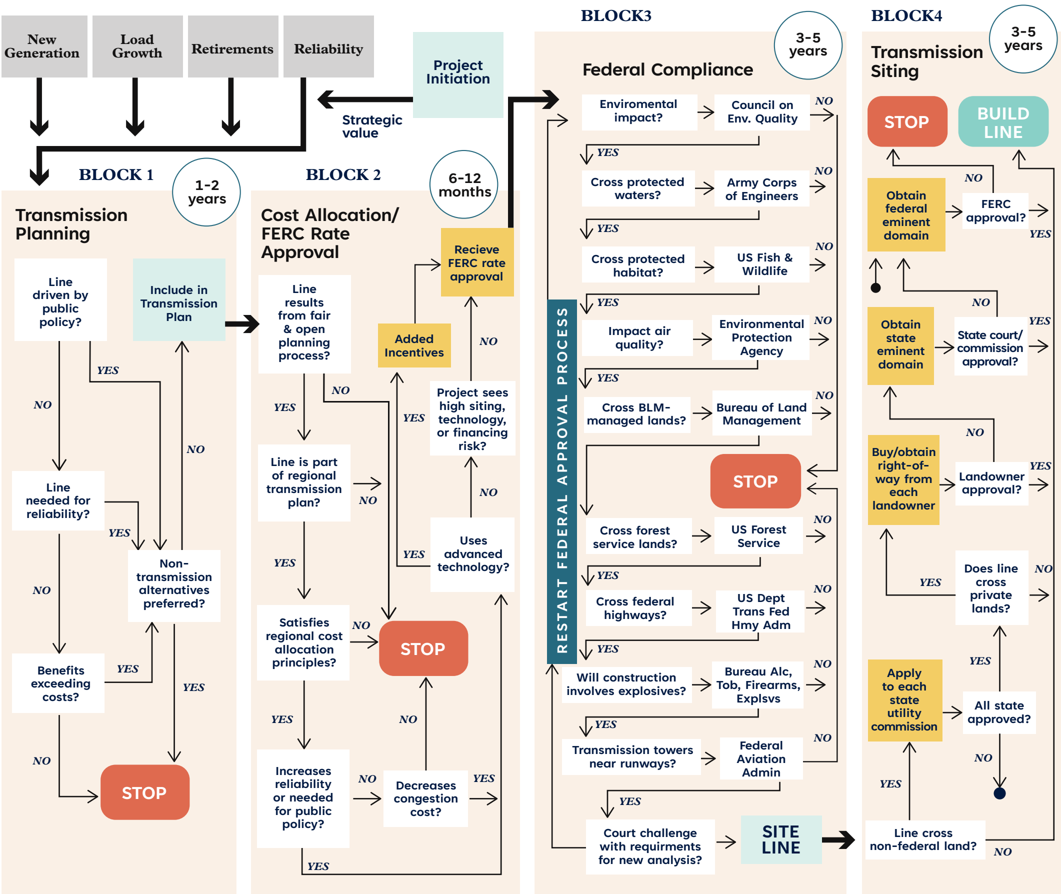


Source: Brookings Institution, How does permitting for clean energy infrastructure work? (Taken from Open Minds presentation)

Transmission lines
Image: Andrew Metelev on Unsplash

When the infrastructure project in question, as is often the case with transmission, crosses multiple regional territories, this requires negotiation with, and agreement from, multiple sets of stakeholders which can be a slow process fraught with challenges and disagreements. Given the complexity of the existing grid network, there is also a complex planning, cost allocation, approval and siting process for new transmission in the US. Exhibit 11 provides a visual illustration of the complexity of the permitting process for transmission. As such, new transmission lines can often take more than a decade to complete planning, siting and construction. For example, in the US the 732-mile TransWest Express high voltage transmission line filed its first permit application in 2007 but did not receive all of the approvals until 2020[5].

Exhibit 11: Transmission planning, permitting, cost allocation, approval and siting is hugely complex

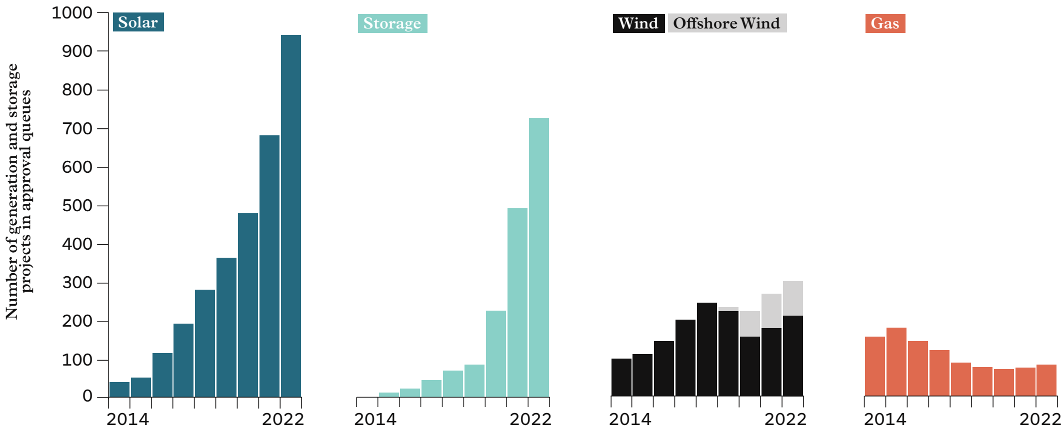


Source: Americans for a Clean Energy Grid, Macro Grids in the Mainstream: An International Survey of Plans and Progress

5 The Challenges of Decarbonizing the U.S. Electric Grid by 2035, Moch & Lee. As at Dec 2021

Another significant obstacle is "interconnection", in effect another permit, which refers to a series of studies that a power project (such as a new wind farm) must undergo before it can be connected to the grid to ensure the grid will remain safe, stable, and reliable when new generators plug in. The list of projects in this process is known as the "interconnection queue". Renewables present a unique challenge in this regard. This decades-old process worked fine for a manageable number of fossil-fuel based power projects that used to enter the queue each year. However, renewables projects typically generate a fraction of the output of fossil-fuel based generation, resulting in a higher volume of requests for connection and a dramatic increase in the number of projects sitting in the queue as shown in Exhibit 12.

Exhibit 12: US interconnections queues are increasingly clogged up with over 2,000GW of generation and storage capacity sitting in queues, exceeding the electricity generation of the entire current US power plant fleet (c. 1,250GW)



Source: Lawrence Berkley National Laboratory, Queued Up 2022. Above data includes generation only projects and co-located generation and storage projects

Understanding the reasons for this dramatic increase in the backlog in the US could guide policy makers to find solutions. Key drivers of the US backlog include:

a) regulators and other approval bodies lack the resources to handle such a large volume of requests;

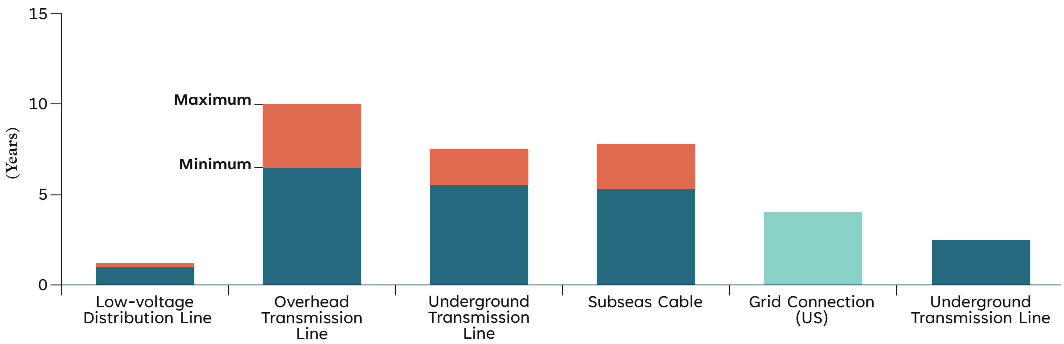
b) project developers have imperfect information on the most effective locations to connect to the grid and engage in "exploratory applications" being added to interconnection queues that use up resources without leading to new generation capacity;

c) a dated, first come, first serve basis queue system which has led to developers submitting interconnection requests earlier and earlier in the development process, long before basic steps such as property rights have been completed, which can delay interconnection studies when these projects get to the front of the queue; and

d) when a project withdraws from the queue, the rest of the queue needs to be reshuffled and re-evaluated.

This crowding of queues has significantly slowed down the pace at which new generation capacity can come online. The median duration from interconnection request to commercial operations date has risen from around three years in 2010 to five years for projects completed in 2022[6]. Average lead time to build new electricity grid assets in Europe and the US from 2010-2021 are shown in Exhibit 13 with overhead transmission lines taking 10 years from planning to commissioning.

Exhibit 13: Planning and permitting are the largest factors in long lead times for new grid assets



Source: IEA Energy Technology Perspectives 2023

Energize Capital, a specalist climate software investor, estimates that there 1.3TW (vs the 2.0 TW shown in Exhibit 12 above) of renewable projects in the queue for connection to the grid with an estimated project cost of $2 trillion. They further believe that current US transmission utilization is between 20-30% and that throughput could be improved by 50 to 100% with utilization tracking technology.

While we strongly believe that the slow pace of permitting, both for renewables projects and new transmission, will be the most significant hurdle to renewables buildout continuing to accelerate, there are two other notable challenges: intermittency and land use. We run through those below.

Intermittency complicates the matching of supply with demand

Wind and solar are intermittent sources of electricity, and this poses challenges to the grid. Unlike dispatchable sources of power, such as a natural gas-fired power plant, we cannot control when the sun shines or when the wind blows. These sources of power generation are inherently intermittent, which presents two key issues.

1. The first of these is simply the **variability** of renewable generation, i.e., that their output is not constant. This presents issues for grid operators, who are constantly monitoring fluctuations in frequency and voltage to ensure these are kept stable, as otherwise these fluctuations could damage the grid and the equipment on it. Additionally, grid operators must track demand for electricity on the consumption side of the grid and ensure that generation always matches that demand or load.

2. The **unpredictability** of renewable power generation also makes it more difficult to match power demand with supply. Grid operators typically manage most of the energy on the grid through "unit commitment", the process of scheduling generation in advance, generally a few hours to a full day ahead of time, to meet the expected load. This process clearly becomes more complicated with renewable generation, given there is a degree of uncertainty around how much power generation will actually be generated from wind and solar in a few hours' time or the next day.

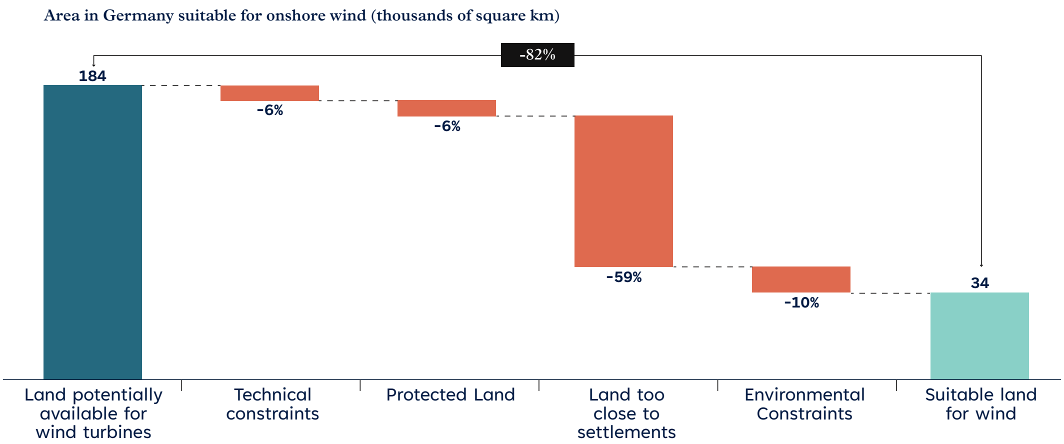
6 Lawrence Berkley National Laboratory, Queued Up 2022

These functions are not new. Grid operators have been regulating frequency and voltage, maintaining reserves and following shifts in load since the development of the electricity grid. However, as renewables penetration rises, this will add much more variability to the energy system than grid operators have managed in the past.

Available land for wind and solar is already running out

While the issue of energy infrastructure requiring land is not a new one, the issue is obviously more acute for solar and onshore wind. Utility-scale solar and wind farms require at least ten times as much space per unit of power as coal- or natural gas–fired power plants, including the land used to produce and transport the fossil fuels[7]. It is also important to note that not all land is suitable for solar and wind generation, limited by technical, regulatory and environmental constraints. A McKinsey study developed a model for evaluating potential onshore wind development sites to illustrate the issue, using Germany as a case study. The analysis found that technical, regulatory and environmental constraints reduce available land for onshore wind by 82%, as illustrated in Exhibit 14[8]. This analysis does not account for public opposition, which is increasingly becoming an issue with renewables projects, and with the rapid pace of renewables buildout in recent years, many of the best sites are already taken. The UK for example put an effective moratorium on new onshore wind farms in England in 2015, which was only eased in September 2023. This means developers need to identify new sites with increasing speed given the pace of buildout required, at a time when the availability of suitable, economically desirable land is getting tighter and, in many cases, the best onshore generation sites, particularly in onshore wind, are already taken.

Exhibit 14: Land available for wind and solar is a finite resource



Source: IEA Energy Technology Perspectives 2023

7 Renewables, land use, and local opposition in the United States, Brookings, January 2020
8 Land: A crucial resource for the energy transition, McKinsey

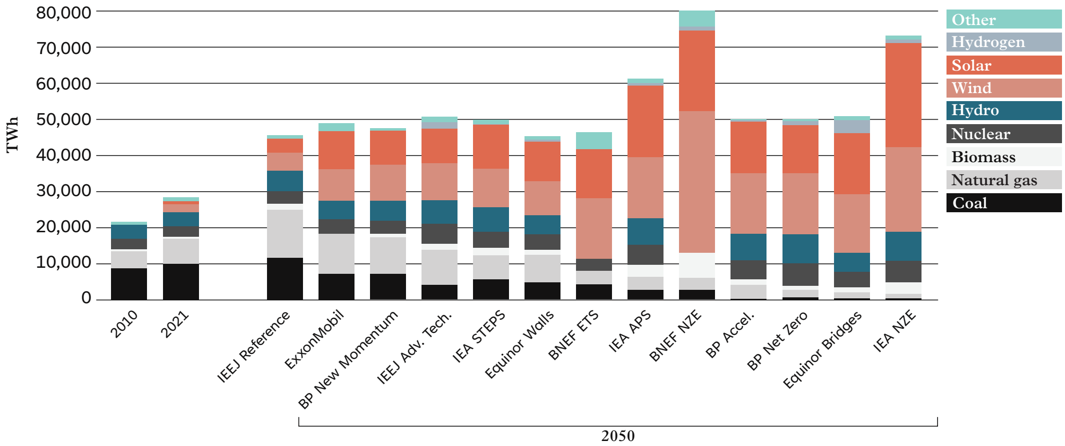
3. How much is global electricity demand forecast to rise?

We estimate that global electricity generation will rise from the current 28,660 TWh to 36,000 TWh by 2030 and 72,000 TWh by 2050, with a skew in the range of likely outcomes to the upside on these figures. Expert estimates average around 36,700 TWh by 2030 and 65,000 TWh by 2050. Our bottom-up estimates of global electricity generation needed by 2030 arrive at 44,000 TWh by 2030 and 88,000 TWh by 2050, 22% higher than our point estimate of 72,000 TWh. This 16,000 TWh difference is explained by our expected shortfalls in electrification relative to the best expert estimates we found for electricity required for transport, buildings, industry, green hydrogen and data centres which summed to 39,000 additional TWh by 2050. The 72,000 TWh 2050 estimate looks at historical electricity build-out growth rates which averaged 2.8% p.a. and caps the potential growth rate at 3.5% p.a. which is 25% faster growth than we have witnessed historically. The "upside scenario" of 88,000 TWh in 2050, would require a 4.3% growth rate which is 54% faster than seen in the past.

Perhaps the least reliable number in this report is the forecast for electricity demand in 2050 and the amount of electricity generation required to meet this demand. A key unknown that is difficult to forecast is end-use electricity efficiency – i.e., the improvements in output from a given amount of electrical current input; this goes for lighting, appliances, electrical heating, EVs, data centres, and virtually every use of electricity. The potential pace of transmission build out is also unknown. In the US for example and as noted earlier, transmission line buildout needs to increase from 2-3000 miles per year achieved in the last few years to c 11,000 miles per year to meet the Biden administration's goal of emissions free electricity by 2035[9]. This simply may not be physically possible. You can see where these two uncertainties interact. If we see major efficiency improvements, we may not need to see a 4.5% annual growth rate in the build out, and vice versa.

9 S&P Global Data; EIA; DOE; Princeton, Net Zero America; NREL, Examining Supply Side Options to Achieve 100% Clean Electricity by 2035. Refers to transmission lines > 100kV

Exhibit 15: Expert forecasts for 2050 global electricity demand ranges from 46,000 TWh to 80,000 TWh (53,000 to 92,000 TWh generation)



Source: Resources for the Future: Global Energy Outlook 2023 https://www.rff.org/publications/reports/global-energy-outlook-2023/

The IEA reports that global energy intensity (the amount of energy required to produce a unit of GDP) has fallen by 1.7% p.a. between 2011 and 2020[10]. That improvement rate is set to rise as the energy transition gathers pace, primarily driven by electrification, because efficiency of electric technologies is generally much higher than fossil fuel-based alternatives. The classic example is electric vehicles, which are roughly twice as efficient as ICE (internal combustion engine) vehicles. We therefore have this dynamic whereby electrification of end-uses leads to an increase in global **electricity demand** while energy efficiency gains contribute to a decrease in global energy demand.

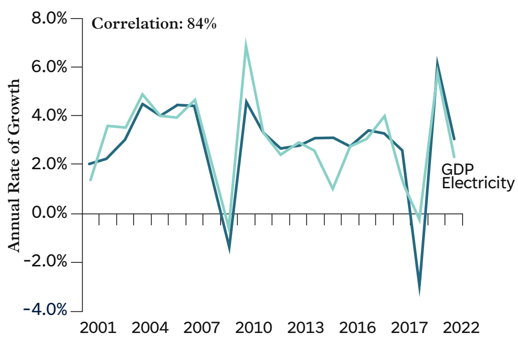
In the context of forecasting the overall path of the global energy transition, it is critical to have the best possible estimate of future total electricity demand along with a forecast of total renewable electricity capacity growth, as these two figures dictate the pace at which coal and gas-powered plants can be shut. Our estimates point to a need for carbon capture and clean hydrogen to fill the "renewables gap". Proof of how uncertain we and others are about this estimate, we see expert estimates for 2050 global electricity generation ranging from 53,000 TWh to 92,000 TWh, with the average forecast around 65,000 TWh. How have we arrived at our forecast of 72,000 TWh?

We used two different approaches:

1) A bottom-up, demand-focused approach that assumes existing electricity demand grows in line with global economic growth, overlaying efficiency assumptions, to which we add estimates of new electricity sources of demand in transport (EVs), buildings (heat pumps), industry (steel, cement, data centres) and green hydrogen.

2) A top-down, supply-based growth analysis of individual sources of energy driven principally by growth assumptions for wind and solar capacity build-out.

Exhibit 16: The relationship between global electricity demand and global real GDP growth has been very consistent since 2000, both growing at an average rate c. 3% p.a.



Source: World Bank, Ember.

10 Long Run Economic Outlook, Capital Economics

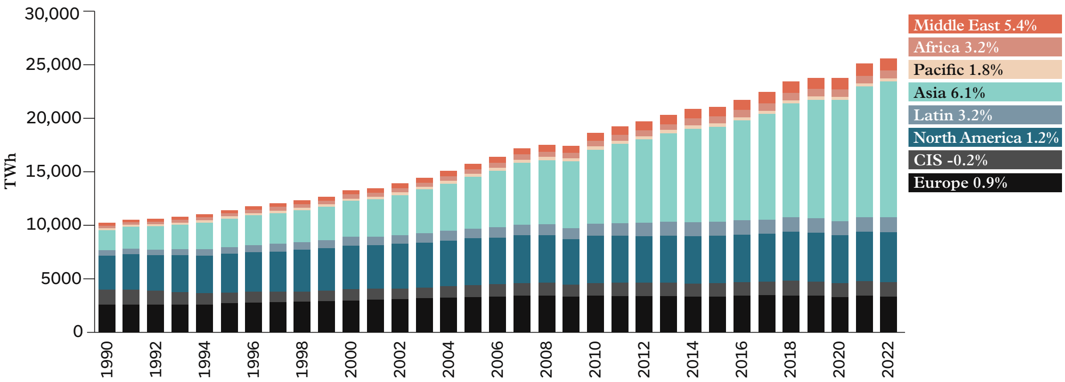
Starting with our bottom-up approach, you can see in Exhibit 16 how close the relationship has been between global electricity demand and real GDP growth over the last 22 years. Real global economic growth is expected to fall from the historical rate of 2.8% to 2.5% p.a. from today to 2050[11]. **A historical annual electricity efficiency improvement of 1.7% is embedded in this historical relationship between real GDP and electricity demand.** So, a conservative, perhaps most realistic, assumption for future electricity growth from traditional uses would be 2.5% p.a.

However, most experts forecast a further improvement in **electricity efficiency** (the ratio of electricity/unit of GDP). Our conclusion from examination of expert forecasts is that most forecasters have not considered the high likelihood that developing economies will continue to see significant growth in electricity demand in line with the growth of their economies. More mature economies like Europe, Japan and the US are seeing electricity efficiency improvements nearly offsetting the growth in electricity needs, through appliance, lighting and building heating efficiency improvements. This is the variable that is hardest to forecast, but we feel we cannot ignore the past strong correlation between developing market economic growth and electricity growth in places like China, South-east Asia and Africa (see Exhibit 17). Electrification of industry, transport and buildings has yet to feature significantly as drivers of recent growth in electricity usage, so past growth is still indicative of growth from traditional usage (buildings and industry) that grow proportionately with their economies.

Nevertheless, our base case forecast reduces the pure GDP based growth driver of 2.5% (equal to the expected rate of real growth of the global economy) down to 1.5% reflecting our assumption that annual energy efficiency improvements will increase from 1.7% p.a. to 2.7%.

How do we arrive at this 1.0% improvement in electricity efficiency? The IEA makes varying assumptions for energy efficiency across its emissions scenarios. In its Stated Policies scenario (their least ambitious emissions scenario) energy efficiency improvements step up from 1.7% p.a. historically to 2.2% p.a. (a 0.5% improvement). In their (most ambitious) Net Zero Emissions scenario efficiency improvements are forecast to hit 4.1% p.a., i.e., more than double the rate we have managed to achieve in the last 10 years. Bain & Co meanwhile has estimated an improvement from renewables (0.3% p.a.) and technical efficiency affecting all usage (0.7% p.a.). The benefits of electrification are netted out from the estimates of increased electricity demand for EVs, buildings and industry already. Triangulating across these sources, we think a 1% p.a. step up in energy efficiency improvement rate is realistic. Reducing the growth for historical uses from 2.5% p.a. (assumption for real global economic growth) to 1.5% p.a. (1% reduction to economic growth assumption to reflect energy efficiency improvement), we arrive at a forecast for electricity demand for existing uses of 28,300 TWh in 2030 and 38,100 TWh in 2050. We note that most of this efficiency improvement would have to be realised from the maturing of Asian economies where recent electricity demand growth has been greatest (6% p.a. 1990-2022 as shown in Exhibit 17).

Exhibit 17: Almost all growth in electricity demand has come from developing economies over the last 30 years



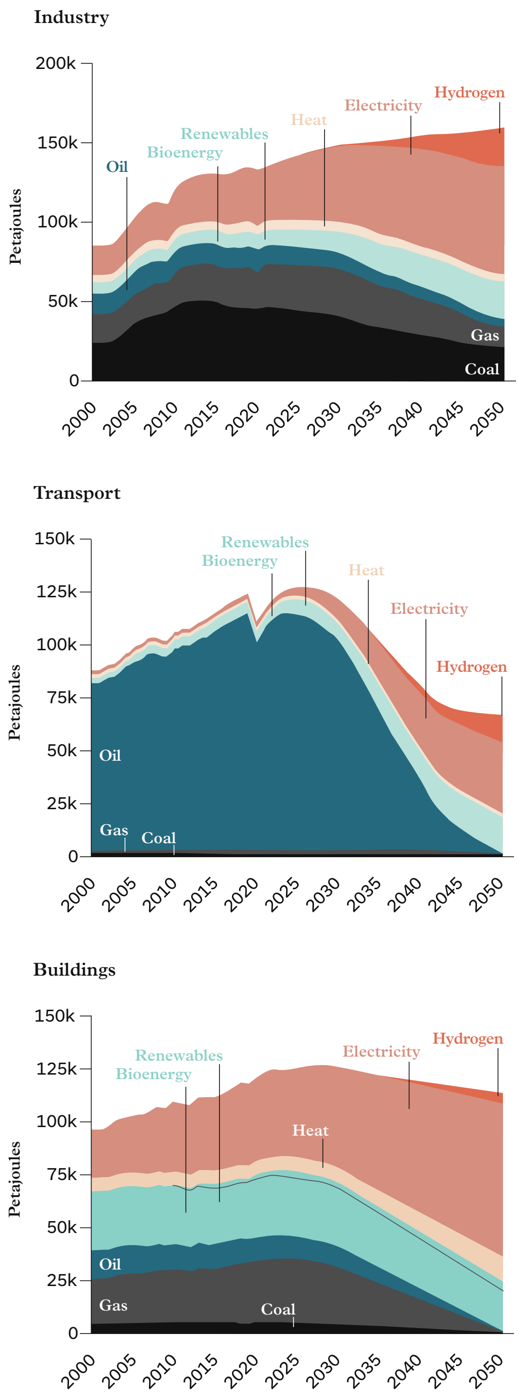
Source: Enerdata (World Energy & Climate Statistics Yearbook 2023)

Each 1% improvement in electricity efficiency in core electricity needs represents a reduction of nearly 12,000 TWh of demand or 14,000 TWh of electricity generation required, which is equivalent to half of the world's current electricity generation. This underscores both the enormous benefits from successful investments in anything that improves electrical efficiency and the realisation that we have to live with assumptions for the energy transition pathway that embraces a wide range of estimates for total electricity production. Below, we carry on with our analysis of growth from new areas of electricity usage.

Electrification of industry, transport and buildings, combined with the needs from green hydrogen production and massive data centres suggest "new uses" of electricity would add 10,000 TWh of demand by 2030 and nearly 40,000 TWh of demand by 2050, giving us demand estimates of 44,000 TWh in 2030 and 88,000 TWh in 2050. From this analysis of electricity needs, especially in the developing world, you might now see why countries like China, India and Indonesia continue to build coal and gas power plants in addition to aggressive renewables capacity additions.

BloombergNEF (BNEF) provides us with some of the key inputs for new electricity uses in Exhibit 18, which shows their most aggressive scenario – the Net Zero Scenario. We convert each petajoule of energy into terawatt hours using a factor of 0.2778. BNEF forecasts that transportation's energy sources will grow from 3% electricity today to 50% by 2050; buildings' energy sources will grow from 33% electricity today to 65% by 2050; and industry's energy sources will grow from 27% today to 44% by 2050. BNEF does not comment on electricity needs of green hydrogen production and from the growth in AI and data centres, which we have separately estimated. In our hydrogen whitepaper, we forecast that to meet 2050 projected demand of c. 280 Mt of clean hydrogen (of which we assume 20-30% is blue hydrogen), green (electrolyzed) hydrogen production would require c. 7,300 TWh of electricity.

Exhibit 18: Estimated mix of energy sources over time for industry, transport and buildings (focus on the growth in electricity in light pink)



Source: BloombergNEF

In Exhibit 19 we sum up the various contributors to the 2030 and 2050 electricity demand forecasts and compare these to expert forecasts.

Exhibit 19: Bottom-up electrification demand forecast out to 2050 points to the need for a 4x increase in electricity

Component of Electricity Demand	2022 TWhs	2030 TWhs	2050 TWhs	Assumptions and Sources
Demand from historical electricity end uses	25,500	30,311	49,700	Grow by 2.5% p.a., in line with real global growth forecasts out to 2050 (Capital Economics). This will carry on as it has for 50 years through to the present where electricity has closely tracked with GDP growth (both growing on average by 2.8% p.a. (since 1990, and since 2010) with no real slowing in the relationship from efficiency improvements which are embedded in this relationship, which the IEA estimates have averaged 1.7% p.a. over the past 10 years.
Increase in electricity efficiency from past 1.7% p.a. to 2.7% p.a.		-2,011	-11,583	Assume a further 1% efficiency gain over and above the historical average of 1.7% p.a. Bain & Co has estimated an improvement from renewables (0.3% pa) and technical efficiency affecting all usage (0.7% pa). The benefits of electrification are netted out from the estimates for EVs, etc below already. This leaves 1.0% from renewables and technical efficiency.
Core "historical uses" demand after 1% p.a. efficiency improvement		**28,300**	**38,117**	This is the forecast before the increases for new areas of electrification.
Electric Vehicles	965	1,894	8,545	BNEF forecasts all transport sources (EVs, commercial EVs, e-buses, trucks and electric two and three-wheelers) of energy to go from 3% electricity today to 8% by 2030 and 50% by 2050.
Building Electrification	11,351	2,053	8,914	BNEF forecasts building sources of energy to go from 33% electricity today to 39% by 2030 and 65% by 2050. 11,351 is the current building electricity demand included in the 25,500 TWh of total electricity demand in 2022. So 2030 and 2050 columns are additional demand from heat pumps, electric boilers, etc.
Industrial Electrification	10,139	3,377	9,232	BNEF forecasts industry's source of energy to go from 27% electricity today to 33% by 2030 and 44% by 2050. 10,139 is included in the 25,500 total current electricity demand. Right columns are additional demand from factory electrification.
Green Hydrogen electrolyzers	0	200	7,300	2050 estimate from Partners Capital Hydrogen whitepaper assuming 280 Mt of total clean hydrogen, of which 170 Mt will be renewable energy powered electrolyzer based green hydrogen.
Data centres / AI trend	300	2,400	4,800	A December 2023 article in the Journal of Cloud Computing (Authors: Wang, Chen, Bai and Gao) claim that by 2030, data center energy consumption could account for up to 13% of the world's electricity production from 1% today; Partners Capital assumes that half of this is achieved by 2030 and flatlines out to 2050, arriving at 4800 TWhs.
Total Electricity Demand Estimate	**25,500**	**38,225**	**76,908**	Demand needs to be "grossed up" to the volume of electricity generated by a factor of 87% based on historical capacity utilisation.
Total Electricity Generation Estimate	**28,661**	**43,937**	**88,400**	Historical average 87% ratio between demand and generation accounting for losses. This has shown almost no improvement over last 32 years (Enerdata). **The result is 4.3% pa growth from 2022 to 2050 vs historical 2.8% average.**
Average of Expert Global Generation Estimates	**28,661**	**36,782**	**64,610**	Average of BNEF, DNV, IEA, IRENA forecasts including all scenarios (incl Net Zero).
Supply Based forecast by energy source	**28,661**	**36,000**	**72,000**	Per Ember historical growth rate data and Partners Capital judgmental assumptions for decelerating growth out to 2050 in line with physical capacity addition limitation assumptions. **This represents a 2.9% pa growth to 2030 and 3.5% from 2030 - 2050.**

Source: 2022 data from Ember Global Electricity Review 2023, BloombergNEF, Journal of Cloud Computing (Dec 2023, Wang et al.). Forecasts based on Partners Capital assumptions and analysis.

Exhibit 19 shows the source of our 88,000 TWh estimate of electricity needed to meet the expectations for electrification, green hydrogen and data centre growth. This exceeds the average of approximately 65,000 TWh from expert base case forecasts. The lower level of these expert forecasts may well reflect what generation growth is practically possible taking into consideration the permitting, land use, transmission line and is likely biased toward what we have all seen from long-term historical growth averaging around 2.8% p.a.

This takes us to our second approach for estimating future electricity generation which is our supply-based top-down growth analysis of individual sources of energy driven principally by growth assumptions for wind and solar capacity build-out.

We start with 2022 electricity generation data by source (wind, solar, gas, nuclear, hydro, etc.) from Ember and apply what we believe to be more realistic and conservative growth rates for each source. Looking out to 2030, we predict that the issues and obstacles outlined above such as the slow pace of transmission buildout and permitting will persist, leading to wind and solar growth rates slowing at the same rate that we have observed over the last 10 years. This contrasts with the expert forecasts, many of which expect recently observed growth rates in wind and solar to be sustained or, in many cases, exceeded. Looking out to 2050, we forecast that the obstacles and bottlenecks noted earlier in the chapter will start to ease from 2030 onwards as policy filters through to action. Further grid buildout, better interconnectedness of grids and advances in storage should lead to renewables capturing additional power generation market share from coal and natural gas as capacity buildout accelerates.

Exhibit 20: Our predictions of the rate of deceleration of the growth rates for wind and solar vs other renewables and fossil fuel

Generation by Source (TWh)	2000-2022 CAGR	10yr CAGR to 2022	5 yr CAGR to 2022	2022 - 2030 CAGR	2030-2050 CAGR	Total 2050 Generation TWh	% of 2050 Generation from Source	2022-2050 CAGR
Coal	2.6%	1.4%	1.3%	0.9%	-3.0%	5,852	8.1%	-1.9%
Gas	4.0%	2.5%	2.1%	2.1%	1.5%	10,082	14.0%	1.7%
Other Fossil	-1.5%	-2.9%	-2.0%	-3.0%	-3.0%	380	0.5%	-3.0%
Nuclear	0.2%	0.9%	0.5%	2.5%	2.5%	5,166	7.2%	2.5%
Bioenergy	7.0%	6.3%	5.8%	4.0%	4.0%	1,981	2.8%	4.0%
Hydro	2.3%	1.6%	1.2%	2.0%	2.0%	7,307	10.1%	2.0%
Solar	38.1%	29.9%	24.1%	19.9%	8.0%	25,486	35.4%	11.3%
Wind	21.1%	14.8%	13.0%	11.4%	6.0%	15,582	21.6%	7.5%
Other Renewables	3.1%	3.4%	2.5%	2.0%	2.0%	165	0.2%	2.0%
Total Generation	**3.0%**	**2.5%**	**2.6%**	**3.0%**	**3.5%**	**72,000**	**100%**	**3.4%**
Total Renewables						**55,686**	**77.3%**	

Source: Historical is Ember and forecasts are Partners Capital

This expected deceleration in growth comes mostly from a growing denominator and the sheer volume of annual wind and solar build-out that would be implied by expert forecasts. The result of this supply-based forecast is total generation of 36,000 TWh in 2030 and 72,000 TWh by 2050. This represents a 2.9% p.a. growth rate out to 2030 and 3.5% p.a. from 2030 – 2050 and leaves us with a theoretical supply vs demand gap of 8,000 TWh in 2030 and 16,000 TWh in 2050.

The insight that strikes us most strongly from this 16,000 TWh gap between 2050 theoretical demand and physical supply may be that fossil fuel-based production with carbon capture may need to bridge the gap if we are to eliminate emissions from the power sector. Gas plants will not be shut down in the face of electricity blackouts. In the out years, nuclear is of course another way to plug this gap. There is little point in electrifying buildings, transport and industry if that electricity continues to be produced from unabated fossil fuels.

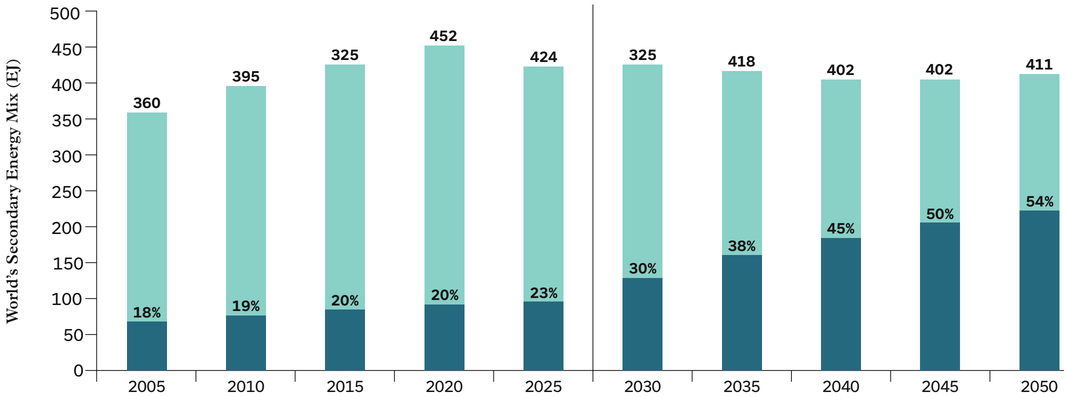
In summary, our 2050 estimate of 72,000 TWh of electricity generation, or 3.3% p.a. growth over the next 27 years, assumes that we see 2.7% annual electricity efficiency relative to the past 1.7% p.a., there are physical and political limits to the rate and extent of renewables and transmission growth in the next 10 years, and we see more fossil fuel plants continuing to operate, but where the carbon is captured and used or stored. In addition, we expect electricity shortages will slow the pace of electrification of transport, industry and buildings. The very prospect of electricity shortages are what then provides us with our range of total electricity generation scenarios skewed to the upside vs experts at 72,000 TWh, where demand is so unmet that more coal plants are converted to gas and more gas plants are left running, but again, with carbon capture.

4. What proportion of total energy will come from electricity?

Under our scenario for growth of electricity demand in 2050 to 72,000 TWh, electricity grows from its current 20% of total global energy demand to 54% in 2050.

Exhibit 21 shows NGFS's assumptions for total global secondary energy demand holding relatively flat at around 400 exajoules per year, due to the higher efficiency of electricity vs fossil fuels. Energy efficiency improvements are expected to offset and moderate how much electricity the world will consume in future as we discussed above. That improvement rate is set to rise as the energy transition gathers pace, primarily driven by electrification, because the efficiency of electric technologies is generally much higher than fossil fuel-based alternatives. Consumer behavioural changes and digitalisation will also contribute to energy efficiency improvements. Against this relatively static energy demand forecast, the NGFS and others forecast electricity growing from its current 20% of total energy to approximately 54% by 2050. Our 72,000 TWh generation estimate translates into 62,600 TWh of demand. Against the 400 EJ of total energy, this amount of electricity will deliver 54% of total energy needs (using 277.8 TWh per Exajoule).

Exhibit 21: Electricity's share of global energy consumption has increased from 18% in 2005 to 20% in 2020, and is forecast to be 30% by 2030 and 54% by 2050

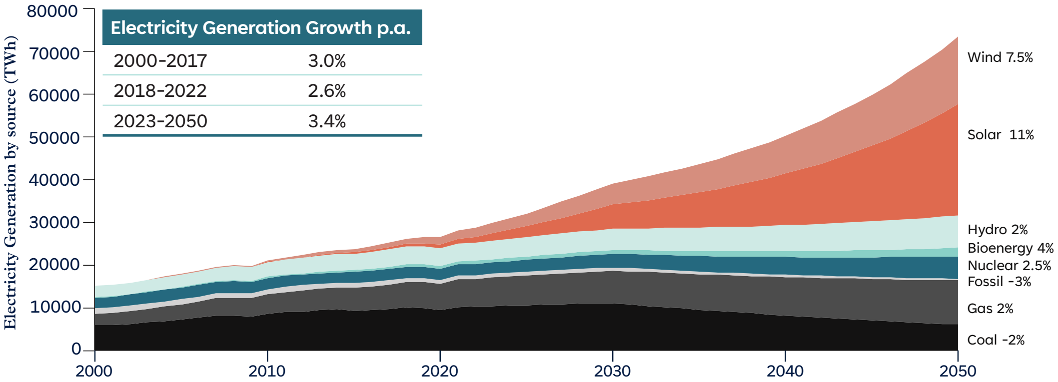


Source: Network for Greening the Financial System (NGFS). The 54% electricity share in 2050 assumes 62,000 TWh of electricity consumption. Primary energy describes energy in its original natural form (e.g., crude oil, sun, nuclear), while secondary is the form in which it is consumed (e.g., diesel, gasoline, electricity). Global primary energy demand is approximately 600 EJ, in contrast to secondary consumption of 425 EJ today.

5. What proportion of total electricity generation is likely to be from renewable sources?

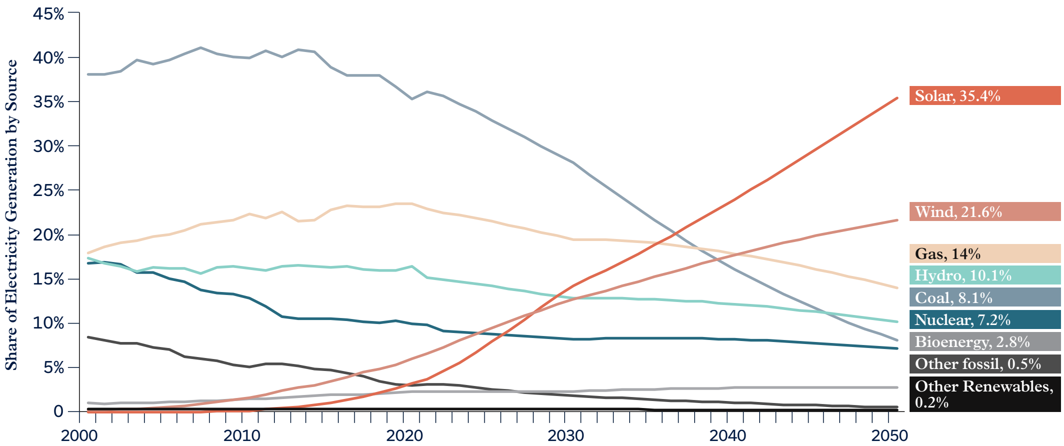
We forecast c. 50% electricity generation from renewables in 2030, up from 39% today and at the lower end of the 42% to 70% range of expert forecasts noted earlier. In 2030, c. 25% of this generation will be from wind and solar, up from 12% today. This 25% is already ambitious but is below what most experts are forecasting, many of which expect recently observed growth rates in wind and solar to be sustained or exceeded. Estimates out to 2050 are clearly much harder to pin down and expert forecasts vary widely as a result. Our own analysis suggests 77% of electricity generation will be from renewables in 2050 of which around 57% will be from wind and solar. Our 77% renewables penetration forecast is at the more conservative end of the 65% to 92% range of expert forecasts.

Exhibit 22: **Wind and solar start to meaningfully capture market share from 2030 onwards driven by grid buildout, more interconnected grids and advances in storage**



Source: Ember Global Electricity Review 2023, Partners Capital forecasts.

Exhibit 23: **Wind and solar will serve 57% of global electricity generation by 2050. 22% could come from coal and natural gas; cost and scale of CCS will dictate how much is unabated**



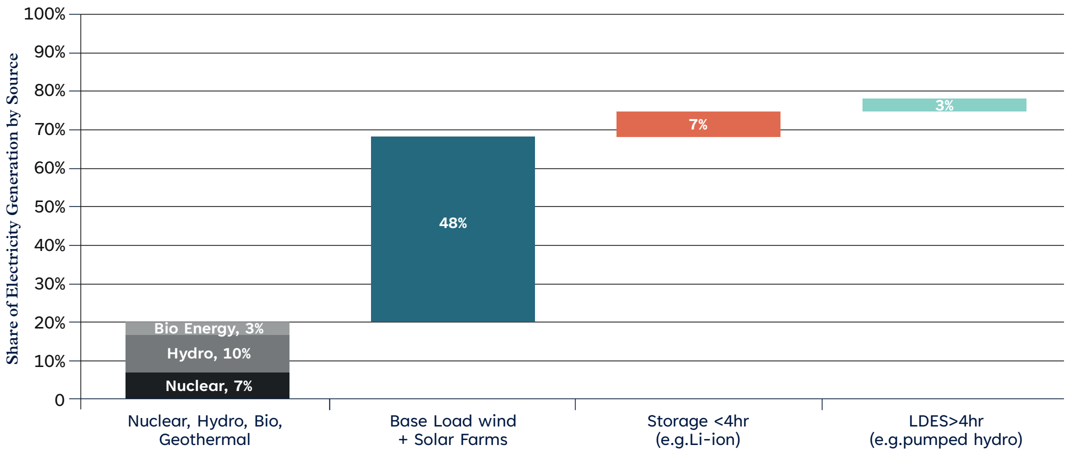
Source: Ember Global Electricity Review 2023, Partners Capital forecasts.

Expert forecasts of renewables penetration of total electricity generated vary widely, ranging from 42% to 70% in 2030 and 65% to 92% in 2050, against varying total electricity generation assumptions as discussed above. We again seek to tackle this question using our own bottom-up perspective, starting with 2022 electricity generation data by source from Ember and applying what we believe to be more realistic and conservative growth rates for each source.

Looking out to 2030, we predict that the issues and obstacles outlined above such as the slow pace of transmission buildout and permitting will persist, leading to wind and solar growth rates slowing **at the same rate that we have observed over the last 10 years.** This contrasts with the expert forecasts, many of which expect recently observed growth rates in wind and solar to be sustained or, in many cases, exceeded. We forecast that c.50% of electricity generation will be from renewables in 2030, up from 39% today and at the lower end of the 42% to 70% range of expert forecasts noted earlier. In 2030, c.25% of this generation will be from wind and solar, up from 12% today.

Looking out to 2050, we forecast that the obstacles and bottlenecks noted earlier in the chapter will start to ease from 2030 onwards as policy filters through to action. Further grid buildout, better interconnectedness of grids and advances in storage should lead to renewables capturing additional power generation market share from coal and natural gas as capacity buildout accelerates. As shown in Exhibit 23 above, we forecast that c.77% of electricity generation will be from renewables in 2050 of which c. 57% will be from wind and solar. Again, we need to underscore the difficulty of forecasting out to 2050 given the plethora of relevant factors that will influence this estimate. We again find ourselves at the more conservative end of the 65% to 92% range of expert forecasts noted earlier, with our assumption that, at a global level, renewables will be fortunate to provide 77% of total electricity needs given the inherent limitations from intermittency affecting wind and solar and the limitations on storage options which we discuss in our battery and storage whitepaper. Exhibit 24 shows estimates of what will be provided from renewables including battery storage and major improvements in interconnections between electricity grids.

Exhibit 24: At a global level, the maximum penetrations from renewables should be expected to be around 77%, but this will vary hugely by region



Source: Partners Capital Analysis. Enlarged interconnection impact is reflected in the maximum wind and solar live offtake estimate, which includes the projected benefits of cross-border grid interconnections but excludes battery and LDES storage.

This leaves approximately 23% of electricity to be sourced from non-renewable sources including gas plants supplied with carbon capture, and clean hydrogen. This global model masks huge variations from one geographic region to another, where some countries like Denmark are supplying 100% from renewables and others like Singapore and Saudi Arabia will struggle to get renewables above 25% by 2050.

6. What are the investment implications?

Investing in renewables is the single largest area of investment in the energy transition. The biggest investors in renewables are incumbent large public or state-owned electric utilities. The “always boring” electric utility industry has been transformed into a growth industry by the energy transition. Backing the most progressive utilities who are leading the transition may well be the largest investment theme emerging from this analysis. The utility sector in most markets today sits at historically low valuations due to the recent rise in interest rates and the perceived high risk of high carbon emitting businesses.

Our four core investment themes behind the renewable energy sector span both public and private equities:

1. **The “first 10%” of Energy Infrastructure Development (pre-construction)**

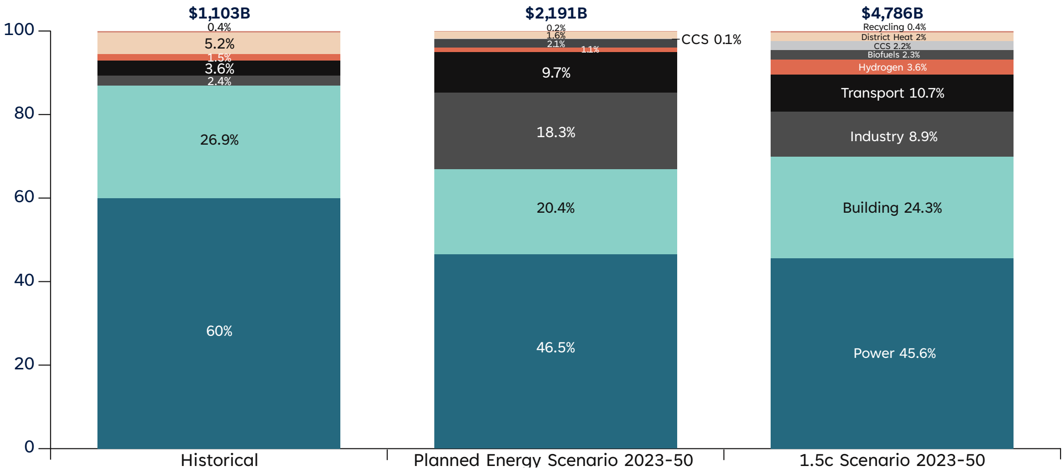
2. **Picks and Shovels (key components, software and services) needed for the infrastructure build-out**

3. **Brown-to-green conversions of high carbon emitting businesses**

4. **Carbon Capture and Sequestration**

Investment opportunities in the renewables space represent the largest area of investment behind the energy transition and is expected to represent $1.0-2.2T of average annual investment out to 2050. This is what is required to virtually replace a 150-year-old power industry in 20 years. This represents 46% of the total $4.8T forecast annual energy transition investments by IRENA in their World Energy Outlook 2023 (“1.5c Scenario”). Renewables end uses, including buildings (24.3%), transport (10.7%) and industry (8.9%) account for another 44%. The remaining 11% is expected to be invested in biofuels, district heating, hydrogen, carbon removal and recycling. Exhibit 25 shows how dominant power investments are in the mix of expected investment across IRENA’s two energy transition scenarios out to 2050.

Exhibit 25: Almost half of the average annual investment in the energy transition is in the power sector



Source: IRENA World Energy Outlook 2023

Exhibit 26 breaks down the individual components of power investment shown in Exhibit 25.

Exhibit 26: IRENA forecasts between $1.0-2.2T of average annual investment will flow to the power sector from 2023-50, of which 81% will be in wind and solar infrastructure including transmission and storage assets

	Annual investments			
		Planned Energy		
Investment Areas	**Historical ($B)**	**Scenario 2023-50 ($B)**	**1.5c Scenario 2023-50 ($B)**	**1.5c Scenario 2023-50 (%)**
Power				
Electricity Network (transmission, etc.)	300	315	630	28.9%
Wind onshore	95	159	356	16.3%
Wind offshore	57	139	283	13.0%
Solar (utility and rooftop)	130	160	333	15.3%
Power Flexibility incl storage	9	66	170	7.8%
Hydroelectric (excl pumped)	40	103	138	6.3%
Bioenergy	24	52	93	4.3%
Concentrated Solar Power	1	9	89	4.1%
Ocean: tides and waves	0	6	63	2.9%
Geothermal	6	9	27	1.2%
Total Power	**662**	**1018**	**2182**	

Source: IRENA World Energy Outlook 2023
Note: 1. IRENA do not consider nuclear to be part of the energy transition capex.
2. Historical is based on IRENA statistics for 2021 investments; IEA 2022 forecast; BNEF, 2023a

The full universe of theoretical investment opportunities is represented by the full renewables value chain as shown in Exhibit 27, starting with raw materials providers such as polysilicon for solar panels and copper for transmission cables. We suggest steering well clear of the commodities end of the value chain. There has been, and will continue to be, a huge burst in demand for commodities including steel, copper, aluminium, nickel, zinc and many other commodities. This is not a surprise to any mining company or commodities trader, and we expect these markets to continue to be highly efficient markets, but an unattractively volatile source of beta, with little prospect of finding exploitable inefficiencies for alpha generation.

Exhibit 27: Renewables value chain defined with company examples

Value Chain	Raw Materials	Manufacturing	Development	Operation
Solar	Steel, Copper, Aluminium, Nickel, Zinc, Silicon, Tellurium, Cadmium, Silver, Gallium	Panels, electric panel, electric meter, inverters and racks	Design, permitting, siting, land acquisition, environmental permitting, regulatory licensing, procurement, interconnection, construction, utility contracting (PPAs), financing Early to late stages	Operation and maintenance
Wind	Steel, Copper, Aluminium, Nickel, Zinc, Dysprosium, Neodymium, Praseodymium, Terbium	Tower, blades, hub, nacelle/drive train, gearbox,generator and yaw system		
Transmission & distribution	Steel, Copper, Aluminium	Transmission substations/ transformers, towers, switches, distribution lines, circuit breakers, insulation		
Other Renewables (biomass, hydro, geothermal, ocean)	Steel, copper, nickel, plants and waste	biomass pellets, hydroelectric power stations, geothermal drilling equipment.		
Software and Services	NA	NA	installation streamlining businesses, consulting	Smart grid software with data analytics to optimise power output: dynamic line rating, FACTS, AI for load prediction, cybersecurity, overhead line monitoring. Energy trading systems

Company Examples				
Solar	Polysilicon suppliers (Tongwei, GCL-Poly, East Hope, Wacker)	**US** – First Solar, Silfab, Jinki Solar, Mission Solar **EU** – RECOM, Solar World, Project Solar, SMA Solar Tech (inverters)	**US Corps:** NextEra, Invenergy, Cypress Creek, Recurrent Energy, AP Solar, Tesla, SunPower, First Solar, EDG Renewables, Empra Generation, Cielo Wind Power, Hexagon Energy, Invenergy, Enel Green Power, and Acciona Wind Energy **EU Corps:** EDP, BayWa, EDF, Enel, Voltalia, Iberdrola,Cloudberry, Eolus Vind, Iberwind, OX2, and Voltalia **Large infrastructure funds:** Brookfields, Blackstone, Macquarie, Global Infrastructure Partners, KKR, EQT, TPG.	**US Corps:** NextEra, Duke Energy, SunPower Services, Berkshire Hathaway, Enel NA, sPower, Invenergy, EDP, Xcel Energy **EU Corps:** Iberdrola, ENGIE, Enel, TotalEnergies, ReNew Energy UK, EDP, Orsted, RWE
Wind	Steel - ArcelorMittal, SSAB, Nippon Steel, Thyssenkrupp, POSCO Aluminium _ Alcoa, Novelis, Constellium, Norsk Hydro	**US** – GE, Vestas, NextEra Energy Resources, Nordex US **EU** – Siemens Gamesa, Vestas, Nordex, Enercon, Senvion		
Transmission	Copper - Aurubis, KME, Luvata, Mitsubishi, Freeport-McMoRan	**US** – Valmont, BOLD, Kiewit, Sabre Industries **EU** – Siemens, ABB, Alstom, Nexans, Prysmian	Bechtel, Black & Veatch, Fluor, ABB, Burns & McDonnell, Seimens	Same as above
Software and Services	NA	NA	Wind and solar project management software (Clir Renewables), solar design, proposal, and sales software (Aurora Solar, PVStream)	E.g., Solar-as-a-service performance monitoring and optimisation (Urbanvolt, PowerFactors), tracker components for utility solar farms (Array Technologies).

Source: Partners Capital analysis

Next up in the value chain are manufacturers of renewable power equipment (e.g., solar panels, wind turbines). Most of these are becoming mature businesses, have generally been overly competitive and, today, are dominated by the Chinese. Perhaps the relatively niche sectors of the renewables market (e.g., biomass pellets, hydroelectric power generators or geothermal drilling equipment) will offer pockets of opportunity in their more nascent stages of development and due to their variable dispatch capabilities to meet peak electricity demand when wind and solar capacity fails to do so. The most attractive opportunities in this part of the value chain are specialist components developers for wind and solar, which have the potential to materially improve efficiency.

The third stage of the renewables value chain is the development and construction of generation assets themselves. This is generally viewed as a hugely capital-intensive business model, dominated by the world's largest asset owners, infrastructure funds and utilities. Competition in this segment, which has steadily been increasing in recent years, has also driven down project economics to mid-single digit IRRs on an unlevered basis. However, we think this segment warrants a more nuanced view, one that segments the development cycle into i) development, which we define as the stages that precede a "final investment decision", and ii) construction. We believe the development segments remains an attractive infrastructure investment opportunity, with skilled developers able to generate 15%+ net IRRs by applying skills that typically comprise:

a) successfully navigating and de-risking key obstacles such as those outlined earlier in this chapter (e.g., securing land rights in attractive areas, or assets with advantaged interconnection access);

b) building scaled platforms with diversified portfolios of assets across technology type, geography and development stage; and

c) prudent and effective financial optimization, primarily through leverage.

Further, our research indicates that there are large pools of capital available for late-stage development (i.e., the construction stage noted above) and operational assets, typically comprising mega-cap core and core-plus infrastructure funds and other direct investors in infrastructure such as large pension plans. As such, early-stage developers who do not want to construct and operate the assets can progress projects through to final investment decision for relatively little capex (typically 10-20% of a project's total capex) before exiting these assets to the groups noted earlier at the construction stage. We think those that are able to successfully execute on this playbook stand to generate private equity-like rates of return.

However, we also note that development of renewable energy and storage is fraught with near-term issues such as cost inflation, supply chain issues and higher costs of debt, all of which are delaying projects and/or making project economics less compelling.

The fourth and final stage of the renewables value chain is in power facility operation. This is a regulated sector with a narrow range of returns, with bond-like pricing with changes in interest rates (i.e., high duration risk). Underpinning the last three sectors of the renewables value chain are component manufacturers, services, maintenance, and efficiency enhancing software. We refer to these as the "picks and shovels" sold into the renewables value chain. With such a rapidly growing customer base, we generally find these to be attractive private and public company investments. In addition, any technology-based businesses seeking to enhance the performance or economics of the renewables value chain are a focus of our energy transition investing efforts.

In summary, the later stages of renewable infrastructure development (i.e., construction) and ownership of operational infrastructure assets are not attractive private equity investment opportunities for most of Partners Capital clients as these are low-yielding, making bad use of scare illiquidity budget allocations. Returns are usually in the single digits on an unlevered basis where offtake risk is mitigated. Emerging market infrastructure may also bring higher returns, but also bring currency and geopolitical risks that are rarely compensated for sufficiently.

One caveat we would note however is that there are investable opportunities in distributed power generation across the residential, commercial and industrial segments, where the renewable energy source is located near the point of use and may or may not be connected to the grid. The more fragmented and small-scale nature of the underlying customer base makes this a more suitable area for smaller, usually private, companies to operate in, thereby being a more attractive area for private equity.

This leads to four core investment themes in the renewable electricity market:

Theme #1: The "first 10%" of Energy Infrastructure Development (pre-construction). Fund early-stage renewables development to progress infrastructure projects from concept through to being "construction ready", taking no significant technology risk, but some development risk. This typically represents c. 10-20% of total project cost. This phase entails value addition from project risk-mitigation including siting, securing land rights, permitting, securing grid connection, putting in place PPAs with electricity customers, debt financing and construction firm shortlisting. This phase of development generally takes 5 years or more to complete and returns are derived from de-risking the project; expect 15% net IRRs. Cambridge Associates Clean Tech benchmark data (as at Q2 2023) reports 19.3% gross IRR for Renewable Power Development from 2015-21.

Theme #2: Picks and Shovels (key components, software and services) needed for the infrastructure build-out. Beyond the actual development of renewables assets, investing in products and services enabling the buildout and increasing energy efficiency of renewables is an attractive second-derivative play for private equity investors. Several segments, for example solar panel manufacturers and wind turbine manufacturing are increasingly commoditized sectors largely competing on price and therefore less attractive today. However, we think attractive opportunities remain for public and private equity investors in niche markets, such as critical efficiency enhancing components going into wind turbine and solar panel manufacturing, products and services related to grid maintenance and buildout, and software solutions for monitoring and optimizing a power system that relies more heavily on renewables. This includes smart grid software and systems for traditional power plants, transmission systems, wind farms, solar farms and hydroelectric. Examples include solar-as-a-service (Urbanvolt), solar tracker for utility-scale solar farms (Array Technologies), key transmission and distribution components (Power Grid Components) and renewables asset performance monitoring software (Power Factors).

Theme #3: Brown-to-green conversions of high carbon emitting businesses. This investment theme can be played out in public and private equity investments, by investing in those companies engaged in the largest scale decarbonisation of their businesses. In the power sector, this is generally focused on the companies participating in the development and operation of renewable electricity generating assets as they replace coal and gas power plants. In the US, energy companies that are leading the way in terms of transitioning their generation capacity from non-renewable to renewables sources include NextEra Energy, Inc. (NYSE:NEE), Duke Energy Corporation (NYSE:DUK) and Southern Company (NYSE:SO). This theme is equally applicable to private equity investments which are typically being managed by veteran traditional energy sector investors like SCF, NGP and Blackstone Energy.

Theme #4: Carbon Capture and Sequestration. This analysis of the maximum renewables penetration points to an opportunity for the emerging Carbon

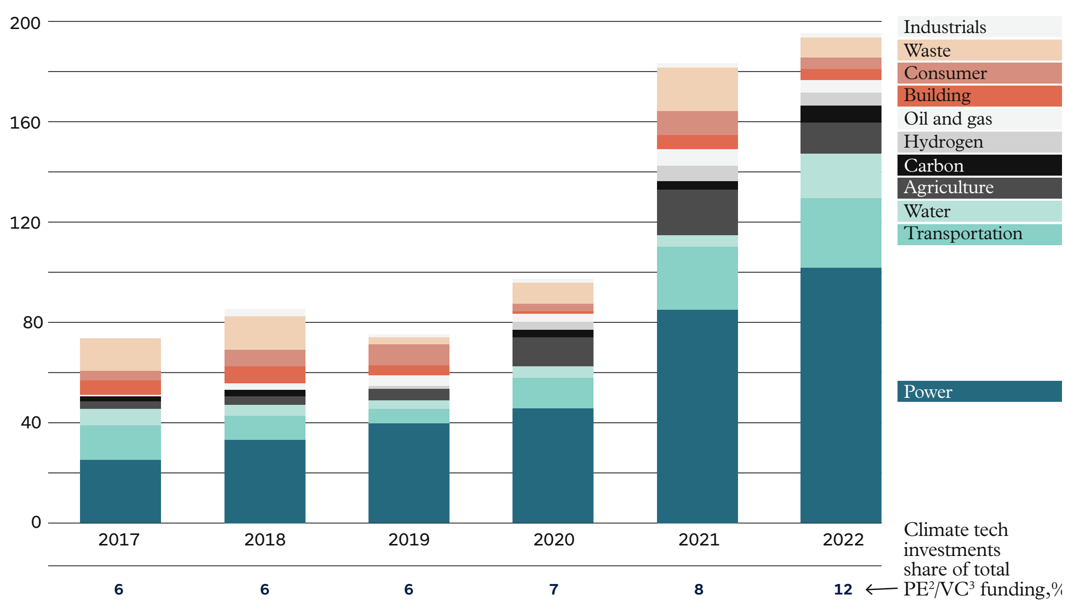
Capture, Utilisation and Storage (CCUS) segment. If we are right that electricity demand will vastly exceed supply in the coming decades, coal and gas plants will continue to be built and old coal and gas plants will likely not be closed on current schedules. We, and others, expect a major investment effort to convert coal plants to lower carbon emitting gas powered plants. But whatever is left of coal and gas plants will have huge pressure for carbon emissions to be captured and either utilised or stored. The three companies leading the charge on carbon capture technology would appear to be Aker Carbon Capture (AKCCF), Bloom Energy (BE) and Fluor Corporation (FLR). We discuss this opportunity further in the chapter on CCUS.

Specialist Climate Tech Private Equity and Venture Capital Firms

Each of these four core themes can be exploited via public or private investments. But we close out this whitepaper with an overview of energy transition private equity and climate tech venture capital investment opportunities. The global volume of climate-oriented private equity transactions, from pre-seed to buyout, increased from about $75B in 2019 to about $196B in 2022, according to data from McKinsey. That represents average annual growth of about 40%. The 7% growth shown from 2021 to 2022 in Exhibit 28, contrasts sharply with the overall private equity deal volume, which declined by roughly 24% from its 2021 levels.

The power sector was the biggest recipient of private equity investments, taking in about 50% of the deployed capital from 2019 to 2022 as investment more than doubled, from $40B to $100B, benefiting from the continued momentum in large-scale renewables. Transportation came in second where investment increased by 370% during that period, from $6B to $30B, driven by the increasing adoption of electric vehicles (EVs). Hydrogen and carbon management each represented only 3% of total climate-focused private-market equity investments in 2022 which must say something about the attractiveness of the opportunity set there. Nonetheless, hydrogen and carbon management recorded the most significant growth in investment inflows since 2019: 460% for hydrogen (from less than $1B to $5B) and 1,400% for carbon management (from less than $500M to $7B) in addition to the significant corporate investments in these fields.

Exhibit 28: The power sector has accounted for about 50% of private equity investments made from 2019-2022



Source: PitchBook McKinsey analysis

Climate technology investing (Clean Tech 1.0) began in the early 2000s as Silicon Valley venture capital firms were propelled by a growing awareness of the urgency behind climate change, following public campaigns from prominent advocates including former US Vice President Al Gore. The demand for positive environmental impact coincided with historically high energy prices and favorable government subsidies. Between 2006 and 2011, Cambridge Associates estimates that approximately $25 billion was invested into clean tech companies.

This first wave of investing saw nearly half of the $25B either lost or impaired with high profile write-offs of companies like Solyndra, Evergreen, EPV, SpectraWatt, and Sterling Energy. This poor performance was driven by investors not fully comprehending the technical risks, capital intensity, and extended timelines of these early clean tech investments. The industry also faced the 2008 Global Financial Crisis, low energy prices propelled by advancements in hydraulic fracturing, and the glut of cheap solar panels from China.

Today, out of the ashes of Clean Tech 1.0, has emerged a wiser group of investors, armed with lessons learned and relevant operating expertise. Many of the generalist VCs do very little in the space, but specialist VCs focused almost entirely on climate tech have emerged including firms such as Breakthrough Energy Ventures, Lowercarbon, The Engine and Capricorn Investment Group.

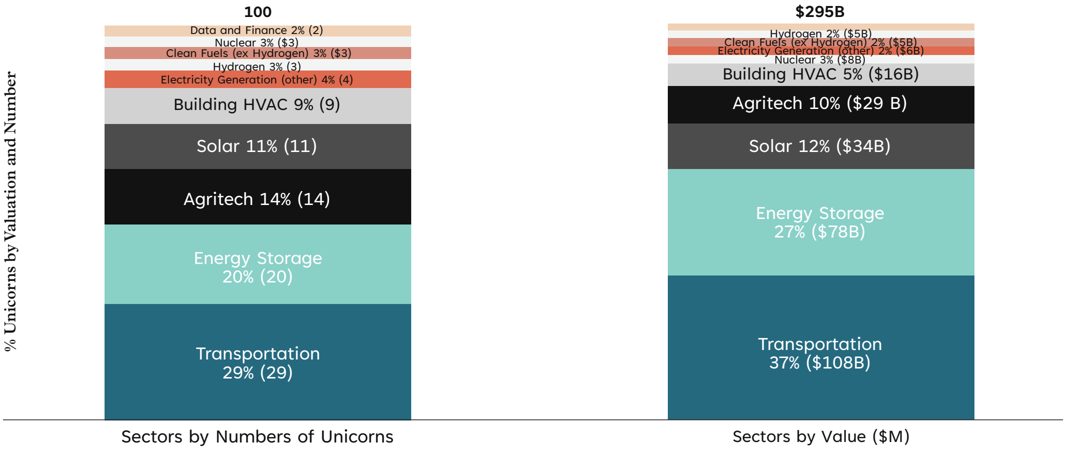
Addressing the need for large amounts of capital, the large buyout groups including TPG, Apollo, General Atlantic, Apax and Blackstone have all launched funds averaging around $3B in AuM, but TPG's Rise Climate Fund closing on $7.3B in early 2022. Most firms have only launched dedicated energy transition funds in recent years, but show selective energy transition investments in their track record dating back to the 2010s. The large infrastructure investors bring more experience investing in this space having started with wind and solar investments during Clean Tech 1.0. Ahead of the pack is Brookfield who are targeting $15-20B for their next Energy Transition fund, closely followed by firms such as, Macquarie, EQT and Global Infrastructure Partners.

In buyouts, growth equity and venture capital, Partners Capital prefer investing with "veteran" specialist energy transition managers who we believe have deep expertise on the likely economics of emerging technologies including battery storage, bioenergy, clean hydrogen, carbon capture use and storage, geothermal, nuclear, etc.

We note that VC-backed companies are working on innovations and solutions that could disrupt the status quo and different aspects of the renewables value chain we have set out. Some examples include: i) Fervo Energy – working on a new horizontal drilling approach to geothermal energy production, ii) various companies working on methods of long-duration storage such as Form Energy, Antora Energy and ESS Inc, which if commercialised could massively increase capacity utilisation rates of renewable generation; and iii) breakthrough generation technologies, principally fusion, which are many years from commercialisation but could significantly disrupt incumbent methods of generation in future.

Clean tech unicorns (private companies with valuations greater than $1B) are growing as a share of all VC-backed unicorns from nearly zero 10 years ago to 12% today. Data from HolonIQ and Pitchbook provides us with a current population of climate tech unicorns of 167 companies out of a total of 1,387 unicorns across all sectors. Just looking at the HolonIQ database of 100 climate tech unicorns as shown in Exhibit 29, we see that unicorns are concentrated in four sectors: transportation (in and around EVs), energy storage/batteries, solar and agtech.

Exhibit 29: Energy Transition Unicorns are concentrated in four sectors



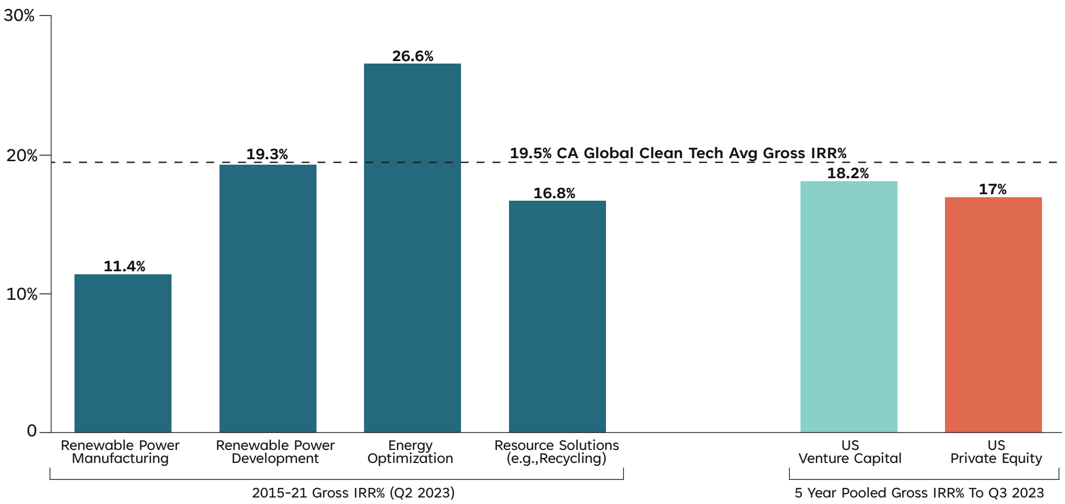
Source: Partners Capital analysis using data from HolonIQ

The fact that past unicorns came from these four sectors does not indicate that all future ones will. It is quite possible that unicorns emerge from carbon capture, transport, storage, clean hydrogen, or industrial and building end uses.

A popular model for investing in the power sector among venture capitalists is to bring large public power companies into the LP base as strategic investors and jointly invest, providing access to company technology expertise and to their operations or customer base for testing new technologies. Energy Impact Partners has been operating this strategy for nearly 8 years now with over 30 industrial partners dominating their LP base.

An indication of potential returns from the clean tech investments are shown in Exhibit 29 from Cambridge Associates' Clean Tech Company Performance Statistics report dated 30 June 2023. The returns shown are gross IRR% from a total of $24B of clean tech VC investments from 2015-21. The average annual gross IRR was 19.3% compared to gross IRRs from overall US private equity (17%) and venture capital pooled returns (18.2%) for the 5 years ending Q3 2023. Note that there is a slight difference in time frame being compared.

Exhibit 30: Clean Tech investment performance has slighted exceeded broader VC and PE investment performance over the 5 years ending 2021



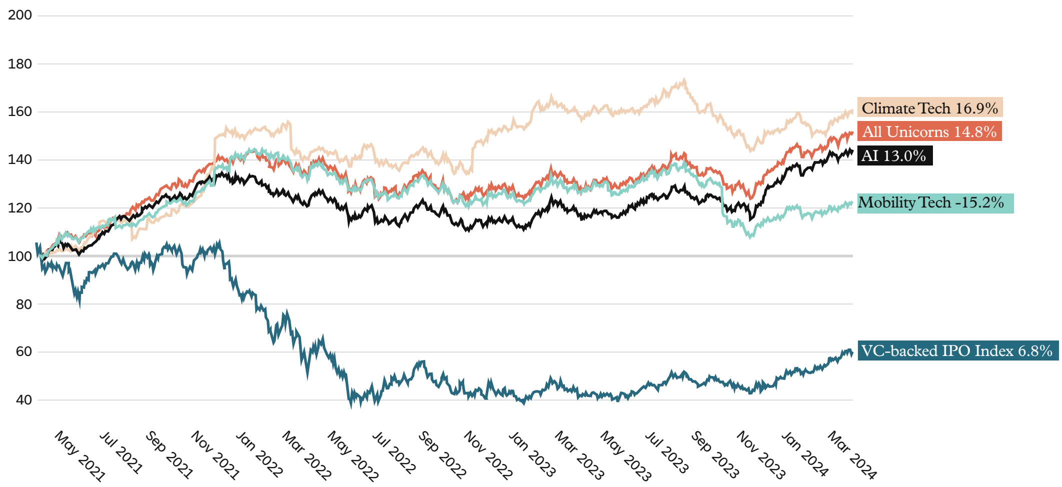
Source: Cambridge Associates (Q3 2023 Report)

Climate Tech early-stage VC deal activity is down by roughly 50% from the peak in 2023, but investment and valuations held up better in Climate Tech than in other verticals in 2023. In others sectors like foodtech, cybersecurity and fintech, deal volumes and values are down approximately 80%, 60% and 65%, respectively. Climate Tech companies have grown headcount faster than their tech peers, and they have significantly increased their share of patents filed, according to Pitchbook.

Among all VC investment segments, Pitchbook reports that Climate Tech companies have seen the largest improvement in expected relative success rates and returns over the past several years. Since 2017, the Climate Tech vertical improved from the worst to sixth best (out of 10) with respect to relative expected returns. This ranking of expected future returns is based on PitchBook research that uses a novel quantitative method to assess opportunities in emerging technologies, which we have not validated. The internet of things (IoT), foodtech and agtech are at the bottom of the list.

Exhibit 31 shows the 3-year performance track record of Climate Tech Unicorns. Over this period, they outperformed the average unicorn, AI unicorns and mobility unicorns.

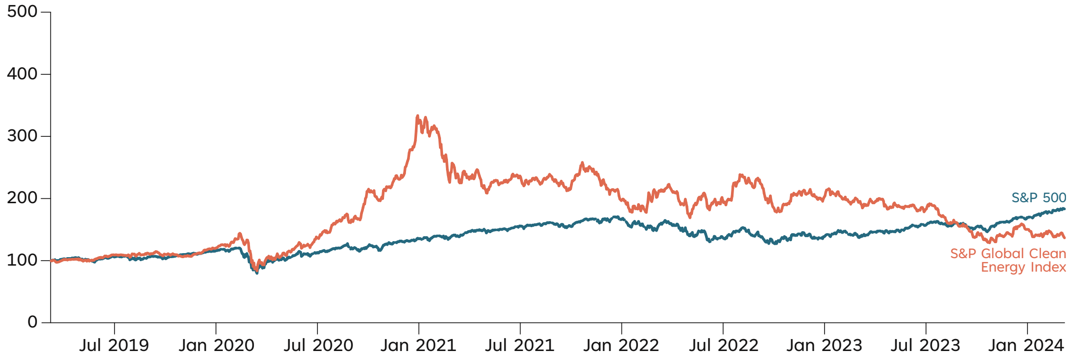
Exhibit 31: The average annual net IRR of Climate Tech unicorns over the 3 years ending March 2024 averaged 16.9% compared to all unicorns at 14.8%



Source: Pitchbook. Indices are Morningstar Pitchbook global unicorn indices plus the VC-backed IPO Index.

However, we caution too much enthusiasm over these results when we look to what has happened recently in the Climate Tech in public equities. Climate Tech valuations may see a further bounce down from the picture in Exhibit 30.

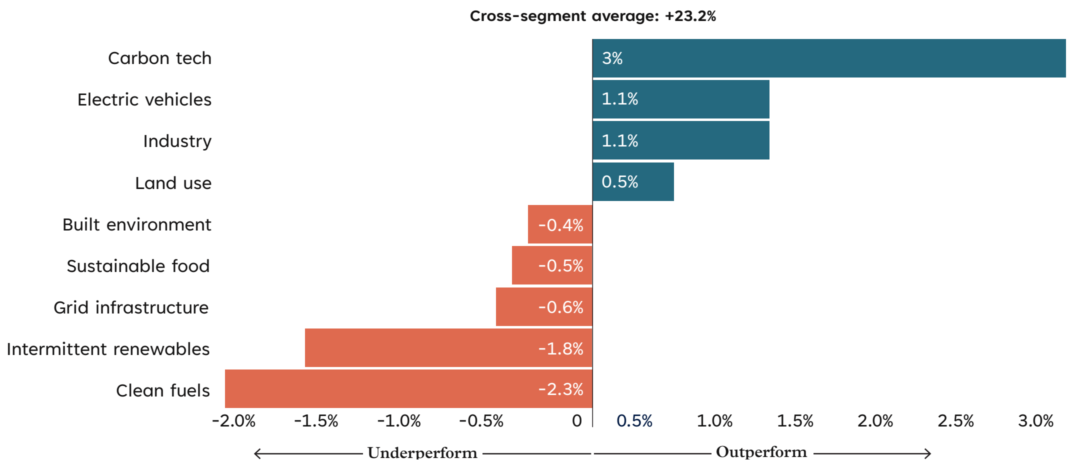
Exhibit 32: Over the last 5 years, the S&P Global Clean Energy Index initially outpaced the S&P 500, only to fall behind in 2023, with a 7.9% CAGR vs 13.0% for the S&P 500



Source: SP Global

Within the Climate Tech VC category, the "Carbon-Tech" subsegment presents the most attractive opportunities for early-stage investors, according to the Pitchbook analysis. This segment includes a mixed bag of carbon capture startups and firms writing the software needed to measure and account for emissions. Note that grid infrastructure and renewables feature relatively low.

Exhibit 33: Carbon tech is the most attractive early-stage climate segment



Source: VC Emerging Opportunities report

In conclusion, renewables present a vast universe of investment opportunities, but is treacherous territory with complex capital supply and demand factors affecting the sector. In many cases, we see young companies having to spend longer on high capital burn rates than they expected waiting for demand to materialise. This is difficult to get right. We believe that if investors focus on the four themes, this capital mismatch may be avoided. In particular, we see a huge opportunity for relatively low capex businesses which aim to improve the efficiency of energy usage; in particular, smart grid software and systems (traditional power plants, transmission systems, wind farms, solar farms, hydro), building energy efficiency, industrial energy efficiency, lighting, energy storage and carbon footprint measurement and reporting.

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