Partners Capital

Global Energy Transition Investment Framework

April 2022

Authors

Stan Miranda

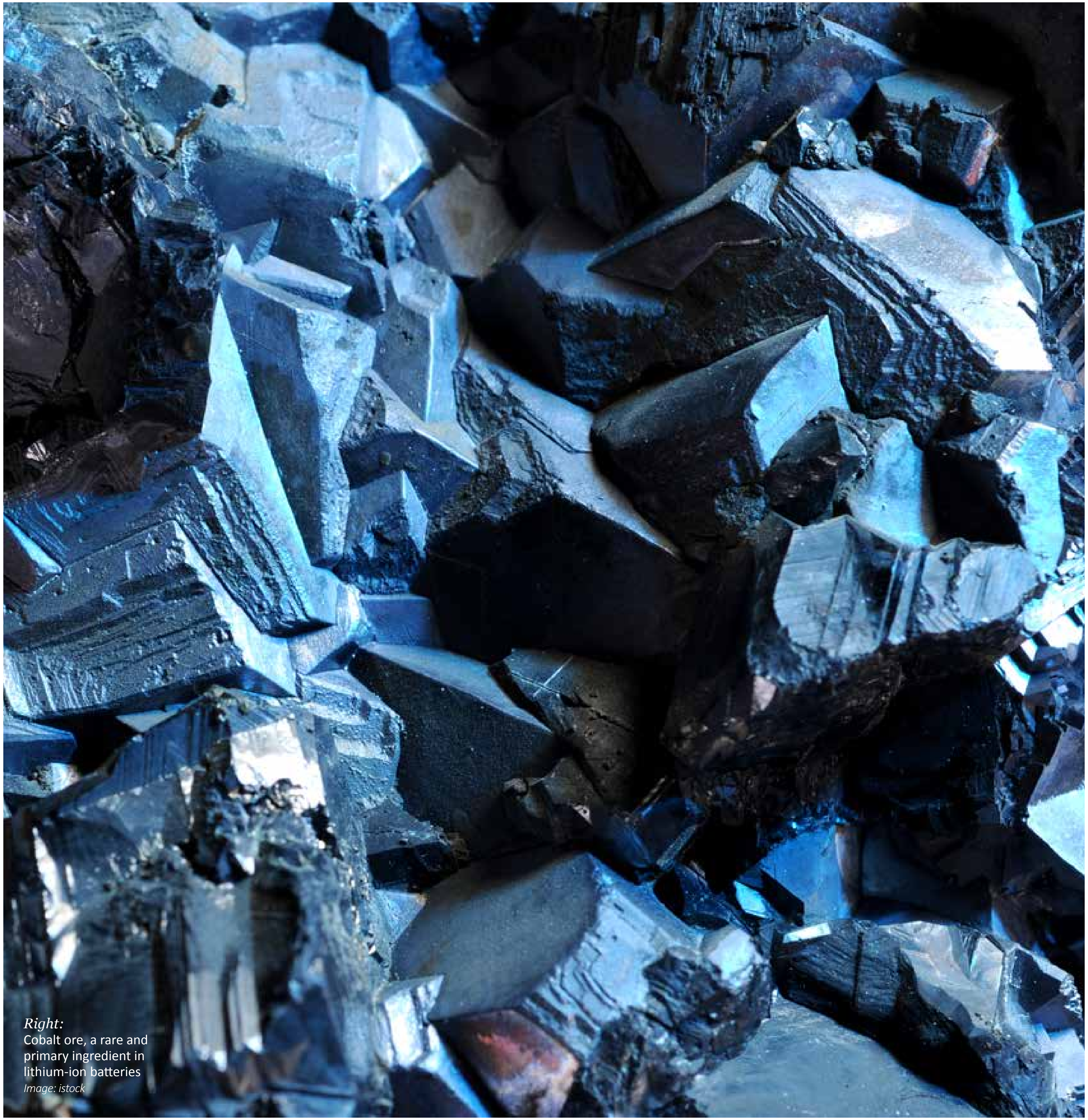
Founder, Chairman

- Partners Capital Chief Executive (2001-2020)
- Evolution Global Partners (Venture Capital)
- Bain & Company Director
- Harvard MBA

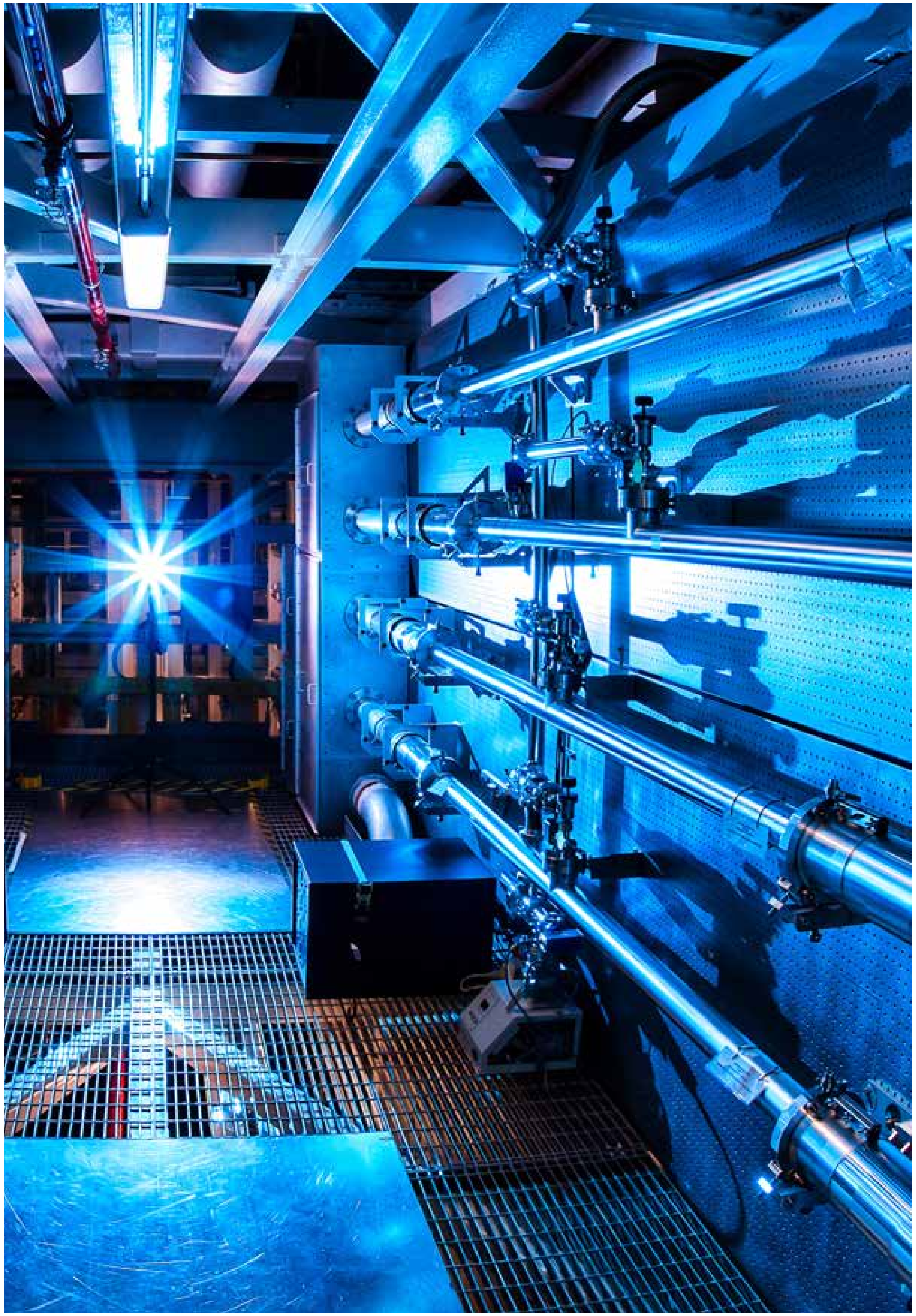
Robert Skelton

Principal

- Coronation Capital
- Mediolanum Asset Management
- Trinity College Dublin
- CFA Charterholder



Right:
Cobalt ore, a rare and primary ingredient in lithium-ion batteries
Image: istock



April 2022

Contents

Left:
The preamplifiers of the National Ignition Facility which uses large-scale lasers to induce nuclear fusion reactions.
Image: Damien Jemison/LLNL

Executive Summary

The energy transition to net zero emissions is one of the largest and most complicated of economic and industrial transformations history will encounter. We think of this very much as the third industrial revolution following the late 1800's industrial revolution and the digital revolution which started in the 1980's. The complexities involve environmental science, technological developments, government regulation, policy and R&D influences, changes in consumer behaviour, and changing the corporate world's purpose to include both commercial performance and environmental impact. With the recent events in the Ukraine, energy security has been elevated as a major government policy initiative in many countries, which has given greater impetus behind the drive to domestically sourced clean energy.

Few investors can see far enough down this path to invest prudently. While climate impact may be the largest investment opportunity of the decade, this is dangerous territory. This document seeks to put a stake in the ground at this moment in time, laying out the most likely path of the energy transition in terms of capital investment, government policy and technological development. Most importantly, we seek to define what we are calling "the biggest unknowns," so that we know which investments to avoid at this point in time, and which are likely to achieve their targeted impact and returns.

Virtually everyone in the investment business today has little choice other than to seek deep insights into what this megatrend means for the economy, the companies they own, and the environment.

These investments will be made across six core sectors that represent over half of the global economy, with the power generation sector being the largest accounting for 34% of the $55T current total market that is addressable from energy transition products and services. As three other sectors: transport, buildings and industrial processes, become electrified in the next three decades, the demand for electricity will triple, putting the focus very much on investments in renewable energy to generate the majority of that electricity. Food and ag tech, along with water and recycling, constitute the remaining sectors of focus for the energy transition, with very different, but exciting investment opportunities.

In the next five years, households are expected to finance 10% of the $4T annual increase in investment, governments 30%, with companies (including financial institutions) financing the bulk of the cost, or 60%. Carbon taxation will be a major incentive for those corporations to invest their share of this $4T into lower emitting ways of operating. Today, carbon taxation already covers 21% of global emissions.

Bloomberg estimates that future carbon tax rates will be based on the **cost of carbon removal** (whether from increasing vegetation or carbon capture equipment) and this could rise from the current average of $14/tonne to $224 per tonne by the end of this decade, before falling to $120 in 2050. Modelling the impact of $100/tonne carbon taxation shows how devastating such taxes would be for the steel and cement industries, while utilities, chemicals and mining suffer significant reductions in profitability. It is not obvious to us that every equity portfolio manager out there today, is contemplating how carbon taxation will affect the valuation of companies in their portfolios as carbon taxes are gradually extended to apply to all industries.

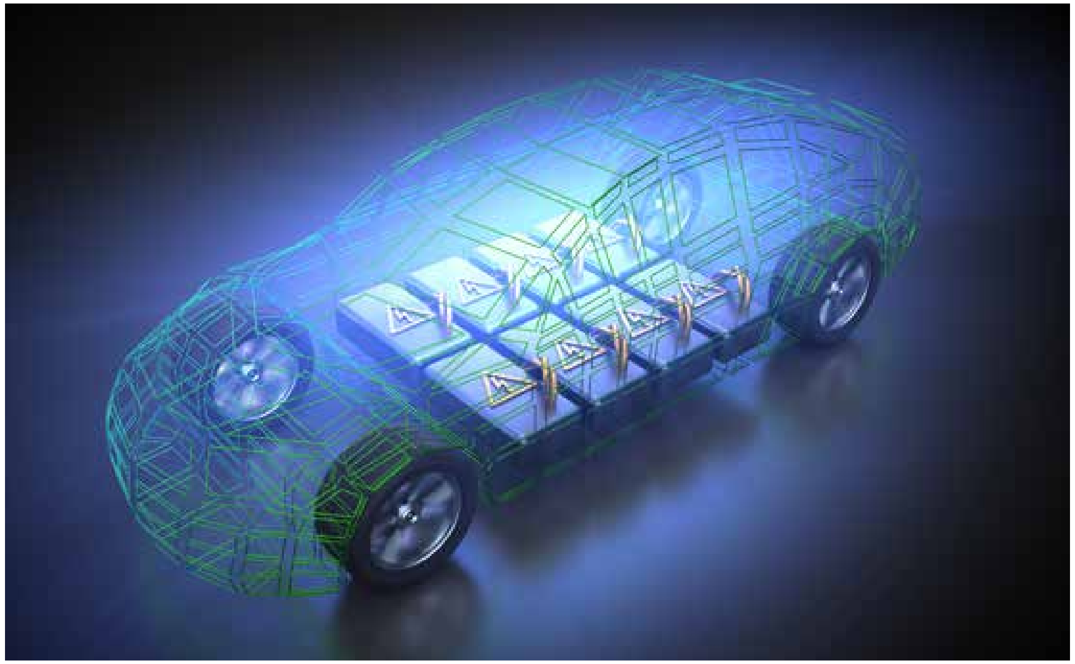
As we think about how best to play the energy transition **investment theme**, we want to avoid a repeat of the Cleantech investing disaster of the 2005-2015 period. Investors lose money when they do not adequately understand the risks. Those risks for this energy transition are made clear by focusing on what major innovations are required to achieve net zero emissions.

Looking at the total electricity forecast out to 2050, we expect to see a near tripling in demand from 27,000 TWhs to 77,000 TWhs, not just from the growing needs of developing economies, but also from the electrification of transport, industry and buildings. Wind and solar power are the bedrock of the energy transition pathway, expected to grow from generating just 8% of all electricity supplied today to over 70% by 2050. But, without a storage medium for wind and solar, its maximum penetration stops at approximately 25% due to the fact that you need to use it precisely as it is being generated.

The bulk of our research in writing this whitepaper was focused on identifying and quantifying all of the key technology and other building blocks that are required to achieve the goal of net zero emissions by 2050. The first major contributor to CO2 emissions reduction between now and 2050, that we are confident can happen, is the growth of wind and solar generated electricity from live offtake, i.e., what can be generated and used without being stored. This is estimated to amount to c. 25% of total CO2 emissions. From there, another 45% in carbon reduction needs to come from storing excess wind and solar power generated for use when it is needed at later points in time by households, offices, industry and electric vehicles. There are dozens of potential storage mediums, but the two most promising at this point in time appear to be storage by way of large-scale lithium-ion batteries and green hydrogen. Lithium-ion battery technology appears to be the long-term winner, but this can only store electricity for up to four hours cost effectively. This will not enable excess wind and solar power produced in the summer to be saved and used in the winter. Green hydrogen (hydrogen produced by electrolysis from water using renewable energy-sourced electricity) and other nascent technologies like compressed air energy systems (CAES) are needed to provide long-term storage solutions.

Included in this additional 45% of carbon emissions reduction is approximately 15% which is expected to come from the combination of electric vehicle (EV) penetration (vs. internal combustion engine-powered vehicles) and supplying that EV electric power from the renewables' live offtake or stored energy. But, today, almost no wind and solar is stored – less than 1/100th of one percent. There are serious technological and cost barriers to overcome to achieve the 45% of additional wind and solar substitution that relies on stored energy. Clearly, the challenge of storing wind and solar sourced energy is the single greatest challenge for the global energy transition.

Below:
Electric vehicle in motion with open carbody with view at the battery pack
Image: Shutterstock



Beyond renewable energy storage, carbon capture and sequestration (CCS) technologies are expected by the IEA to account for 15% of the needed carbon emissions reduction, but that technology is also in its nascency. The final brick in the CO2 reduction wall is natural carbon offsets (such as forestry and conservation projects), where emitters are taxed to finance projects that enlarge earth's natural carbon sinks. These are expected to account for the final 15% of carbon reduction.

In summary, the most profitable and impactful investments are likely to be in companies and sectors which sit in pivotal positions that unlock the ability to succeed on the path to net zero emissions. So, rather than investing in the infrastructure buildout of wind and solar farms or EV charging infrastructure that are indeed critical to the transition, we are focused on investment in the energy transition "enablers" such as battery storage, green hydrogen electrolysis, small modular nuclear fission plants, carbon capture, building energy efficiency (electric heat pumps), and ag and food-tech. Philosophically, we are also more focused on the "picks and shovels" in and around the energy transition, which includes critical components of core technologies or specialist services in supporting the buildout and operation of industries' carbon reduction initiatives.

Unfortunately, the universe of talented managers with investible track records in this space is not large, despite the hundreds of "ESG or Climate Impact" labelled funds that exist in the investment world today. But therein lies the opportunity for Partners Capital to find that small subset of extraordinary managers with deep insights about the likely path of the energy transition and to work most closely with them in the years ahead. We are already well down that path.

Learning from Cleantech 1.0 (2005 – 2015)

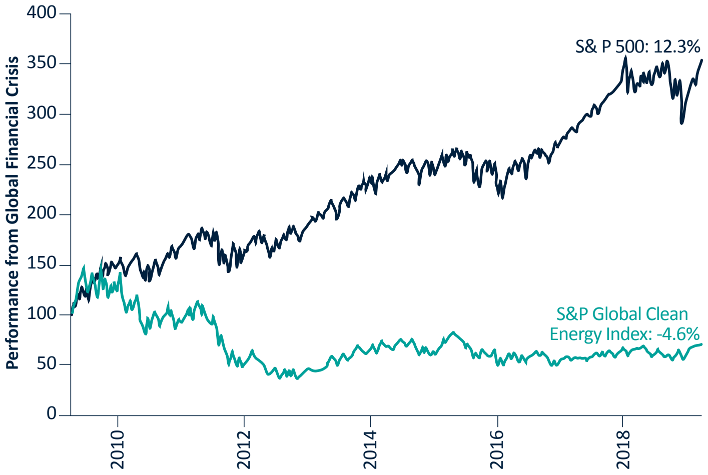
The focus of this whitepaper is on environmental impact and ensuring we achieve the mutually reinforcing set of impact and return objectives. The first go-around in this endeavour known as Cleantech 1.0, which took place over the decade from 2005-15, did not end well. We had little impact and returns were disastrous in both public and private equity investing. Investors often lose the most money when they dive into an area they don't understand, often with a heavy "fear of missing out" element. $100 invested in the S&P Global Clean Energy index at the beginning of 2009, was worth $70 eleven years later in 2019. This compared to $100 invested in the S&P 500 that was worth $350.

Private equity focused on cleantech across venture, growth and buyouts in the 2005-09 vintages had a similarly poor track record, losing 1.5% per year on average. Cleantech venture capital lost 10% a year in that period (source: Cambridge Associates).

When we look back on this, investors were fairly blind

Exhibit 1

The S&P Clean Energy public equities index lost -5% per annum since the financial crisis in 2008, underperforming the S&P 500 index by c. 17% per annum



Source: *Bloomberg*

to how large the opportunity would be over what time frame, what political support it would be given, what alternative energy would cost and what the international competitive dynamics were. Investors were blindsided by government subsidies being withdrawn, the slow pace of technological breakthroughs, China's dominance of the solar panel industry and the capital intensity of alternative energy infrastructure. Most of these investors closed down their cleantech operations with significant scar tissue.

The aim of this whitepaper is to have at least Partners Capital flying less blind into "Cleantech 2.0", which will be an opportunity of a scale that even Cleantech 1.0 investors never dreamt possible. The uncertainty is huge and the opportunities for being blindsided far greater.

Our Energy Transition Investment Framework

When we embarked on this exercise late last year, we were concerned that we would be biting off more than we could chew given the massive complexity involved. It turns out that those concerns were underestimated. It may be impossible for anyone to get their arms fully around this, even when we are leveraging a huge universe of excellent research including the US Department of Energy, the International Energy Agency, BloombergNEF, Goldman Sachs and McKinsey, among many others. Reflecting on the finished document, we are confident that what we now understand is of considerable value to the extent that it enables us to ask more intelligent questions in sorting through and finding the best investments behind the energy transition.

To this end goal, below we identify the major macro climate change questions that are largely unanswered today and have attempted to answer these by finding the deepest and most knowledgeable thinkers on each risk area and summarising their views. Partners Capital and your asset managers are the primary audience, but given the importance of this, we thought that our clients may find this highly interesting and valuable as we carry on the path to net zero emissions (NZE).

One important investment implication that this framework aimed to explicitly deliver, was guidelines on where not to invest. Where there are major uncertainties that could make or break a given business, we do not want to see our managers investing there. Saying what we can know and what we cannot know about each of the big questions listed below around the energy transition, will hopefully serve as valuable guidance to our asset managers, so that they will not be blindsided in the way that earlier investors in this space have been. This is dangerous investment territory, but therein lies the opportunity for extraordinary returns.

This document is structured around 16 energy transition foundation questions. The answers constitute our framework for investing behind the global energy transition. Before we dive into each question, we briefly lay out the critical climate change context, including how carbon circulates on the planet. Without that basic understanding, we cannot talk about what the human race needs to do.

What you first need to know about climate change

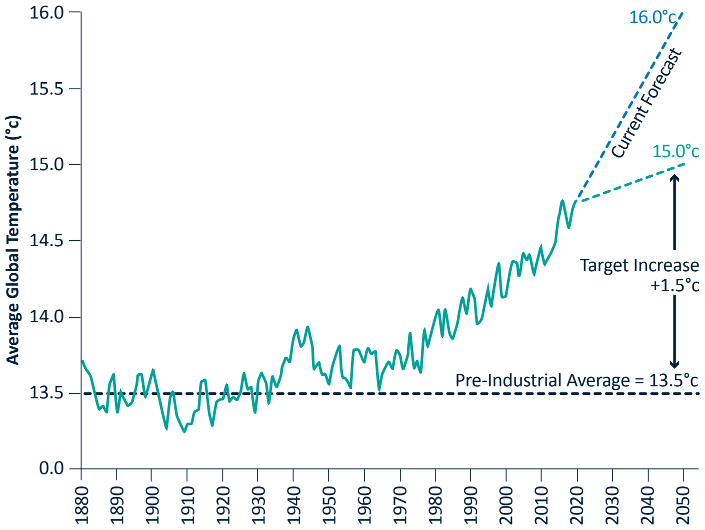
What is the core problem we are facing?

Carbon dioxide is the most important of the earth's greenhouse gases (GHGs) as it is the most abundant and remains in the atmosphere for the longest period of time. GHGs (carbon dioxide, methane and nitrous oxide) absorb heat and release it gradually over time. Without a natural greenhouse effect the average temperature globally would be below freezing instead of just below 15°C[1].

At the global scale, the key greenhouse gases emitted by human activities annually are estimated to total 50B tonnes, 38B tonnes from CO2, 8B tonnes from methane, 3B tonnes from nitrous oxide and 1B tonnes from F-gases. These GHGs are all defined in the appendix. Because Earth is a closed system, the amount of carbon never changes. The carbon cycle keeps carbon moving from one reservoir to another. When carbon stays in a place where the absorption of carbon is bigger than the amount of carbon it releases, we have a "carbon sink." The ocean is the largest carbon sink absorbing around 30% (10B tonnes) of annual carbon emissions. Vegetation and soils capture another c. 25% leaving 45% in the atmosphere, heating our planet. The problem is that this 45% emitted into the atmosphere is far too much carbon dioxide, currently about 20B excess tonnes each year (40-50 billion tonnes of total gross emissions), and this has led to a rapid warming of the planet with dire consequences. Exhibit 3 illustrates the atmospheric growth in carbon dioxide over time which is effectively the difference between gross emissions and natural sink absorption (the light blue layer)

Exhibit 2

The Paris Agreement's 1.5°C target represents a goal to limit the increase in global temperature since the pre-industrial average of 13.5°C to just 15°C. Without action, the temperature is expected to reach 16°C by 2050.



Source: *Historical temperature data is from NASA GISS. Forecast assumes no success in reducing the pace of carbon emissions and we see the same trajectory as during the 1960 to 2020 period, of each decade accelerating: 0.2 degrees in 2020 to 2030, 0.25 degrees from 2030 to 2040 and 0.3 degrees from 2040 to 2050.*

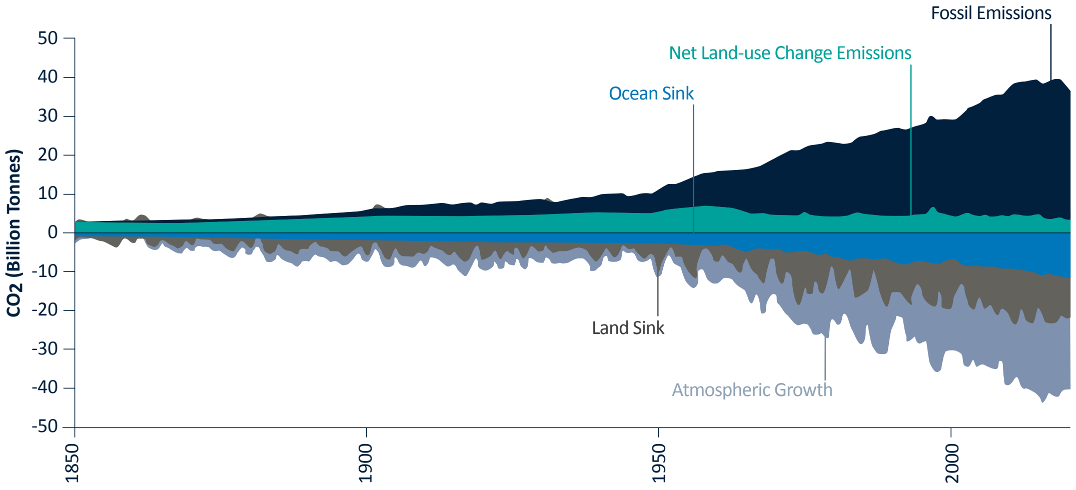
Since the industrial revolution, the earth has warmed by 1.2°C as shown in Exhibit 2. The effects of this warming are already evident. Children born today are up to 7x more likely to face an extreme weather event than their grandparents. Severe droughts in large swaths of the world are now

---

[1] https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide#:~:text=It%20absorbs%20less%20heat%20per,causing%20Earth's%20temperature%20to%20rise.

Exhibit 3

Over half of all carbon emissions are naturally absorbed by the ocean, soil and vegetation and the remaining c. 20B tonnes is added to the atmosphere each year



Source: *Global Carbon Project*

4x more likely than they were in the previous century and the World Bank estimates that there will be more than 200M climate refugees over the next three decades[2].

Experts estimate that just over two thirds of the global warming post the industrial revolution is the result of rising carbon emissions[3]. In 2021, the UN's Intergovernmental Panel on Climate Change noted that even in the best-case scenario, the world was likely to warm by 1.5°C, relative to the period prior to the industrial revolution, within 20 years. Piers Forster, the report's lead author, noted that "if the world can substantially reduce emissions in the 2020s and get to net zero carbon emissions by 2050, the temperature rise from the late 1800's industrial revolution, can be limited to 1.5°C". This will however be a significant challenge and experts believe that, at our current trajectory, there is a 25% chance we will reach 3°C of warming relative to pre-industrial levels before the end of the century. The Economist estimates that, at this level of warming, over a quarter of the world's population could endure extreme droughts for at least one month a year and the roughly 10% of the world's population that currently live on a low-lying coastline will lose their homes.

How is the energy transition going so far?

The aggregate impact of nuclear, hydroelectric and solar/wind generation reduced global reliance on fossil fuels from approximately 95% of primary energy consumption in 1975 to 85% in 2020. The IEA expects fossil fuel reliance to decline at a more rapid pace now, to 73% by 2040. In 2021 renewables are for the first time expected to garner more capital spending than upstream oil & gas. According to JP Morgan, this process is heavily influenced by diverging costs of capital: 3%-5% for solar and wind, 10%-15% for natural gas and up to 20% for oil projects.

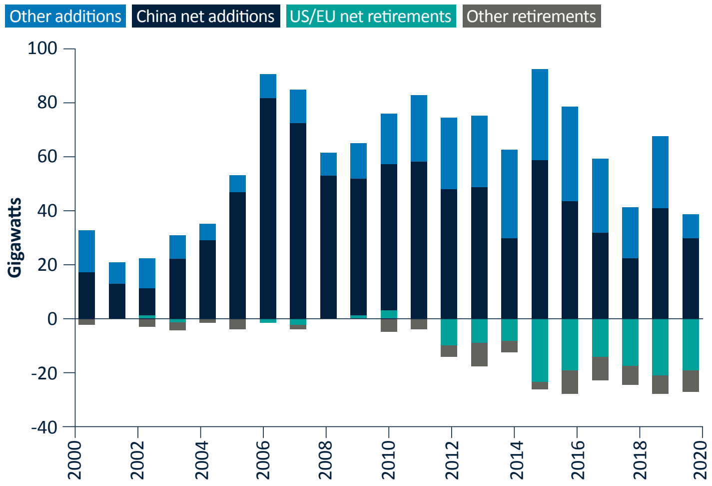
Why only 73% by 2040? Renewable energy's only application is to replace fossil fuels as a source of electricity. Electricity, as a share of final energy consumption on a global basis, is just 18%. The other 82% of energy usage is powered by burning fossil fuel for transportation, industry and heating homes, offices and factories. So the energy transition is mostly about replacing fossil fuels with electricity for these three major fossil fuel consumers. For this reason, the "Energy Transition" is often equated to the "Electrification of industry, transportation and buildings".

World fossil fuel demand has not yet peaked. Exhibit 4 below shows the path of coal net capacity additions are nearing zero but are still positive due to China's needs. Global coal consumption is projected to decline by 240 million metric tonnes from 2019 to 2025, but the IEA's projected increase for global natural gas consumption by 2025 of 390 billion cubic meters is 2.8x the decline in coal in energy (exajoule) terms. So, even if liquid fuels consumption peaked at 2019 levels, world fossil fuel demand has yet to reach peak levels due to the slow pace of coal reductions and the need for natural gas to supply growing consumption needs.

Global carbon dioxide (CO2) emissions from fossil fuels and industry have increased considerably since 2000, and in 2019 reached a record high of 36.7 billion metric tons of CO2. In 2020, the COVID-19 pandemic caused global CO2 emissions to plummet five percent to 34.81 billion metric tonnes. It is projected that emissions rebounded in 2021 as lockdowns eased.

Exhibit 4

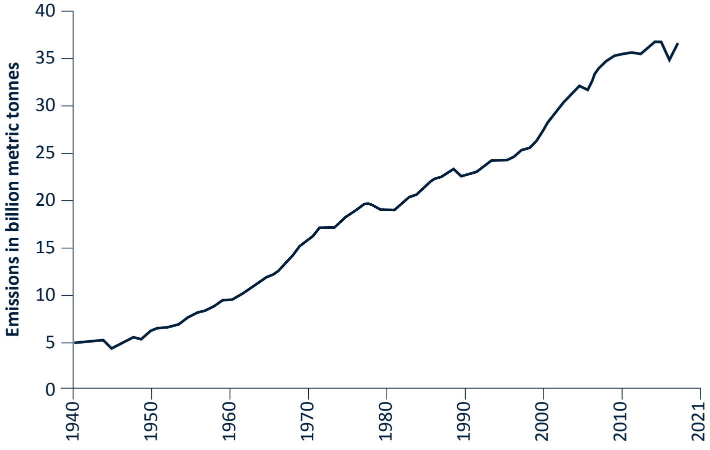
The path of net coal capacity additions are nearing zero but are still positive due to China's needs



Source: Centre for Research on energy and clean Air, February 2021

Exhibit 5

Covid caused CO2 emissions to fall by 5% but the energy transition has yet to have a more systemic impact



Source: *Statista 2022*

---

2 The Economist/The World Bank

3 Climate.gov

SECTION 1:
The Macroeconomics of the Greenhouse Gas Reduction

Question 1: What will be the biggest sources of emissions and emissions reduction?

The global greenhouse gases emitted by human activities are estimated to total 50 to 52B per annum: 38B from CO2, 8B from methane (CH4), 3B from nitrous oxide (N2O) and 1B from F-gases (see appendix for definitions and sources). Agricultural activities, waste management, energy use, and biomass burning all contribute to methane emissions. Focusing on the 38B metric tonnes per year of CO2 emissions, power generation and industry (steel and cement in particular) account for 62%, with transport, agriculture and building accounting for the rest. China, US and Europe account for 60% with China's emissions growing more than those of any other large country. India, Emerging Asia and Africa will also be crucial to any hopes of achieving net zero. Renewables are clearly the dominant contributor to emissions reduction between now and 2050, but success is also dependent on meaningful contributions from carbon capture, hydrogen, battery technology and increases in our natural sinks like forests.

Exhibit 6 illustrates that power generation (31%), industry (31%) and transportation (19%) represent the largest contributors to carbon emissions at present. Analysis from Goldman Sachs shows that in a scenario where global temperatures are kept below 1.5 oC of warming, the power generation and agriculture sectors are likely to make the most significant contributions to emissions reductions by 2030. This scenario would see global emissions decline by -29% (11.7B tonnes). It will, however, be far more challenging to remove emissions for heavy industry, transportation and buildings by 2030, as they will likely rely more on emerging technologies such as carbon capture and hydrogen which have yet to reach a cost effectiveness that is commercially viable. We discuss these emerging technologies in greater detail in the next section.

Exhibit 6
Power generation and industrial processes account for 62% of emissions and are expected to contribute to 64% of carbon reduction by 2030

2030 Scenario	Global CO2 Emissions by source 2022 (Billion tonnes)	Current % by source	CO2 Emissions Reduction Required (Below 1.5 Degrees warming scenario)	Expected % Reduction by source	% Contribution to overall reduction
Power generation	12.5	**31%**	7.5	-40%	43%
Industry & other	12.5	**31%**	10	-20%	21%
Agriculture	3.7	9%	0	-100%	32%
Transportation	7.5	**19%**	7.5	0%	0%
Buildings	4	10%	3.5	-13%	4%
Total Emissions	**40.2**	**100%**	**28.5**	**-29%**	**100%**

Source: *Goldman Sachs*

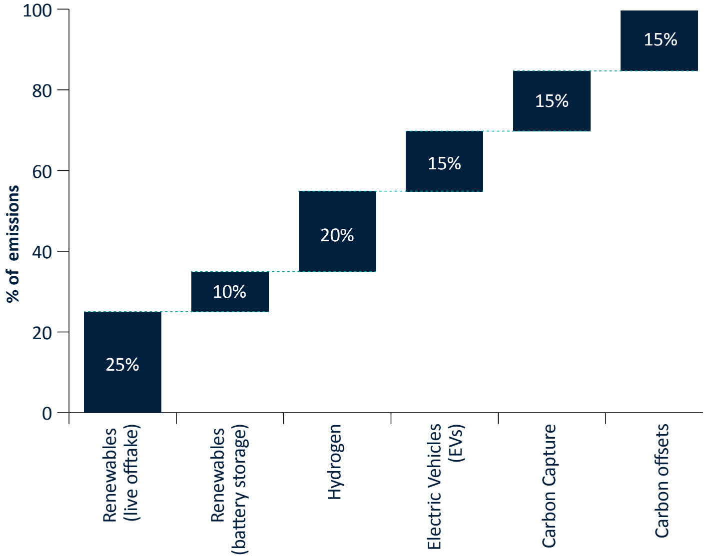
Exhibit 8 shows that the move to renewable energy and the continued move away from coal to natural gas and nuclear should allow the power generation sector to reduce emissions by -40% out to 2030 and to be fully carbon neutral by 2040. One of the more challenging aspects for the power generation sector is that demand for electricity is set to triple out to 2050, thanks to electric vehicle adoption and a growing income level in Asia and Africa.

Today, two decades into the renewable power revolution, wind and solar only supply approximately 2% of global energy demand. Currently, wind and solar can only reach about 20% of total energy demand as that is the proportion served by electricity today. 80% of energy is served mostly by the direct combustion of fossil fuels in vehicles, industry and buildings. Not until there is direct electrification of industrial processes, light and heavy vehicles and building space, will we be able to take wind and solar up to the 70% level required to achieve NZE as estimated by Goldman Sachs and others. Public acceptance of this level of buildout may be one of the primary hurdles for wind and solar given the huge proportion of land mass required to achieve this level of substitution (the EIP expect that usage of 7% of US lower 48 states acreage will be required). Transmission constraints are also a major hurdle due to the cost of upgrading the grid to safely add new wind and solar projects. It is our view, as we discuss later in this document, that we will see higher levels of nuclear and hydrogen sourced power, as a result of public acceptance hurdles surrounding wind and solar.

Agriculture and forestry has the potential to achieve carbon neutrality by 2030, according to Goldman Sachs, primarily through a combination of improved land use, agricultural practices and natural carbon offsets (planting trees).

Last year, the International Energy Agency (IEA) published their 222 page "Net Zero by 2050 – A Roadmap for the Global Energy Sector" report which is the research that Goldman Sachs, McKinsey, The Economist and Partners Capital refer to most for the answers to many of these questions. Exhibit 7 captures their answer to what will be the largest contributors to emissions reduction. The first major contributor that we know can happen is 25% from wind and solar's live offtake. From there, another 45% needs to come from storing wind and solar power generated when it is not needed; storage by way of large-scale storage batteries and hydrogen produced from excess wind and solar. We have to store even more renewable energy to keep up with the needs of electric vehicles (15%). Today almost no wind and solar is stored – less than 1/100th of a percent. There are serious technological and cost barriers to overcome. Carbon

Exhibit 7
Renewable energy is expected to do the initial heavy lifting in terms of carbon reduction supporting the abatement of c. 50% of global CO2 emissions by 2050



Source: *Economist, using estimates from the IEA, Journal of Cleaner Production, Energies 2021 "Short-, Medium-, and Long-Duration Energy Storage in a 100% Renewable Electricity Grid (Cardena, Swinfen-Styles, Rouse and Garvey), US Energy Information Administration (EIA)*

Note: *Figure for hydrogen will include renewable storage as well as industrial processes and heavy goods transportation* capture and sequestration technologies are expected by the IEA to account for 15% of the needed carbon emissions reduction, but that technology is also in its nascency. Finally, natural carbon offsets (such as forestry and conservation projects) are expected to account for the final 15% of carbon reduction.

The IEA estimate that approximately 45% of the target level of emissions reduction assumed in the Exhibit 7 is dependent on technologies not yet in the market, but which are under development. In particular carbon capture (including direct air carbon capture), electrification of industrial processes, hydrogen (in various forms including ammonia) and storage batteries to deal with the intermittent nature of wind and solar.

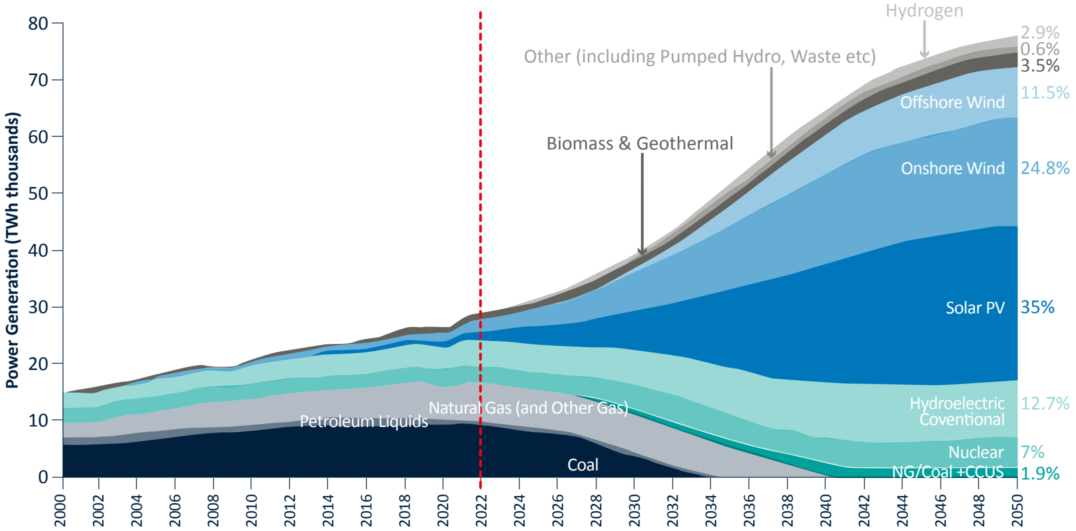
Goldman Sachs relies on this same IEA estimate which lays out what has to be true between now and 2050 to achieve zero net emissions. The IEA has laid out the path of wind and solar's growth to account for over 70% of total power generation by 2050 to achieve NZE. Between now and 2030, this anticipates a fourfold increase in wind and solar capacity globally from 230 GWs to over 1,000 GWs.

We should underscore that in 2020, before the IEA published its Net Zero by 2050 research used in Exhibit 8, its estimates for a "business as usual scenario" saw global energy consumption (not just electricity as shown Exhibit 8), forecast natural gas, oil and coal to still account for 80% of energy consumption in 2040, with just 15% from renewable energy. This underscores the extent to which we require anything other than business as usual.

Exhibit 9 displays the forecast from the US Energy Information Administration (EIA) for global emissions out to 2050 by country or region. The forecast is based on the current commitments or pledges by nations and their expected constraints, and it suggests that overall emissions will actually expand slightly out to 2050 (relative to 2020). This would be in line with an expected global temperature rise of 3.7°C (relative to pre-industrial levels) out to the end of the century. In this forecast scenario, Europe and the US will cut emissions by 30-40% out to 2050 (relative to 2020), China and developed Asia will see emissions contract slightly but emissions will increase significantly in India (+172%), other EM Asia (+95%) and Africa (+64%). The data also emphasises the crucial role that China in particular will play given that its emissions represent roughly 30% of total emissions today. One should also note that the EIA figure for total emissions as of 2020 (35B tonnes) is below the estimates provided by the Global Carbon Project (38B tonnes) and The Economist who suggest a range of 40-50B tonnes. This demonstrates the difficulty in accurately accounting for emissions.

Exhibit 8

Goldman Sachs forecast power mix out to 2050 to be 70% solar and wind



Source: *Goldman Sachs.*

Exhibit 9

Forecasted change in CO2 Emissions 2020 - 2050: India, Emerging Asia and Africa will be crucial to any hopes of achieving net zero

Regional CO2 Emission B Tonnes	% Share of current emissions	2020	2025	2030	2035	2040	2045	2050	% Change 2020 - 2050
China	31%	10.9	11.1	10.8	10.7	10.6	10.6	10.5	-4%
India	6%	2.1	2.9	3.4	4.1	4.8	5.5	5.8	172%
Developed Markets Asia	6%	2.3	2.3	2.3	2.2	2.2	2.1	2.1	-7%
US	15%	5.3	5.3	4.7	4.2	4	3.8	3.2	-40%
Europe	10%	3.6	3.7	3.4	3.1	2.9	2.7	2.5	-32%
LATAM	5%	1.7	1.9	2	2.1	2.2	2.3	2.4	45%
Africa	4%	1.3	1.4	1.5	1.7	1.8	1.9	2	64%
Emerging Markets Asia	7%	2.5	3	3.4	3.8	4.1	4.5	4.9	95%
Other	16%	5.5	5.9	6	6	5.9	5.8	5.7	4%
Total Tonnes CO2 (B)		**35**	**38**	**37**	**38**	**38**	**39**	**39**	**11%**

Source: *EIA*

This differential in the trajectory of emissions between developed and emerging nations underscores the importance of richer nations assisting developing nations in the energy transition. Almost one billion people across the globe still lack access to reliable electricity at present[4]. There is a strong relationship between per capita income and carbon emissions. The richest 10% of the world are responsible for roughly 50% of global carbon emissions. As nations develop, an increasing proportion of their emissions are derived from consumption as opposed to directly from industry. Attributing emissions between consumers and corporations is complicated and potentially pointless. Consumers emit CO2 by virtue of heating their homes and driving their internal combustion engine (ICE) powered cars. Power utilities supply the electricity to heat the home, energy companies supply the petrol and auto companies sell the cars. Consumers and companies are each responsible for emitting the same CO2. So we will not devote time to discussing who can make the biggest change, but ultimately we, as consumers, must change our behaviour and companies have to change what they produce. Around a third (37%) of historic emissions have come from publicly listed investor-owned companies (e.g., ExxonMobil, Shell, BP, Chevron, Peabody, Total, and

---

[4] UNICEF

BHP Billiton), 54% from state-owned companies (e.g., Saudi Aramco, Gazprom, National Iranian Oil, Coal India, Pemex, CNPC and Chinese Coal Energy), and 9% from private investment. Just 100 companies are responsible for 71% of global industrial GHG emissions (scope 1, 2 & 3 emissions)[5].

---

[5] Carbon Majors Report

Biggest unknowns:

- Given the pace of economic growth of many developing nations, along with their emissions, to what extent will energy affordability in the early years force them to carry on producing and consuming high CO2 emitting sources of energy (coal and natural gas)?
- Will the public accept the scale of wind and solar land appropriation required?
- Technology is a huge uncertainty, with c. 45% of the targeted global emissions reduction dependent on technologies not yet in the market.

Below:
China coal plant, Nanjing
Image: Alamy

Question 2: What level of investment is required?

In order to achieve net zero by 2050 experts, including the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), BloombergNEF and McKinsey estimate that getting to net zero emissions by 2050 will require an average annual capital expenditure of over $6T, which is $4T higher than recent (2017-20) annual capex spend on the transition. This level of investment represents an increase from being 2% of global GDP to over 6% going forward. Nearly $1T (22%) per year will be spent on retrofitting buildings. $625B (14%) will be required for the wind and solar buildout and $733B (17%) will be spent on the grid to accommodate more wind and solar.

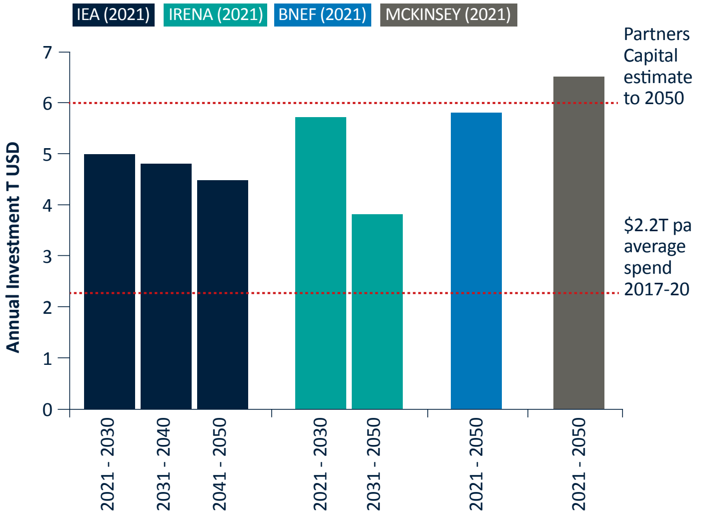
Our estimate of $4T of incremental required investment is skewed towards the high end of the range of estimates collected from the four sources shown in Exhibit 10.

The International Energy Agency (IEA) frontloads the necessary spending, estimating annual investments of $5.0T, $4.8T, and $4.5T in the 2020s, 2030s and 2040s respectively, or an average of $4.8T. The International Renewable Energy Agency (IRENA) estimate that total investment of $4.4T will be required. This is broken down as $5.7T per year until 2030 and then a reduced amount of $3.8T thereafter. Bloomberg New Energy Finance (BNEF) estimates average investment requirements will be $5.8T per year until 2050. McKinsey estimate a total spending of $6.5T on all physical assets using the Net Zero 2050 scenario from the Network for Greening the Financial System (NGFS) as illustrated in Exhibit 10.

It is anticipated by most forecasters that this average level of annual spending will be required out to 2050 with

Exhibit 10

Average annual global capital investment required ranges from $4.4T to $6.5T to reach net zero CO2 emissions by 2050



Source: *IEA, International Renewable Energy Agency (IRENA), BloombergNEF, McKinsey, Financial Times (all being 2021 research reports).*

a peak in spending around 2035-2036. IRENA's estimate of an annual average spend of just under $4.4T between 2020 and 2050, for a total investment of $132T, is one of the more prudent estimates of required spending. Their specific breakdown of the underlying areas of focus of this investment is shown in Exhibit 11. This shows the annual capex including the estimated $2.2T historical spend. The single largest investment (22% and nearly $1T per year) will be spent on building conversions/retrofitting to electric heating, insulation and other efficiency improvements. $625B/year (14%) is required for the wind and solar buildout. $733B (17%) annually is needed for converting the electricity network or grid to accommodate more wind and solar, including transmission lines and storage batteries. 12% will be required for fossil fuels and nuclear, which will continue to play a significant role during the energy transition. 8% will need to be invested in electrification of industrial processes, steel and cement in particular. Electric vehicles and charging networks are a relatively small investment, adding up to $131B or 3% of the total.

This analysis highlights how broad-based the energy transition will be across the global economy, highlighting the vast opportunity set for investors and the need for focus in certain areas given the unlikely prospect that any one investor could understand all the complexities in each of these sectors for investment.

Exhibit 11

Annual average investments by category to meet a 1.5°C scenario ($B/year)

Capex Category	Capex Sub-Category	Annual Average Investments ($B) (2021 - 2050)	% of total investment
Power Generation	Grids and flexibility (grid storage batteries)	733	17%
	Switch to lower carbon fossil, ongoing requirements	528	12%
	Wind Onshore & Offshore	389	9%
	Solar PV (utility and rooftop) & Concentrated Solar	321	7%
	Hydrogen - electrolysers and infrastructure	116	3%
	Biofuels - supply	87	2%
	Hydro - all (excl. pumped)	85	2%
	Renewables direct uses and district heat	84	2%
	Biomass	69	2%
	Marine	59	1%
	Hydrogen-based ammonia and methanol	45	1%
	Geothermal	24	1%
	Bio-based ammonia	22	1%
	Bio-based methanol	12	0%
	Total Power Generation	**2,574**	**59%**
Smart Buildings	Buildings Energy Efficiency	963	22%
	Heat Pumps for buildings	102	2%
	Total Smart Buildings	**1,065**	**24%**
Industrial	Industry Energy Efficiency	354	8%
	Carbon removals (CCS, BECCS)	65	1.5%
	Total Industrial	**419**	**9.6%**
Transport	Transport Energy Efficiency	157	4%
	Charging Infrastructure for EVs	131	3%
	Total Transport	**288**	**7%**
Recycling	Recycling and biobased products	25	0.6%
Total		**$4,371B**	**100%**

Source: IRENA; "World Energy Transitions Outlook: 1.5°C Pathway"

Biggest unknowns:

- The true cost of any of the components of the energy transition can only be rough estimates, especially given the fact that much of it is tied to technology that is yet to be proven commercially viable and that many components are early in the lives of their cost curves (e.g., what will the 2040 generation of solar PV cells and wind turbines look like?).

Question 3: Will the needed investment be made and who will pay for this?

In the next five years, governments are expected to finance 30% of this investment, households 10%, with companies (including financial institutions) financing the bulk of the cost, or 60%. It would appear that most of the governments of major emitters are committed to this transition and the money will be found. Ultimately, every household foots the additional $168T bill ($6T per year x 28 years). It will be paid through the prices we pay for everyday goods and services and via the taxes we pay for governments to invest in the transition. Increased government debt will have a role. But most of the capex cheques will be written by companies and governments. Individuals will be responsible for modifying their homes, but companies and governments will be modifying commercial buildings, building out renewable networks and investing in the required R&D. The source of investment in any given sector from across government agencies, large corporations, banks and private capital will have a major impact on the attractiveness of any given investment. Governments, in particular, can have perverse impact on the economics of any sector key to the energy transition – both positive (R&D on critical tech, subsidies) and negative (taxes and excess capacity buildout, R&D on competing tech). Private equity investors, in particular, need to pick their spots very carefully where their cost of capital makes sense, and where they bring unique skills.

We have already been paying c. $2.2T per year toward the energy transition as explained above. To fund the additional c. $4T households have to shift 4-5% of their current spending towards the cost of decarbonisation. Most will be legislated by governments who will have to be sensitive to the impact on low-income households, especially in low-income countries.

Affordability will vary significantly by country. China and the US should represent the greatest percentage of overall and incremental net zero infrastructure investment needs (in 2020, China emitted around 31% of global carbon dioxide, while the US emitted about 15%). To date, the fiscal initiatives proposed by governments have been underwhelming. The EU's green spending package (NextGen EU) is a package which is looking to mobilise roughly €1T of spending over the next decade. In the US, the November 2021 infrastructure bill provided just $73B of explicit spending on clean energy and the Build Back Better bill looks increasingly unlikely to become law.

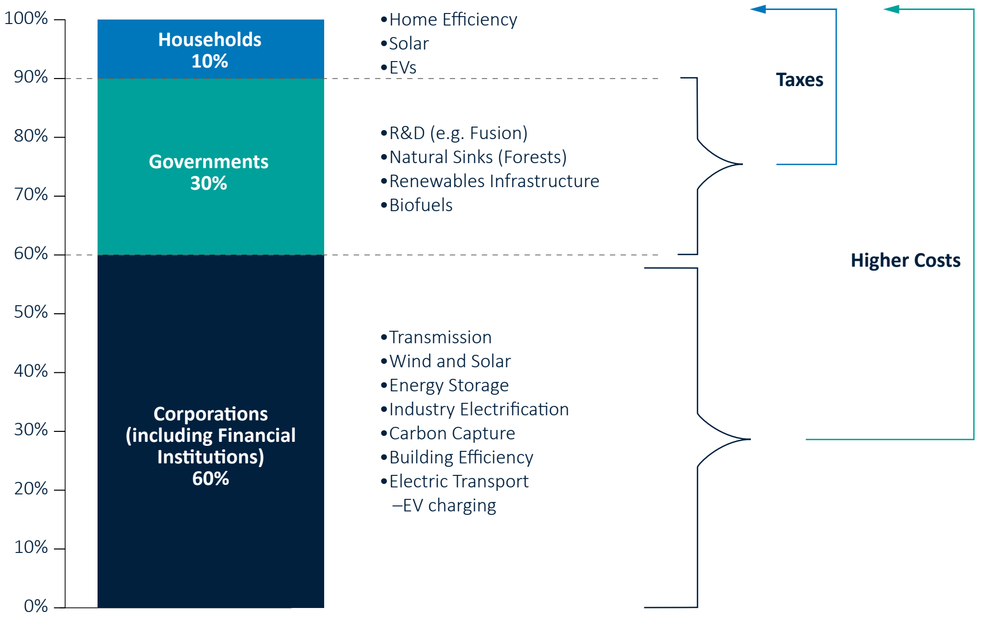
Emerging markets will approach decarbonisation on different timetables and with different migration plans. The International Energy Agency (IEA) estimates that all of the net growth in emissions will come from emerging markets over the next two decades. Coal is by far the cheapest and most abundant source of fuel in developing nations where the average age of coal mines is just 12 years in contrast to 43 years in more advanced economies[6]. The IEA suggests that coal mines have an average lifespan of 50 years meaning the implicit cost of decommissioning young mines and coal powered

---

[6] IEA

Exhibit 12

Who will pay for the energy transition?



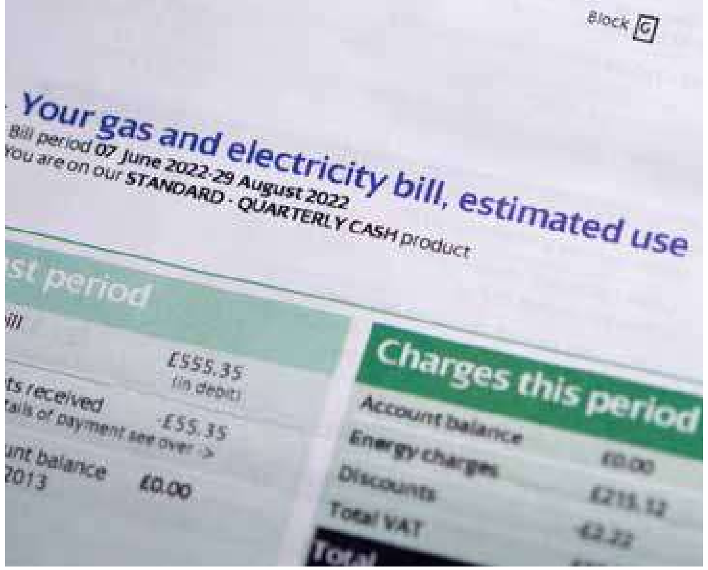
Source: *Partners Capital Vivid Economics based on IEA and additional modelling*

plants is very significant and will set back economic development in these regions unless replaced with an equivalent low-cost source of energy. In Europe and the US the solution that has garnered the most collective support is a carbon border adjustment tax, which policy makers believe will equalise the cost of carbon globally. Kenneth Rogoff, professor of economics at Harvard, argues that the developed world needs to offer incentives as opposed to punishing forms of taxation. He believes that concessional financing, a sharing of technical expertise and the establishment of a world carbon bank that facilitates transfers from advanced nations based on revenue from carbon taxation/credits should all be part of the solution[7].

In November of 2021, the UN Climate Change Conference published "Net Zero Financing Roadmaps" which provides some estimates of where the financing for $2.7T annual capital investment will come from in the next five years. This $2.7T represents the IEA's estimated incremental annual investment from 2021-25. As shown in Exhibit 12, 30% will come from public (governments, SOE, NGOs), 60% from private funding, primarily from public companies and financial funding institutions, and the final 10% from households. Carbon taxes will land in energy prices and in goods and services' prices the consumer pays which include the corporation's tax on its carbon footprint. So, as households, we pay via companies or the government. One can argue that it doesn't matter much what the mix is between governments footing the bill or companies, but it will matter to investment strategies as our asset managers need to understand how corporate earnings will be affected most. From an investor's perspective, the division of responsibilities and funding between government and corporations drives any given investment's success. A deep understanding of the source of funding into R&D, infrastructure and product manufacturing will be critical to investors and businesses being blindsided by perverse economic outcomes. But it will always be a source of huge uncertainty and risk, suggesting the returns must be extraordinary when a given business is in essence taking such risk.

We estimate that only $20B will come from private equity and venture capital each year, plus $60B from infrastructure funds. This is almost certainly understated. Campbell Luytens calculates that private fund managers are currently raising $183B to invest in climate solutions in 2021/22, which includes infrastructure funds. Regardless, Exhibit 12 makes a very critical point for private equity investors have to very much pick their spots where their capital and skills are uniquely suited and not try to compete with governments, large public companies and big banks with much lower return expectations and cost of capital.

Right:
Ultimately, users will pay for the energy transition
Image: Alamy

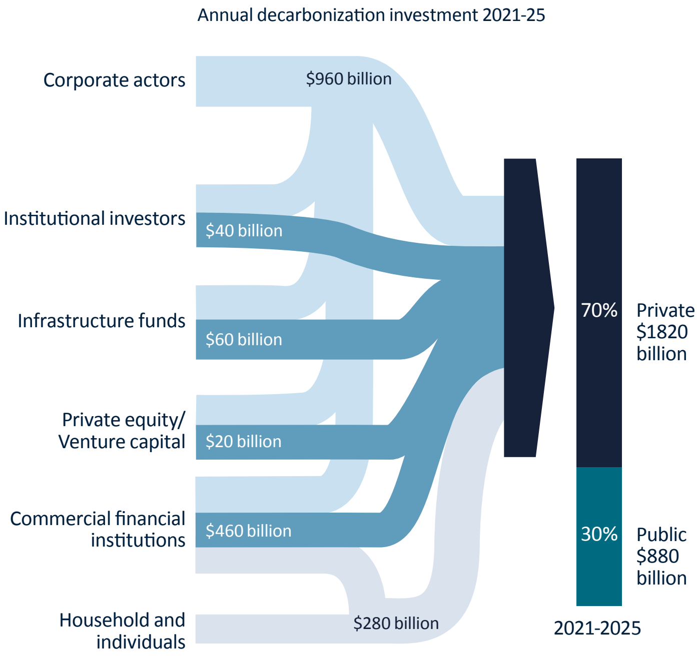


Biggest unknowns:

- Will consumers struggle to afford the rising cost of energy, curtailing the pace of the overall energy transition?

Exhibit 13

70% of funding for $2.7T annual capital investment in the 2021-25 period will be private funding primarily from public companies and financial institutions



Source: *Vivid Economics based on IEA and additional modelling*

---

[7] https://www.theguardian.com/business/2021/jan/07/developing-economies-need-a-fairer-way-to-help-them-decarbonise

Question 4: How will governments (regulators) drive the energy transition?

The jury is out on true government commitment, but the war in Ukraine has helped, given the increased importance of energy self-sufficiency and security. Many global policy makers have committed to NZE targets with timelines, but most have not put legal teeth into these targets to enforce households and corporations to make the needed investments. Ultimately, governments will be sensitive to the impact of the costs of the transition on households which may slow the transition. Regulators, such as the SEC in the US, are imposing reporting requirements which we expect to give positive momentum to corporate action. Governments are already funding significant R&D programs to support decarbonisation and are likely to increase such funding behind the most promising technologies that cannot get off the ground without this support.

Countries representing c. 70% of global carbon emissions (and 80% of global GDP), have announced net zero goals with countries representing approximately 12% of global emissions having officially codified it in law as illustrated in Exhibit 14. This includes the European Union and eight other countries. China, the world's largest emitter, has yet to formally submit a target but announced its intention "to achieve the peaking of carbon dioxide emissions around 2030" and to be carbon neutral by 2060. The US, the second largest emitter but the largest on a historic basis, has set a target of cutting net greenhouse gas emissions by 50% below 2005 (peak) levels by 2030.

In July 2021, the European Commission released its "Fit for 55 package", a set of policy proposals spanning all major sectors of the economy to achieve emissions reductions of at least 55% below 1990 (peak) levels by 2030.

Exhibit 14

Countries accounting for 70% of global emissions have made policy commitments to carbon emission targets but few countries have codified climate objectives in law

In Policy Document						**Proposed Legislation:**		**In Law:**		**Achieved:**
Finland	2035	Slovakia	2050	Malawi	2050	South Korea	2050	Germany	2045	Suriname
Austria	2040	Dominican Rep	2050	Maldives	2050	Ireland	2050	Sweden	2045	Bhutan
Iceland	2040	Panama	2050	Barabdos	2050	Chile	2050	European Union	2050	
US	2050	Costa Rica	2050	Andorra	2050	Fiji	2050	Japan	2050	
South Africa	2050	Uruguay	2050	Cape Verde	2050			United Kingdom	2050	
Italy	2050	Slovenia	2050	Grenada	2050			France.	2050	
Brazil	2050	Latvia	2050	Vatican City	2050			Canada	2050	
Switzerland	2050	Nepal	2050	Marshall Islands	2050			Spain	2050	
Argentina	2050	Laos	2050	Nauru	2050			Denmark	2050	
Norway	2050	Jamaica	2050	China	2060			New Zealand	2050	
Colombia	2050	Mauritius	2050	Kazakhstan	2060			Hungary	2050	
Portugal	2050	Monaco	2050	Ukraine	2060			Luxembourg	2050	

Source: *Goldman Sachs*

Left, above:
Climate Change Conference (COP26) in Glasgow 2021
Image: Alamy

Having provided a timeline, governments will utilise carbon taxation/credits (discussed in question 6), subsidies and investment support through R&D programmes to assist in the energy transition. Corporate financial reporting requirements will also play an important role.

Government supported R&D programmes have a strong track record of success. During the oil crisis of the 1970's, the US government targeted a drive to boost energy independence through investment in a collective research project between NASA, the Department of Energy, industry experts and other agencies. This drive resulted in many of the technologies that are being utilised today including the majority of the core components of modern solar/wind farms and horizontal fracking techniques. The US Department of Energy announced its Earthshots initiative in 2021, which is investing in technologies to take a billion tonnes of carbon out of the atmosphere each year. Similarly, the EU's NextGen EU initiative is a fiscal package which is seeking to mobilise €1T of spending on renewables over the next decade.

Beyond investments and subsidies, governments will implement punitive measures to deter emissions. This will include decisions about the breadth of industries covered by carbon taxation/credits and the associated costs of these taxes/credits. They will also look at other more explicit measures such as banning internal combustion engine (ICE) cars. The EU has already proposed banning ICE vehicles from 2035 and the UK will do so in 2030. The EU is also starting the process of eliminating so-called F-gases (HFC, PFC, SF6) and that trend is likely to spread, so any asset relying on these faces early obsolesce.

Environmental reporting regulations: Today, environmental impact reporting by corporations can be divided into those that are mandatory regulatory obligations and those which are voluntary frameworks. Currently, few jurisdictions are subject to regulatory mandated reporting obligations with companies more commonly reporting based on a patchwork of different voluntary standards. Our expectation is that we will witness a migration from voluntary standards to regulatory imposed frameworks in the coming years, starting in Europe.

The most notable first step towards regulatory imposed ESG reporting is the European Union's Non- Financial Reporting Directive which mandates around 6,000 large EU based companies (those with over 500 employees) to report on their policies in relation to environmental protection, treatment of employees, respect for human rights, anti-corruption and diversity on company boards.

The European Union has gone further with the introduction of the Sustainable Finance Action Plan, also known as the "European Green Deal", which is aimed at mitigating climate change, reducing pollution and protecting biodiversity. This includes a number of initiatives but, most notably, the introduction of an EU Taxonomy and the Sustainable Finance Disclosure Regulation (SFDR). The EU taxonomy provides a framework to classify whether a company's activities are contributing to and in alignment with the EU's six defined environmental objectives. As of early 2022, large European businesses are mandated to include in their non-financial annual report the proportion of their revenue and capital expenditure which is consistent with the six defined environmental objectives.

Outside the EU, the majority of companies who report sustainability metrics generally use one of the various voluntary frameworks including the TCFD (Task Force for Climate Related Disclosures), CDP (Climate Disclosure Project), GRI (Global Reporting Initiative) and the SASB (Sustainability Accounting Standards Board). There are a large number of organisations globally who have proposed reporting frameworks, but these four have become the most closely followed. In March of 2022, the US Securities and Exchange Commission proposed rules that require registrants to include certain climate-related disclosures in their registration statements and periodic reports, including "information about climate-related risks that are reasonably likely to have a material impact on their business, results of operations, or financial condition, and certain climate-related financial statement metrics in a note to their audited financial statements. The required information would include disclosure of a registrant's greenhouse gas emissions."

Biggest unknowns:

- Governments are the ultimate "wild cards" in the energy transition but are very much in the driving seat and need to be. How will each government act in recognition of what other governments are doing?
- What will be the pace of carbon taxation application across countries and industries including carbon border adjustment taxes?
- What are the most likely areas of government R&D investment behind technologies unblocking many aspects of the transition?
- What will be the pace of regulation banning ICE vehicles or forcing decommissioning's of fossil fuels extraction and production?

Question 5: To what extent will corporations drive the energy transition?

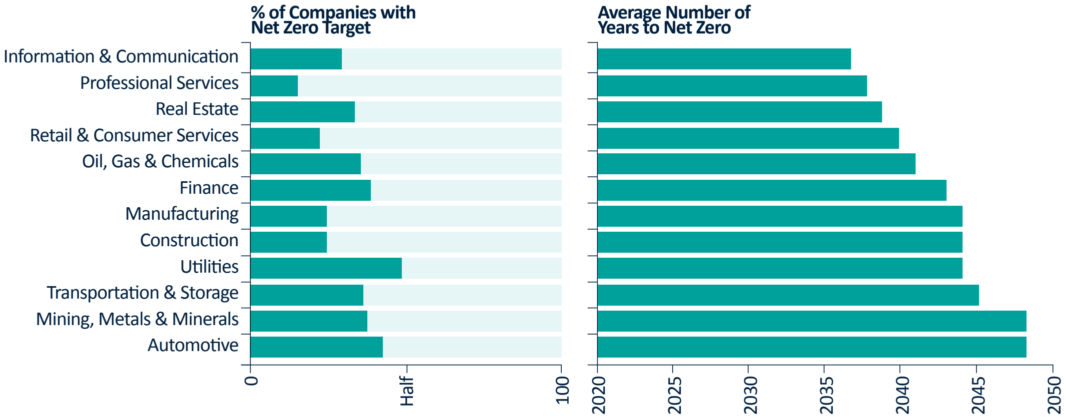
In just the last couple years, corporate commitments to net zero emissions have picked up steam. It is not clear to us that these companies have clear plans and the means for achieving such goals. We believe that companies will ultimately be guided by enforcement mechanisms such as regulatory curtailment of investment in high carbon emitting industrial modes (e.g., fossil fuel extraction, fossil fuel fired power plants, ICE vehicles, gas-fired industrial processes), carbon taxation, credits, subsidies or implicit investor driven carbon impact accounting which will see shareholders rewarding or punishing companies based on their practices. But confusion will reign as global coordination of regulations and other government actions is required to avoid effective subsidisation by one country taking advantage of another.

Mentions of net zero in corporate financial statements have increased by 5x in the last two years. 45% of the Russell 1000 constituent companies have committed to getting to net zero and c. 10% of companies have stated they will reach net zero by 2050 (see Exhibit 15). Outside of G7 nations this figure falls to just 6%.

What governments enact will have dramatic, almost existential implications for companies. But global standards are essential for government regulation of many sectors, so as to not create global losers by virtue of different regulation. This would seem to be a monumental task, getting governments to agree on carbon taxation, subsidies and mandatory transition timelines. Mary Schapiro, head of the secretariat of the Task Force on Climate-related Financial Disclosures, notes that "if carbon is priced and transparently reported, it will mean that some product lines for companies will become unprofitable, particularly if competitors

Exhibit 15

Thanks to the recent spate of corporate commitments, 45% of companies have net zero targets in place today



Source: *Financial Times*

are not applying the same standards".

Corporate spending will be driven by a confluence of factors including what governments are investing in or subsidising, what regulations shift the burden to them, and what shareholders are seeking. The largest investments will come from the energy sector (utilities and energy producers) and the transport sector. Many companies will be legally obliged to curb emissions via carbon credit/taxation schemes if they fall into scope but others may choose to voluntarily reduce emission through explicit actions or via carbon offset projects (discussed below).

Biggest unknowns:

- The pace and degree of global government regulatory coordination. We may be positively surprised as global standards are agreed sooner than expected or we may see a form of competition where governments seek to give their domestic companies an advantage.

Question 6: What role will carbon taxes and credits play?

Carbon credits, taxation and offsets are powerful mechanisms for influencing corporate behaviour, by economically motivating high carbon emitters to invest in lower or zero carbon alternatives. Today their application is limited, with Europe taking the lead. At present, 21.5% of all global carbon emissions are covered by a taxation scheme or an ETS (emissions trading scheme). Industry experts estimate that the annual value of carbon credits and offsets grew by 164% in 2021 to $851B. But, carbon taxation's application growth will be limited if carbon prices are not equalised on a global basis. Carbon border adjustment taxes are viewed as the solution to this problem and could rapidly affect international competitiveness of many traded commodities including steel, oil and agricultural products.

The common objective of carbon taxation, offsets or credits is to motivate companies to reduce emissions. Putting a price on carbon emissions has a company facing a trade-off of paying the tax or investing to reduce emissions. The higher the tax, the greater the investment. At present, taxation plays a relatively minor role in catalysing higher levels of investment. We define the current state of carbon taxation through credits, offsets and outright taxes below and then summarise where experts think taxation is going in the future.

Carbon credits are the "currency" of an Emissions Trading Schemes (ETS), which is used to tax high GHG emitting industries for their "excess" emissions. Regulators set a cap each year for companies whose emissions fall within the scope of the scheme. This cap on these emissions is expected to be reduced over time. If the company emits less than the cap in a given year, it earns "allowances" or owns credits it can sell. If it emits more than the cap, the company must buy credits from the companies holding such allowances or, if permitted under the scheme, purchase carbon offsets (detailed below). The credits are traded at a market-determined price per tonne of carbon emitted. There are 17 GHG emissions trading schemes that have been established globally, operating in 35 countries, including Europe, the US (state level), the UK, Canada, China, Japan and South Korea. The supply of credits is a by-product of just two inputs, the caps set by regulators and the emission levels of the regulated entities. If the cap is set too high, there is a surplus of credits generated with too few buyers, and prices are too low. If the cap is set too low relative to what companies can practically achieve within their emissions reduction programmes, then there is excess demand and prices will rise substantially.

Carbon offsets allow companies to invest in approved carbon reduction projects which enable them to offset any carbon emissions for which they are responsible. The assumption of carbon offsets is that all emissions are equal and can be anywhere in the world. A company can invest in a project anywhere in the world to offset their domestic emissions. Carbon registries or carbon exchanges, such as the American Carbon Registry, will establish a set of rules for projects to meet before they can be listed for sale on the exchange. Once listed, carbon emitting companies can then purchase or invest in these projects which in theory allows them to neutralise their carbon impact.

There are four main types of carbon offset projects:

1) Forestry and conservation. Credits are created based on either the carbon captured by new trees or the carbon not released through protecting old trees.
2) Renewable energy projects
3) Community projects to introduce energy-efficient methods or technology to undeveloped communities, and
4) Waste to energy projects which usually involve capturing methane and converting it into electricity.

The carbon offset market is predominately utilised by companies who fall outside of the scope of taxation or ETS schemes where adherence is voluntary. However, schemes such as the EU's ETS allows mandatory participant companies to purchase carbon offsets, which they refer to as "international credits", as part of their obligations under the scheme. The market value for these offsets is estimated to have reached $6.7 billion at the end of 2021, according to a September report from Ecosystem Marketplace.

Carbon tax is a government or state mandated tax that sets a price on emitting a tonne of carbon. The key issues for a carbon tax are what emissions and industries are covered by the tax and the point of taxation. For instance, the simplest approach, which would see the tax applied to the fewest entities, would be an "upstream" tax that is applied to the suppliers of carbon such as coal, natural gas and oil refineries. Sweden has one of the world's oldest carbon tax systems which was introduced in 1991 and currently has the world's highest tax rate at roughly $120/tonne of carbon emitted. In 2020, only $25B of carbon taxes were collected by governments, with France being the highest ($9.6B), followed by Canada, Japan, Sweden and Norway. In the US, carbon taxes have failed to gain much traction.

What are the issues with carbon taxation/ credits and offsets?

Coverage: At present, just 21.5% of all global carbon emissions are covered by a taxation scheme or an ETS (emissions trading scheme/ carbon credits). At a global level, power generation and heavy industry are the most widely covered but transportation, agriculture and buildings have yet to be brought into scope in a meaningful way. Data from the world bank suggests that carbon initiatives (taxes or ETS's) are in place or in the process of being implemented in 45 national jurisdictions. The EU is the world leader with roughly 40% of its emissions currently included in the ETS. They also intend to expand this coverage to include shipping, buildings and agriculture in the coming years. In the US, twelve states that represent 25% of the US population and 33% of US GDP have carbon pricing initiatives (taxes/credits) in place. China, the world's largest emitter, launched the world's largest ETS in

Below:
A commercial carbon offset project producer, Northallerton's Make it Wild, plants trees in Yorkshire, UK
Image: Make it Wild

July 2021, however analysts note that its present scope is extremely limited.

Consistency of pricing and carbon leakage: Perhaps the most significant issue is a lack of consistency in carbon pricing. As of February 2022, the cost of a tonne of carbon (based on respective ETS) in Europe is roughly $100. In China, the figure is closer to $10 and in California a tonne of carbon costs $35 [8].

The differential in carbon pricing leads to domestic companies exporting their carbon production needs overseas to locations that have a cheaper carbon price or are not covered by a carbon pricing scheme, a process known as carbon leakage. In the UK for example between 1990 and 2016, domestic emissions fell by more than 40% but emissions associated with imports (embedded emissions) rose by 15-20% over the same period . This issue has prompted concern in Europe about a hollowing out of industry, particularly in the steel sector which is covered by the EU ETS. European steel makers have suggested that they cannot compete with their counterparts who do not face the same equivalent carbon costs. They argue that, as a result of this price differential, the end consumer of steel will in effect choose to "export their emissions" from Europe. In response to these concerns, the European Commission's latest policy proposal includes a "carbon border adjustment mechanism (CBAM)" which would in effect price imported goods based on their embedded emissions. This will not come into full effect until 2030 however. An associated issue is measurement. Companies that fall outside the scope of ETS/taxation schemes (which have voluntary adherence) will usually self-report and it is very difficult to assess the accuracy of their true carbon footprint.

Validity of carbon offsets: The most significant issue with these projects is that the environmental benefits are often not what they seem. An investigation by Bloomberg news looked at carbon offset projects being offered by the Nature Conservancy, a high profile environmental group, and found that they appear to have been re-selling offsets based on the same projects on multiple occasions. The analysis also found that market participants were incentivised to create a high frequency of projects at a depressed price.

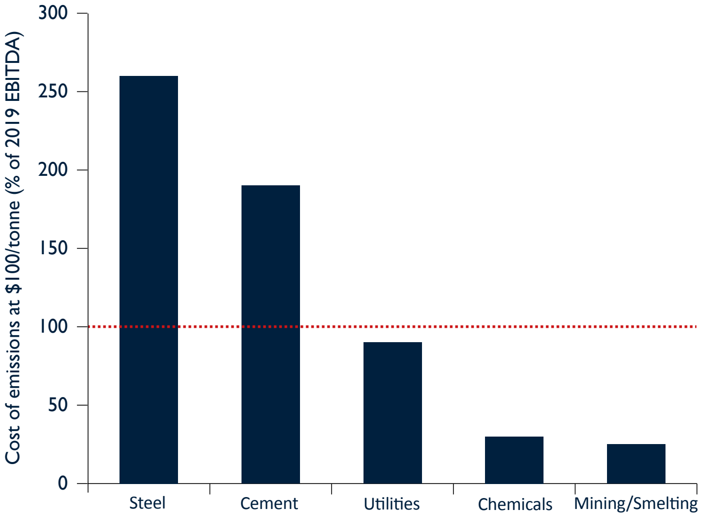
Corporate/Household impact: Lastly there is the direct impact of pricing on corporations and consumers. Exhibit 16 shows, at a corporate level, how significant an impact this would have on profitability if emissions were priced globally at $100/tonne. The steel and cement industries would become loss-making given their current margins.

Clearly, this will not be the outcome. Rather, companies will have to pass cost increases on to consumers but will only succeed if all industry participants are subject to the same cost increases. This, once again, underscores the importance of a carbon border adjustment mechanism (CBAM). The IMF has estimated that household electricity bills would rise 43% on average over the next decade if carbon was taxed appropriately. Equity portfolio managers, today, need to contemplate how carbon taxation will affect the valuation of every company, as carbon taxes are gradually extended to apply to all industries.

What does the future hold for carbon pricing? In a 2019 study, Nicholas Stern and Joseph Stiglitz, two noted economists, suggested that it would require a carbon price in the range of $40-80/

Exhibit 16

Many companies across industries would theoretically go into significant losses if the cost of annual carbon emissions reduction is $100 per tonne



Source: *Financial Times*
Note: *Applies $100 cost to all emissions in 2019 and displays as a percentage of 2019 EBITDA (based on EU companies)*

---

8 Bloomberg
9 https://www.theguardian.com/environment/2020/apr/16/britain-climate-efforts-undermined-failure-imports-carbon

10 https://www.imf.org/external/pubs/ft/fandd/2021/09/five-things-to-know-about-carbon-pricing-parry.htm

tonne levied on all the world's industrial greenhouse-gas emissions to prevent global temperatures from rising by more than 2°C (relative to pre-industrial levels) by 2050. The IMF have also estimated that the average price of carbon required to achieve this goal is roughly $75/tonne. In late 2021, the average price of carbon on the world's ETS schemes was just $3/tonne[10] and as mentioned above just 21.5% of global emissions are currently covered by taxation or an ETS scheme. Despite the lack of coverage and a price level that would appear inadequate, the value of global markets for carbon rose significantly in 2021. Refinitiv estimate that the annual value of carbon credits/offsets grew by 164% in 2021 to $851B. The EU's ETS accounted for roughly 90% of the global ETS market value at $760B with prices surging in Europe as a result of a more ambitious climate policy in the EU and soaring natural gas prices, which prompted a switch to coal which requires a higher amount of carbon credits.

McKinsey estimates that the demand in the market for voluntary carbon offsets could increase by a factor of 10 or more by 2030 and up to 100x by 2050. They estimate that the global market for voluntary carbon credits could be worth upwards of $50B by 2030[11] from roughly $6-7B today. BloombergNEF suggest that the voluntary market could be as large as $550B by 2050. From a taxation perspective, the EU expects to raise roughly €10B per year from their proposed carbon border adjustment tax once it is fully operational in 2030[12]. This border tax would initially be limited to imports of iron, steel, cement and fertilisers but will likely be expanded in the future. Similar legislation proposed by the Democrats in the US estimated raising $16B annually from a carbon border tax[13].

The effect of carbon taxes could be greater within a sector across companies than across sectors. In each industrial sector, there are a set of assets that are in the bottom quartile of carbon intensity that are at the greatest risk of being stranded. For example, some oil fields produce oil with 5-10Kg of greenhouse gas emissions (ghge)/barrel and others produce at 200kgs ghge/bbl with the mean for the oil industry at 50kgs ghge/bbl. The 200kg ghge assets will become unfinanceable and highly vulnerable to regulatory shut down. The same phenomenon is true in steel, cement and aluminium.

Similarly, there are a set of assets coming up for major investment decisions that merit close scrutiny. According to Matt Rogers of McKinsey's energy practice, some 40% of the steel plants in the world face a $1B+ decision in the next eight years on whether to rebuild their blast furnaces or shift to Direct Reduction Iron (DRI) through a process which produces steel using green hydrogen and uses an Electric Arc Furnace (EAF) production method or to hydrogen on its own. This would transform the profitability of the industry along the lines of that indicated in Exhibit 16.

Biggest unknown:

- To what extent will we see effective international coordination on environmental policies? More specifically, will carbon border adjustments unlock the potential for expanded application of carbon taxation, which could accelerate corporate investment in low or zero emission alternatives?

---

[11] https://www.mckinsey.com/business-functions/sustainability/our-insights/a-blueprint-for-scaling-voluntary-carbon-markets-to-meet-the-climate-challenge

[12] https://www.ft.com/content/7a812f4d-a093-4f1a-9a2f-877c41811486

[13] https://www.nytimes.com/2021/07/19/climate/democrats-border-carbon-tax.html

SECTION 2: Technological Enablers for Greenhouse Gas Reduction

Question 7: What likely technological breakthroughs will contribute most to emissions reduction?

We believe that a solution to long term, large quantity renewable energy storage is the most significant hurdle on the path to achieving net zero. Continued improvements in existing storage battery technologies (e.g., lithium-ion batteries) will be commonplace during the transition. Achieving commercial scalability on newer technologies such as Compressed Air Energy Storage (CAES) and green hydrogen will be potentially more important than battery storage. Green hydrogen is a likely feature of this future, but it will take time to achieve this at scale. There are some "moon-shot" projects, requiring major government funded R&D, such as low-cost direct air carbon capture (DACC), nuclear fusion and small modular nuclear fission reactors that have the potential to change the path to NZE.

In his book, "How to avoid a climate disaster", Bill Gates provides a list of the technologies that he believes are crucial to making the transition to net zero emissions, which are listed 1 to 18 below. We have added four more which deserve mention which will attract our attention in future editions of this document.

Omitted from this list are electric vehicles and the charging station infrastructure required. In this section we look specifically at the six technologies which we believe will have the greatest impact on decarbonisation including 1) electric vehicles, 2) renewable energy (largely wind and solar), 3) green hydrogen, 4) carbon capture, 5) nuclear and 6) battery storage technology. While there are too many moving parts to say with certainty which technologies will be the true game changers, we do believe that there is high potential in these six.

Technologies needed

1. Green Hydrogen
2. Grid-scale electricity storage that can last a full season
3. Electrofuels
4. Advanced biofuels
5. Zero-carbon cement
6. Zero-carbon steel
7. Plant-and cell-based meat and dairy
8. Zero-carbon fertiliser
9. Next-generation nuclear fission
10. Nuclear fusion
11. Carbon capture (both direct air capture and point capture)
12. Underground electricity transmission
13. Zero-carbon plastics
14. Geothermal energy
15. Pumped hydrothermal storage
16. Drought-and flood-tolerant food crops
17. Zero-carbon alternatives to palm oil
18. Coolants that don't contain F-gases
19. Super conducting transmission/distribution to increase grid capacity
20. Low-cost graphene for greater battery density and solar efficiency
21. Long duration heat storage
22. Farming innovations to cut methane (e.g., rice and ruminants)

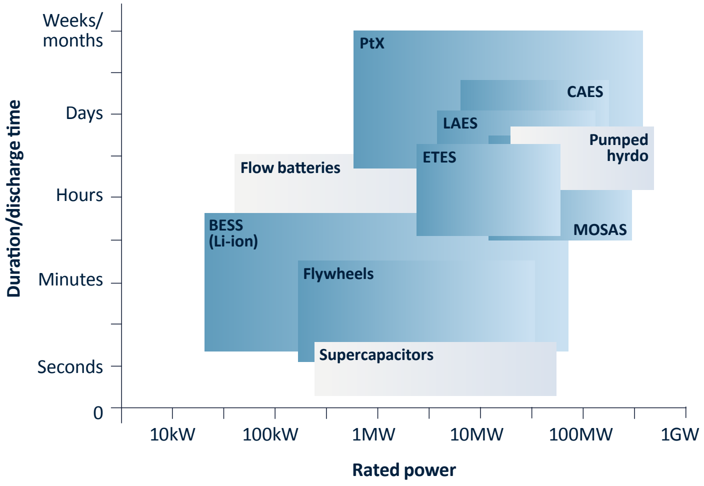
Storage Technologies. Renewables sourced energy is estimated to be able to only supply up to 25% of electricity needs from its live offtake (i.e., without any storage) due to its intermittency. Exhibit 17, we show different technologies with different storage duration/ discharge times and rated power that are currently being deployed or experimented with to solve the problem of intermittency. The range of discharge times can be divided into four main categories:

(I) very-short-duration storage (<5 mins), arguably handled best by flywheels and supercapacitors;
(II) short-duration storage (5 min–4 hrs), which is dominated by electrochemical batteries such as Lithium-ion;
(III) medium-duration storage (4–200 hrs), where thermo-mechanical solutions such as CAES comprise the main options; and
(IV) long-duration storage (>200 hrs), which will require by far the largest storage capacity and is mainly achieved by storing fuels such as hydrogen, ammonia or bio-gas.

We define a few of these below but spend the most of our discussion on lithium-ion batteries and green hydrogen.

Exhibit 17

There are a wide array of current technologies in development to solve the problem of energy storage with certain technologies more cost effective for different discharge timeframes



Source: *MAN Energy Solutions marketing materials (Germany)*

Flywheel energy storage (FES) works by accelerating a rotor (flywheel) to a very high speed and maintaining the energy in the system as rotational energy. Cost effective for storage under 5 minutes.

Supercapacitors (SCs) are energy storage devices that bridge the gap between batteries and conventional capacitors. They can store more energy than capacitors and supply it at higher power outputs than batteries. These features, combined with high cyclability and long-term stability, make SCs attractive devices for energy storage, usually for discharge times of under 5 minutes. SCs are already present in many applications, either in combination with other energy storage devices (mainly batteries), or as autonomous energy sources.

Compressed air energy storage (CAES) uses surplus energy to compress air which is then stored in an underground reservoir. The compression of the air generates heat. The air can be released to a combustor in a gas turbine to generate electricity. Unfortunately, large-scale CAES plants are very energy inefficient. Compressing and decompressing air introduces energy losses, resulting in an electric-to-electric efficiency of only 40-52%, compared to 70-85% for pumped hydropower plants, and 70-90% for chemical batteries.

Pumped Hydropower (or pumped-storage hydroelectricity or "PSH"). Water is pumped from a lower elevation reservoir to a higher elevation reservoir. Low-cost surplus off-peak electric power or excess renewable power is typically used to run the pumps. During periods of high electrical demand, the stored water is released through turbines to produce electric power. Although the energy consumed in the pumping process make the plant a net consumer of energy overall, the system generates net positive revenue by selling more electricity during periods of peak demand, when electricity prices are highest. Pumped storage is by far the largest-capacity form of grid energy storage available today, and, as of 2020, the United States Department of Energy Global Energy Storage Database reports that PSH accounts for around 95% of all active energy storage installations worldwide, with a total installed throughput capacity of over 181 GW, of which about 29 GW are in the United States, and a total installed storage capacity of over 1.6 TWh, of which about 250 GWh are in the United States. The main disadvantage of PSH is the unique nature of the site required, needing both geographical height and water availability.

To help decipher Exhibit 17, we define the abbreviated names for each storage technology but will not take the time here to discuss these.

BESS Battery energy storage system (Li-ion batteries)
ETES Electro-thermal energy storage
LAES Liquid air energy storage
MOSAS Molten salt energy storage
PtX Power-to-X (hydrogen, synthetic natural gas, synthetic liquids)

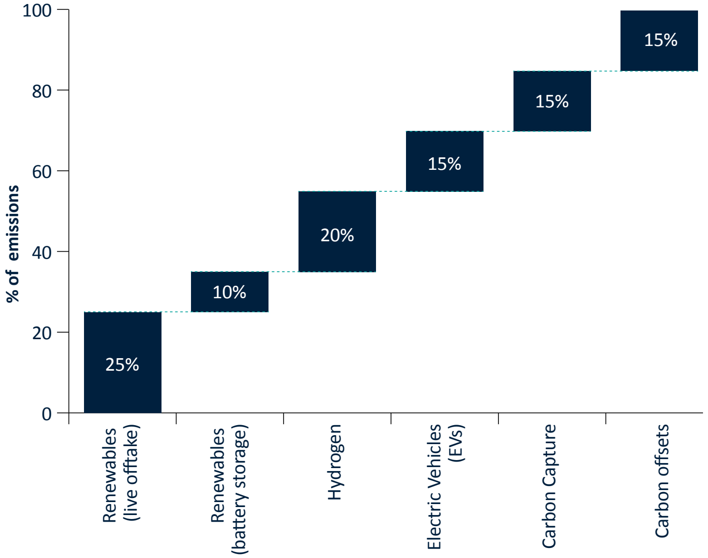
This array of alternative storage technologies highlights the uncertainty around how sustainable or large any one technology will be. For some helpful insights on alternative storage technologies, we refer you to a very thorough November 2021 research report by Energis called "Short-, Medium-, and Long-Duration Energy Storage in a 100% Renewable Electricity Grid: a UK Case Study". Their report overlaps with McKinsey's Long Duration Energy Storage (LDES) report which we summarise below in response to question 9 on battery storage.

The current level of energy storage is nascent. The US Energy Information Administration (EIA) reports only 27GWs of power discharged from stored energy sources in 2021, out of a total of 1,137 GWs of power produced in the US (2.4% of power is pulled from stored sources). 23GWs is from pumped hydroelectric (wind and solar powered water is pumped uphill, only to be released when needed through hydroelectric power generators). Only 4GWs of power was pulled from batteries in the US in 2021. The EIA in their Annual Energy Outlook 2021 has forecast US Power Capacity will grow to 1,700 GWs by 2050 from the current 1,137GWs by which time they expect 15% or 260 GWs to be drawn from stored sources (e.g., hydrogen, batteries, CAES, etc).

While the future is very difficult to predict, we refer back to (Exhibit 18), to illustrate how much of the heavy lifting must be done by **renewable energy.**

Exhibit 18

Renewable energy is expected to do the initial heavy lifting in terms of carbon reduction supporting the abatement of c. 70% of global CO2 emissions (once EVs have achieved 70% penetration, and battery and hydrogen storage mediums have enabled 30% additional use)



Source: *Economist, using estimates from the IEA, Journal of Cleaner Production, Energies 2021 "Short-, Medium-, and Long-Duration Energy Storage in a 100% Renewable Electricity Grid (Cardena, Swinfen-Styles, Rouse and Garvey), US Energy Information Administration (EIA).*
Note: *Figure for hydrogen will include renewable storage as well as industrial processes and heavy goods transportation*

Wind and solar power must ultimately be the source of c. 70% of global CO2 emissions reduction (once EVs have achieved 70% penetration, and battery and hydrogen storage mediums have enabled 45% additional wind and solar power use – including 15% to power EVs). This presumes that wind and solar continue down a steep efficiency and cost curve, unhindered by geographic roll out. We address that issue in question 13 below. Experts believe that new **carbon capture technologies** may be able to capture up to 15% of today's emission levels by 2050. Enlargement of natural **carbon offsets** (natural sinks) may reduce emissions by another 15%. There is no technology involved here as the carbon sinks are defined as anything, natural or not, which absorbs more carbon from that atmosphere than it releases. This 15% reduction is the estimate of the maximum practical net increase in carbon absorbing vegetation. **Hydrogen technology** is believed to have the potential to eliminate 20% of current emissions with the remaining 10% of emissions reduction targeted through advancements in other technologies such as **storage/ battery technology.**

The projected flow of state investment has helped to guide us to the trends and potential winners in these spaces. The EU for its part has focused in on hydrogen technology with 80% of the global active green hydrogen projects taking place within the union and a stated goal to make hydrogen 14% of the power mix by 2050 from less than 2% today. China has in the last decade become dominant in renewable wind and solar infrastructure as well as battery technology, but one of China's key points of differentiation is its ambitions in nuclear. China has tilted aggressively towards nuclear, planning at least 150 new reactors in the next 15 years, more than the rest of the world has built in the past 35 years. Current projections suggest China will surpass the US as the world's largest generator of nuclear power as early as the middle of this decade. Experts believe that nuclear could represent up to 16% of China's energy mix from a base of just over 1% today[14]. The Economist notes that the US by contrast "has to date offered no comprehensive outline of the goals and strategies it will use to tackle greenhouse-gas emissions" despite having re-joined the Paris Climate Accord. The White House's Green Energy fact sheet, released in 2021, provides a target and a timeframe for emissions reductions and name checks emerging technologies but fails to pin down any specific area of focus.

---

14 Cornerstone Macro

Below:
Japan, Dam, Hydroelectric Power
Image: istock

Biggest unknowns:

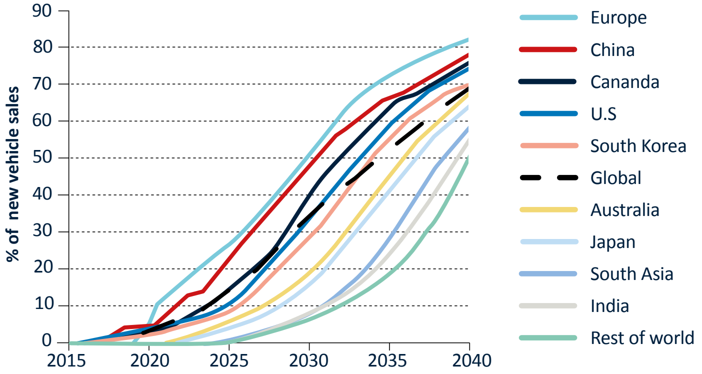
- Upsetting our assumptions above could be "moon-shot" breakthrough technology that comes about from the sheer weight of a combination of government and private capital being invested and are game changers like direct air carbon capture, nuclear fusion, or small modular nuclear fission reactors.

Question 8: What will be the pace of electric vehicle (EV) substitution of petrol-powered vehicles around the world?

The transport sector accounts for approximately 19% of total CO2 emissions today. 75% of this is road transport, 13% aviation, 11% maritime and 1% rail. Accordingly, the successful transition from petrol fuelled internal combustion engine (ICE) powered vehicles to electricity powered vehicles is one of the most critical components of the energy transition pathway. The combination of regulation, policy incentives and falling battery costs are expected to see EVs accounting for more than 35% of global auto sales by 2030 and over 70% of sales by 2040 as you can see in Exhibit 19. While the supply and cost of raw materials and the scale of the charging infrastructure buildout may create headwinds, it is expected that explicit policy actions, consumer demand and battery chemistry innovations will enable these targets to be met.

Exhibit 19

EV share of new passenger vehicle sales gets to 70% by 2040



Source: *BloombergNEF using Economic Transition Scenario in the 2021 Electric Vehicle Outlook (EVO)*

Forecast of EV penetration:

EVs represented just 0.1% of all global vehicle sales ten years ago. In Q4 2021, 20% of all sales in China were EVs, 17.5% in Europe and 5% in the US[15]. For the world to reach net zero CO2 emissions by 2050, the International Energy Agency estimates that electric models need to make up 60% of global car sales by 2030. BloombergNEF estimates that the world will fall short of this target however with EV sales reaching 35% of total vehicle sales by 2030 and 70% of total vehicle sales by 2040.

The forecasts in Exhibit 19 show that Europe and China will lead the way with adoption thanks to a mix of regulation and subsidies. In Europe, the sale of ICE vehicles is expected to be banned by 2035. In the UK, this will happen by 2030. The US will initially lag Europe and China due to less explicit policy support, but adoption is expected to accelerate as charging infrastructure is built out and a greater selection of EV models become available post 2025. Adoption in India and the rest of the world will take longer with little in the way of policy support and ICE vehicles being offered at a far lower price point.

Electric Vehicle Range. One of the most commonly cited reasons for not owning an EV is "range anxiety" which is effectively a fear that EVs have very limited driving range

---

15 BloombergNEF

and sparse public charging infrastructure. Several Teslas now have a range of over 300 miles. Most new EVs today go for 200+ miles on one charge. In 2022, the average EV range is estimated to be 275 miles and by 2028, 400 miles. Researchers at Samsung say that using silver-carbon in new solid-state battery packs will allow EVs to have a range of over 500 miles and will last for over 1,000 recharges. Elon Musk said that people don't really need more than 400 miles of range and, hence, Tesla cancelled their Model S Plaid+ which was advertised as having over 520 miles of range. This gave Lucid Motors the opportunity to be the only automaker with an electric car with over 500 miles of range today. However, Lucid is having issues ramping up the Lucid Air, but has sold 300 cars to date, most in the 4th quarter of 2021.

Charging infrastructure. The pace of EV charging infrastructure network roll-out will determine whether the BNEF penetration estimates shown above will be achieved. For EVs, there are different types of charging stations that take different amounts of time to provide a charge. Level 1 charging stations are the equivalent to the outlet one uses to charge a phone and can add 5 miles of range per hour of charge, requiring two days to complete a charge for a vehicle with 240-mile range. Level 2 stations use a higher voltage outlet and add about 35 miles of range per hour of charge, or 7 hours for 245 miles of range. These charging stations are typically used by EV owners at their homes or in parking lots. DC fast chargers use a much higher voltage and can add up to 240 miles range for an hour of charge. DC fast chargers are typically used on a long trip by EV drivers when they are in need of a rapid charge. 80% of EV drivers primarily utilise level 1 or level 2 chargers and the average driver accesses a DC fast charging just six times per year.

The Economist estimates that as EV ownership broadens by 2040, around 60% of all charging will need to take place away from home, requiring a vast public network of charging stations. As EV penetration increases, the network of these stations will have to be built out considerably. A study by the National Renewable Energy Laboratory estimates that 3.4 DC fast charging points and 40 level 2 charging ports are needed per every 1,000 EVs. Assuming a 35-40% penetration rate for EVs by 2030 they estimate that the US will need to build 50,000 DC fast charging stations and 1.2m level 2 charging stations. This equates to adding roughly 400 EV charging stations per day which is a 10x increase on the 40/day that have been added over the last 10 years. At a global level, the economist estimates that we will need 40m charging stations by 2030 and 200m by 2050. Regulation and policy is expected to help support this rollout with explicit EV infrastructure spending allocated in the US, the EU and the UK. America's infrastructure law sets aside $7.5bn to create 500,000 stations by 2030. The UK, in November 2021, introduced legislation that required new homes and offices to be fitted with charging stations for electric vehicles.

Raw Materials. EVs are expected to be a significant incremental demand driver for copper as they require four times as much copper as a traditional ICE power vehicle. The batteries in EVs require lithium, cobalt and nickel as their core components and demand for these metals is expected to increase by 10x and 5x, respectively out to 2030. BloombergNEF estimates that by the end of the decade new battery chemistries using more manganese will become prevalent to reduce pressure on nickel supply. Lithium and cobalt mining and refining capacity is believed to be sufficient for the 2020s and 2030s, but new manganese salt production capacity will need to come online to avoid a supply crunch.

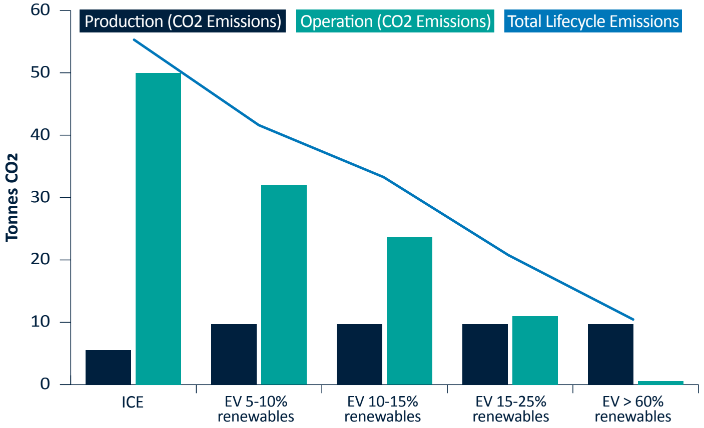
Carbon breakeven analysis:

Analysis from McKinsey suggests that the CO2 created when producing an EV is about 80% higher than when producing a traditional internal combustion engine vehicle as illustrated in Exhibit 20. A study by Volvo in late 2021 arrived at a slightly lower estimate of 70% greater than an ICE vehicle. The majority of this increase in CO2 emissions is attributed to the battery manufacturing process. The battery requires the input of raw materials that must be mined and smelted. Amounts vary depending on the battery type and model of vehicle, but a single car lithium-ion battery pack (of a type known as NMC532) could contain around 8 kg of lithium, 35 kg of nickel, 20 kg of manganese and 14 kg of cobalt, according to figures from Argonne National Laboratory. Analysts estimate between 5 and 15 tonnes of CO2 are produced per tonne of lithium extracted, suggesting that each EV produced, generates 80 kg of CO2 from the lithium in the battery alone. But this is a small fraction of the estimated 9 tonnes of Co2 that is estimated to be generated in the production of the average EV vs. 5 tonnes of CO2 for the average ICE vehicle as you can see in the blue bars in Exhibit 20.

The key benefit of an EV is its environmental impact once it is operational, which is quantified in the green bars. The magnitude of this benefit is very much dependent on the electricity grid power source mix. The line in Exhibit 20 represents the total lifecycle emissions including both the initial vehicle production and the lifetime operating emission. This line indicates the CO2 savings relative to the 55 tonnes of CO2 an ICE vehicle generates over its lifetime. When renewable energy becomes the primary source of electricity, the lifetime EV emissions drop to around 10 tonnes per EV or an 80% reduction. A 2021 study by the International Council on Clean Transportation estimated that in Europe where renewables make up 20-25% of the grid, the total lifecycle emissions of an EV are roughly 66% lower than an ICE vehicle. In the US, the lifecycle emissions from EVs are 60% lower than an ICE vehicle, but in countries that have a higher proportion of the grid powered by fossil fuels, coal in particular, the gap is much smaller. They estimate that lifecycle emissions are 40% lower for an EV in China, where coal represents c. 60% of the power grid, and just 26% lower in India where renewables make up less than 7% of electricity generation.

Exhibit 20

CO2 emissions from production of an EV are 80% higher but lifecycle emissions are highly dependent on the grid power mix



Source: *McKinsey & International Council on Clean Transportation*

Relative costs vs. ICE vehicles:

Data from Oliver Wyman and the Financial Times suggests that electric vehicles in Europe are currently 35-40% more expensive to produce relative to an ICE vehicle. The most expensive component is the battery which accounts for 35% of the cost base. The analysis, shown in Exhibit 21 suggests that the cost of electric vehicles will decline to roughly the same price point as ICE vehicles by 2030 primarily due to the declining costs of lithium-ion batteries. The cost of a 50kWh battery will fall from the current average of €8,000 to approximately €4,300 by the end of the decade, primarily thanks to economies of scale from the completion of several giga factories across Europe, the US and Asia.

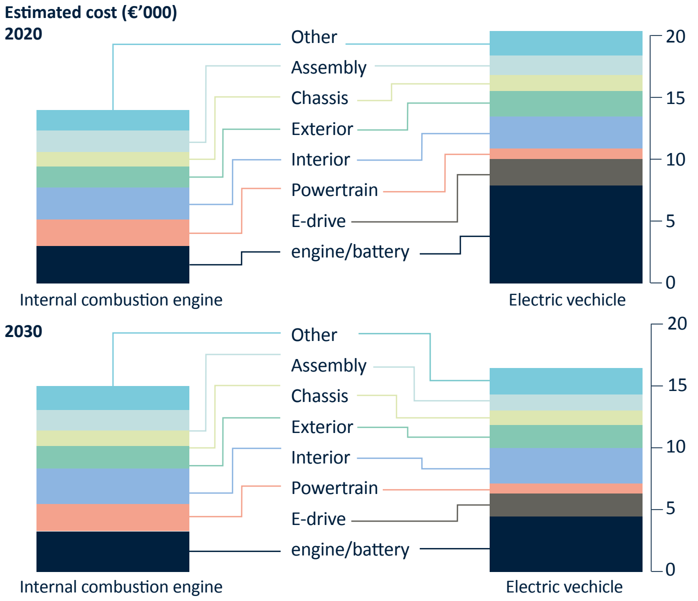
As for total running costs, a report from the US Department of Energy showed that over a 15-year ownership period, electric cars on average have a lower lifecycle cost than a traditional ICE vehicle. Assuming a total life of 200,000 miles, the total average cost of an ICE vehicle was estimated to be roughly $94,500 vs $90,200 for an EV. Fuel/charging costs are estimated to be 50-60% lower on average but will depend on a range of factors. Maintenance costs over the life of a vehicle are expected to be 30% lower due to the significantly fewer parts in an EV[16]. The powertrain in a traditional auto can have hundreds of parts. In an EV, this can be as low as 17 parts. EVs no longer have a need for an engine, radiators, fuel tanks or exhaust systems.

Alternatives to Electricity for low carbon transport

In the IEA NZE analysis, shown in Exhibit 22, the share of total energy demand from fossil fuel drops from the current 90+% to less than 75% in 2030 and slightly over 10% by 2050. By the early 2040s, electricity becomes the dominant fuel in the transport sector worldwide, and goes on to account for nearly 45% of total final consumption in 2050, followed by hydrogen-based fuels (28%) and bioenergy (16%). Biofuels almost reach a 15% blending share in oil products by 2030 in road transport, which reduces oil needs by around 4.5 million barrels of oil equivalent per day. Beyond 2030, biofuels are increasingly used for aviation and shipping, where the scope for using electricity and hydrogen is more limited. Hydrogen carriers (such as ammonia) and low-emissions synthetic fuels also supply increasing shares of energy demand.

Exhibit 21

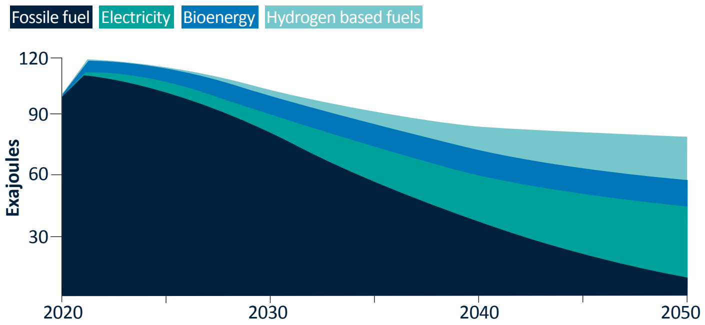
EVs are estimated to have the same production cost as traditional ICE vehicles by 2030



Source: *Oliver Wyman/The FT*

Exhibit 22

Electricity and hydrogen-based fuels account for more than 70% of transport energy demand by 2050 (Exajoules)



Source: *IEA*

Biggest unknowns:

- Who will be the biggest winners and losers out of the rapid penetration of EVs? EV substitution of ICE vehicles will drive significant industrial dislocation and massive employment migration given the significant job losses related to the drop in combustion engine and component manufacturing along with significant reductions in petrol station employment. In the US, gas stations alone employ nearly 1M people[17].

Question 9: Will there be enough battery storage to enable a sufficient transition to renewables?

The intermittency of renewable energy generation means that battery storage technology is one of the most important pieces of the energy transition puzzle. Electricity storing batteries play two major roles: one in powering EVs and the other in storing renewable energy on the grid to address wind and solar's intermittency. The strategic future of these two uses are intertwined to the extent that the same technology, lithium-ion, is presently dominant for both. Additionally, with the greater scale and earlier penetration of batteries powering EVs, whatever technology wins with EVs, is likely to have the competitive edge as the winner for the grid-storage application. So far, that is how it has evolved. However, EVs will only ever need short term (hours, not months) storage capability, while the electricity grid is currently handicapped by the short discharge time of lithium-ion batteries. So the biggest unknown is around longer discharge battery technology, which has yet to rear its head. At COP26, an organisation comprised of technology and energy sector CEOs was created which is dedicated to the innovation and deployment of long duration energy storage (LDES), called the LDES council. McKinsey estimates that between $1.5T and $3.0T of total investment in LDES will be required between now and 2040 (or approximately $125B per year).

Recognising the limitations of current battery technology, experts are still calling for the growth of a very large industry in short discharge electricity grid-scale batteries. If wind and solar operated 24/7 year-round, only 25% of the electricity generated is used. This is not to say that 75% of wind and solar generated electricity is wasted, as wind and solar offtake is curtailed. Wind curtailment is the reduction in electricity generation below what a system of well-functioning wind turbines are capable of producing. It represents a significant loss in economic and energy efficiency.

The ability to store wind and solar for as little as 4 hours, can increase the 25% that is used, up to something higher, but experts have not yet quantified this upside as far as we can find. The way grids are managed have a lot to do with base load power from coal, natural gas, hydro and nuclear which operate continuously and pick up the slack when wind and solar are not generating enough, even for short gaps of a few hours. For penetrations up to ~80%, a relatively small storage capacity is needed. When the penetration of renewables approaches 100%, there is a very large increase in the storage capacity needed.

In order to facilitate the increasing proportion of renewables on the power grid, roughly 350GW of capacity will need to be built between 2020 – 2030, and a potential further 1,200–2,200GW between 2030 and 2040. The installed capacity globally has risen from 3GW in 2019, to 6GW in 2020, and to 18GW in 2021. While this is an impressive rate of increase, the annual

---

[16] https://www.cnbc.com/2021/12/29/electric-vehicles-are-becoming-more-affordable-amid-spiking-gas-prices.html

[17] Forbes

battery installation rate needs to roughly triple again in order to achieve the 350 GW target. The global lithium-ion batteries market is projected to grow from $69 billion in 2021 to $216 billion by 2028 (a CAGR of 12.3%). Costs are decreasing rapidly with the increasing economies of scale of large-scale projects. Lithium-ion batteries cost $1200/kwh in 2010 compared to $132/kwh in 2021 (Exhibit 24).

Energy storage will be required over a wide range of discharge durations in future zero emission grids, from milliseconds to months. No single technology is well suited for the complete range, so the solution to the global energy storage problem will come from a combination of different approaches. Lithium-ion batteries ("LIBs") dominate current research and are already proving useful in shorter duration (5 minutes to 4 hours) technologies, such as Electric Vehicles. However, technology still limits the possibility of a long duration (>200hr) grid-scale solution that is low-cost and environmentally friendly. This in turn limits how much a modern energy system could rely on renewables without periods of serious energy blackouts. The cost, resource scarcity (cobalt and lithium), resource geography, and the inherent chemical limits of LIB technology mean research is focused on potential alternative technologies, in particular those that could offer large grid scale solutions to the seasonality of power demand and supply.

The single biggest limitation to the growth of wind and solar power is the fact that the source of power is wasted if we cannot use it immediately, or nearly immediately. It is estimated that of the wind and solar power that is not consumed immediately, almost all of it is lost. The power generation mix should be optimised so that its profile matches the profile of demand as closely as possible, to reduce the storage capacity required. A small amount of over-generation (and curtailment) can reduce the requirement for energy storage. Based on present cost assessments, future systems that generate ~15% more renewable electricity than what is needed appear to be optimal. As wind and solar costs continue to reduce, then higher proportions of over-generation will be appropriate. As a general rule, according to Energies research house, no energy storage is needed for renewable penetrations lower than ~25% and for penetrations up to ~80%, a relatively small storage capacity is needed. When the penetration of renewables approaches 100%, there is a very large increase in the storage capacity required.

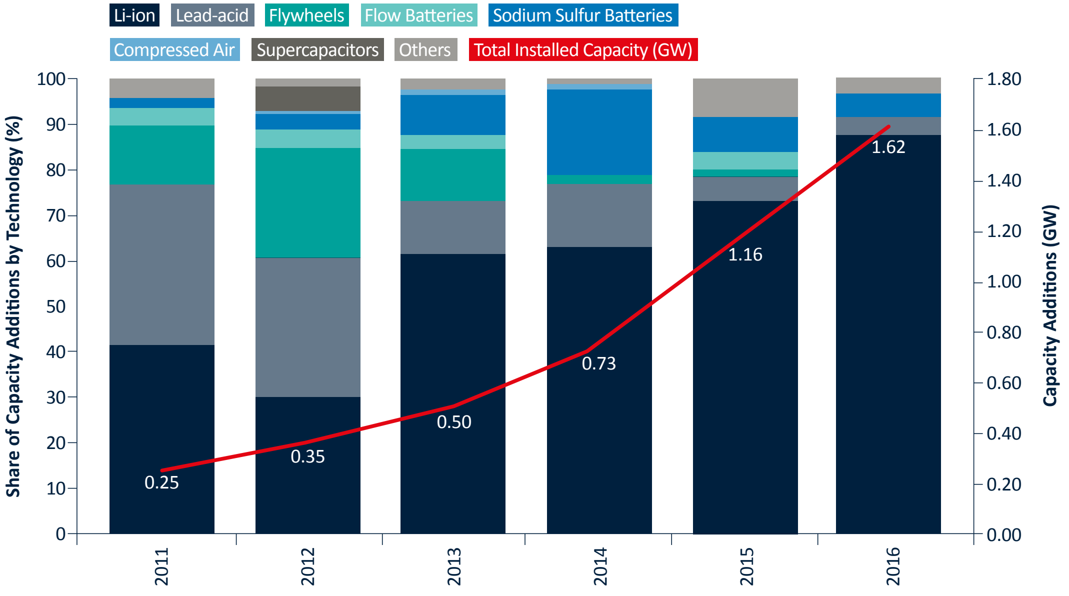
In 2017, the United States generated 4 billion megawatt-hours (MWh) of electricity, but only had 431 MWh of electricity storage available. This is why breakthroughs in this particular technological decarbonisation enabler, are the most important ones to understand.

In future net zero energy transmission grids, storage will be required over a vast range of discharge times, from fractions of a second up to several months. The short answer to our question is that there will be enough storage, but it is more important to understand the technology mix that makes up the storage, as no single technology will be capable of dealing with the entire discharge time spectrum.

Lithium-Ion batteries ("LIBs") have been the dominantly researched and developed storage technology in the last decade, and are already commercially scaled, providing solutions in powering EVs and many other industrial end uses where power storage is needed. This battery has many advantages, especially high specific energy density, simple charging and low maintenance cost, and it is environmentally friendly. LIBs have dominated the energy and transport sector battery storage, due to their maturity as well as the entrenched knowledge base of the associated commercial-scale manufacturing process and of their cathode/anode materials. In addition to powering cell phones, laptops, digital cameras, power tools and medical devices, lithium-ion batteries are also used in electric vehicles, satellites and Mars rovers. **This technology is likely to continue dominating the short duration storage space (charges between 5mins and 4 hours).**

Exhibit 23

From 2011 to 2016, LIBs share of battery storage additions went from 42% to 87%

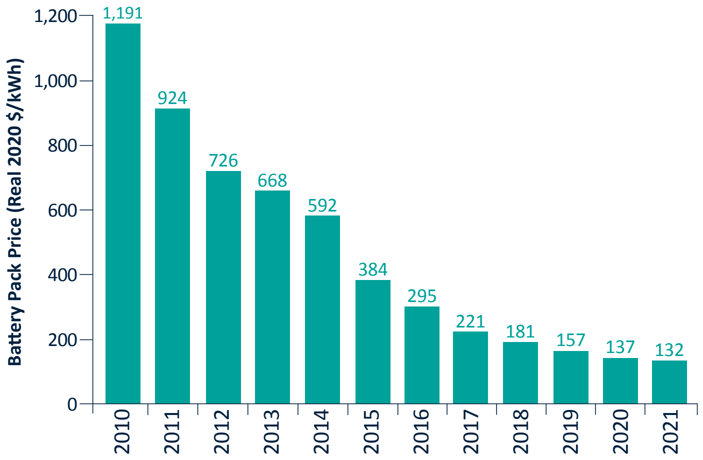


Source: IEA

The increasing share of LIBs in storage capacity additions has been largely driven by declining costs, which has in turn been driven by the ramp-up in production to meet growing demand for electric vehicles. It is fairly clear that LIBs, in some incarnation, are going to dominate EVs, at least for the foreseeable future. There is no other commercial battery that can pack as much power into as small a space and as lightweight a package, with the quick responsiveness needed for a motor vehicle.

Exhibit 24

Lithium-ion batteries' prices have fallen by nearly 90 percent from their 2010 average of $1,100 per kWh to $132 per kWh in 2021



Source: BloombergNEF

---

18 18% learning rate indicates that every time the cumulative volume of batteries deployed on the market doubles, pack prices fall by 18%.

By 2024, average prices will be close to $100/kWh, according to the latest forecast from research company BloombergNEF (BNEF). There is much less certainty on how the industry will reduce prices even further from $100/kWh down to BNEF's expectation of $58/kWh by 2030, which assumes an 18% learning rate.[18] However, moves in a positive direction continue, with reductions in price in 2021 largely due to low-cost cathode chemistry known as lithium iron phosphate (LFP), while the use of expensive cobalt in nickel-based cathodes continued to slide. The average fall in this battery technology prices from $137/kWh in 2020 to $132/kWh in 2021 could see a reversal, however, as the world sees rising prices for many key commodity inputs. Since September 2021, Chinese based producers have increased LFP prices by 10-20%.

Theoretically, there is enough lithium in the world to support a global transition to EVs, but we're still in the very early days of tapping into that theoretical resource. While there are several other critical battery metals that the industry needs to focus on as well, lithium itself could become a bottleneck without new, more efficient and sustainable methods of extraction. Today, extraction of lithium from brines relies on high water- and land-consuming evaporation ponds which yield <50% of available lithium and have rapidly become much more difficult to site and permit. Hence, forecasters (like S&P) expect most of the near-term growth in supply to come from hard rock mines. Yet longer-term, the hard rock resource is not large enough to keep up with EV demand. Consequently, the lithium-ion battery industry will require a step-change in brine extraction technology. Direct Lithium Extraction (or DLE) is one family of dramatically more efficient and lower land use alternatives to evaporation ponds.

While LIBs will dominate the short duration battery storage space (e.g., EVs), the largest amount of storage required (c.60% of all storage) will be to support the intermittency of renewable energy generation (intra-day and seasonally). Despite the high cost of these systems, Li-ion battery storage also dominates large-scale grid storage market today. The key unknown here is, as the grid integrates more renewables and that mid-duration market develops, whether LIBs will simply continue their dominance of the utility scale storage battery market. Right now, a few competitors can claim lower kWh costs over longer (20+ hour) durations, but Dan Steingart, a materials scientist and co-director of Columbia University's Electrochemical Energy Centre, thinks that some variant of the basic LIB architecture is "going to get to somewhere between $45 and $60 per kilowatt hour" eventually. That is a difficult trajectory for alternative battery technology to keep pace with. Steingart believes that LIBs will still be the best option for up to eight to 10 hours battery life. But if LIBs fail to satisfy the needs of longer duration storage, markets for the alternatives are unlikely to mature fast enough naturally, and we would expect governments (e.g., DoE) to step in with investments in the needed research and development. But there is nothing to say that that such government research wouldn't focus on LIBs. As with any technology, just because it is currently being used for a solution, it does not mean it is the best solution. For a number of reasons, many forecast that the future storage solutions that will dominate the medium- (4 hour – 200 hour) and long- (>200 hours) duration requirement areas of the market will not be LIBs. The grid will still feature LIBs, but more likely as "peaker" plants, that can come online very quickly to supply a shortfall in energy during peak demand periods during the day.

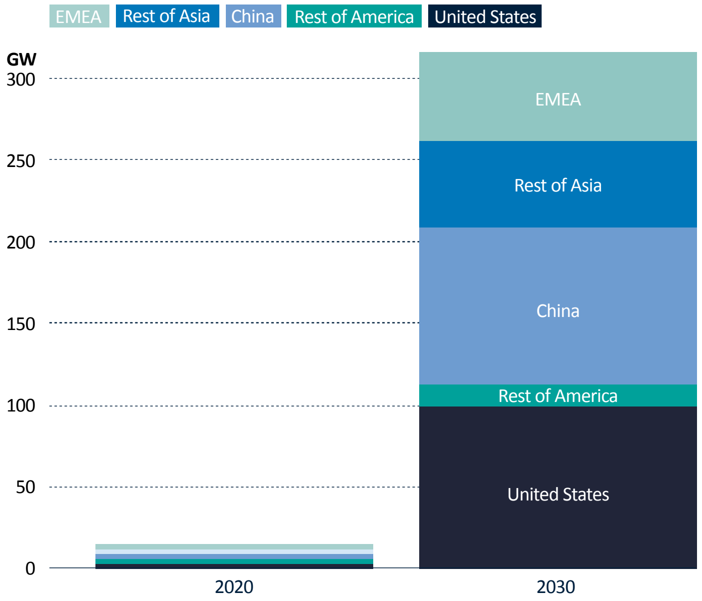
Scale of grid-scale battery capacity required. BNEF's 2021 Global Energy Storage Outlook estimates that grid-scale energy storage installations around the world will reach a cumulative 358 GW or 1,028 GWhs by the end of 2030, more than twenty times larger than the 17GW/34 GWhs online at the end of 2020. BNEF's definition includes stationary batteries used in ancillary services, energy shifting, transmission and distribution grids investment deferral, customer-sited, and other applications. It excludes pumped hydro storage. This growth out to 2030 in stationary energy storage will require more than $262 billion of investment, BNEF estimates. Exhibit 25 highlights that the US and China will be leading the race.

This means that 341 GW of new energy storage capacity will be added globally between 2021 and 2030, which is more than Japan's entire power generation capacity in 2020. 2021 production was 12.5GW, suggesting an annual run-rate of capacity additions of 35GW for the period 2021 – 2030 is required.

BNEF's forecast suggests that the majority, or 55%, of energy storage built by 2030 will be to provide energy shifting (for instance, storing solar or wind to release later). Co-located renewable-plus-storage projects, solar-plus-storage in particular, are becoming commonplace globally.

Exhibit 25

Global cumulative energy storage installations 2020 - 2030



Source: *BloombergNEF*

The size of battery storage needed is directly linked to the amount of renewable energy penetration in energy generation. A study by Imperial College London, taking results from 28 studies of the future UK electricity system, found that to support an energy system with 80% renewables penetration, battery storage would need to be sized at 40-50% of peak energy demand. A paper[19] published in Energies Journal analyses potential future configurations of energy generation and storage to find the lowest cost solution. They conclude that a system in the UK of 85% wind, 15% solar, and 15% over-generation would be optimised with storage capacity of 55TWh hydrogen, 11TWh in CAES (compressed air energy storage) and a relatively tiny 168 GWhs in LIBs. The recommended storage capex investment was 43% hydrogen, 47% CAES and 10% in lithium-ion batteries. We should stress that we have seen many other reports suggesting no CAES, and more of a 50/50 mix of battery and hydrogen storage capacity. This study estimates that over 60% of energy is released from medium-duration stores (hydrogen and CAES), with the rest being live-offtake supported by short duration battery draws. Based on the current cost, this storage capacity would require an investment of £170B, or approximately 8% of UK GDP.

We find this UK-based research to be fascinating to the extent that it underscores the complex inter-relationships between alternative energy storage mediums in driving the ultimate demand for any one, storage batteries in particular. The Bloomberg estimates of a 358GW lithium-ion battery storage capacity demand by 2030 must certainly be dependent on how successful hydrogen, CAES and other long duration storage technologies are.

---

[19] https://www.drax.com/press_release/ten-times-more-energy-storage-needed-for-britain-to-reach-net-zero-climate-target/

Energy Storage Battery (and some non-battery) Alternatives to Lithium-ion

A number of alternative technologies are in various stages of research or real-life application that could complement or potentially compete with Li-ion technology in the coming years. Some of these are shown in Exhibit 26.

One of the most promising potential replacements for Li-ion for transport is solid state batteries. Presumably, if it gets If they gain significant traction against Li-ion for EVs, they may well prove to be a competitor for grid-scale storage applications. However, the latter possibility is not an immediate concern for proponents of Li-ion.

Solid-state batteries. A solid-state battery utilises the same ingredients as a lithium-ion battery but replaces the liquid electrolyte with a solid electrolyte. This change nearly eliminates the risk of spontaneous combustion, which is one of the reasons why lithium-ion batteries have limitations for applications such as commercial aviation. Secondly, the solid electrolyte makes the battery far more compact and lightweight with a higher energy density. Research from Samsung SDI suggests that a fully charged solid state battery could provide more than 2x the energy of an equivalent lithium-ion battery. They also suggest that the recharge time could be 5-6x faster than the speed of a lithium-ion battery. If they were to be utilised in an electric vehicle it could mean in theory that the average range for an EV would be extended from 300 miles to 600 miles with a charge time of roughly 12-15 minutes, down from roughly an hour with a lithium-ion battery at a DC fast charging station.

Solid state battery technology has been around since the 1970's where it was originally utilised in pacemakers. While the benefits of solid-state batteries are clear and obvious, there are significant challenges. The main issue is cost. Costs are still prohibitively expensive to produce solid-state batteries for large scale items such as EVs or gird scale batteries. The chemistry is also said to be challenging as well with solid state batteries performing poorly when mixed with water which can be challenging to avoid. Another problem is that they degrade faster than lithium-ion batteries after a number of charge-discharge cycles due to the accumulation of lithium dendrites which are thin, tree-like pieces of lithium that branch out and can pierce the battery, thereby causing short circuits and other problems. Researchers believe they may be close to solving this final issue which would leave cost as the main hurdle. The latest forecast from BloombergNEF suggests that solid state batteries will remain roughly 35-40% more expensive that lithium-ion batteries out to 2030. Research for grid scale application is still very much at the early stage given cost limitations but battery makers Samsung SDI, Panasonic and SK Innovation are all actively investing in the space. For the EV market we are at a far more advanced stage with nearly every major automaker investing heavily in the technology, but breakthroughs have been slow. Toyota is said to have the lead position and released a prototype solid state EV in February 2022. For commercial purposes they intend to launch a hybrid in the next two years, but do not plan a fully solid-state battery EV until later in the decade. Experts suggest that the luxury vehicle market (>$100,000) could be first to see a fully solid-state EV potentially by 2025 with success in this space potentially leading to lower costs and wider scale adoption as the main technology of choice.

Exhibit 26 provides a side-by-side comparison of various alternative battery technologies beyond lithium-ion. These alternatives may be able to address some of the shortfalls of lithium-ion batteries, but not any time soon.

None of the alternatives shown in Exhibit 26 have reached the $1B revenue level. The most interesting new battery technology may be the **Iron Air batteries** now being developed by Form Energy, a firm started in 2017, funded with $360M of equity from a consortium including TPG, Temasek, Gate's Breakthrough Energy Ventures, MITs The Engine, Energy Impact Partners and Capricorn, among others. Form Energy says its iron battery can deliver electricity for 100 hours at a cost competitive with conventional power plants' live offtake and at 10% of the cost of lithium-ion batteries, or $20/KWh at present, with the aim of getting it down to $10/KWh by the end of the decade.

Flow batteries have demonstrated success in recent years and have the advantage of requiring less scarce raw materials (lithium, cobalt, nickel) and offer a more effective medium duration storage option. Upfront costs and scalability are an issue, however.

Sodium-ion and **lithium-sulfur** batteries are also being explored as genuine alternatives to lithium-ion batteries with the former not requiring lithium as an input. Both batteries are however still some ways off commercial scale application, but the markets for these batteries are forecasted to grow between 20-30% per annum out to 2030. The power industry desperately needs an alternative to lithium-ion batteries, and one will be developed, but well into the future, probably after Li-ion hits problematic raw material supply shortages.

Looking out at longer term potential innovations, McKinsey and the **Long-Duration Energy Storage (LDES)** Council released a report[20] suggesting that the lowest cost path to net zero power will be by deploying LDES technology and that this would require the installation of 1,500-2,500 GW of long-duration storage between 2020 and 2040. This is a figure that would equate to 10% of all electricity being stored in LDES "at some point". While this is a high capacity requiring installation, the report highlights that this storage would require an investment of between $1.5T-3T, similar to the amount that is currently spent every 2-4 years on electricity transmission and distribution networks, highlighting the scale of investment that is needed. The definition of LDES explicitly excludes Lithium-ion batteries, grey hydrogen and pumped storage hydroelectric (PSH) but includes four categories of energy storage mediums defined (paraphrasing McKinsey's definitions) below:

Electromechanical LDES includes many of the battery technologies we have already named above and in Exhibit 26 with a focus on flow batteries and metal air batteries.

Mechanical LDES store potential or kinetic energy in systems for future use. Pumped hydro (PSH) is an example of mechanical LDES but is excluded from the LDES mission given it is a well-developed and a known storage medium. Beyond PSH, mechanical LDES includes compressed air energy storage (CAES) and gravity-based energy storage. Gravity-based energy storage is another promising form of mechanical storage, which stores energy by lifting mass that is released when energy is needed. This technology is in an earlier stage of commercial development. Lastly, mechanical LDES can also take the form of liquid CO2 which can be stored at high pressure and ambient temperature and then released in a turbine in a closed loop without emissions. Liquid air energy storage (LAES) works similarly to CAES by compressing air but uses electricity to cool and liquify the medium and store it in cryogenic storage tanks at low pressure.

Thermal energy storage technologies store electricity or heat in the form of thermal energy. In the discharge cycle, the heat is transferred to a fluid, which is then used to power a heat engine and discharge the electricity back to the system. These technologies use different mediums to store the heat such as molten salts, concrete, aluminium alloy, or rock material in insulated containers. The most widespread thermal LDES technology today are molten salts coupled with concentrated solar power (CSP) plants.

Chemical energy storage systems store electricity through the creation of chemical bonds. The two most popular emerging technologies are based on power-to-gas concepts: power-to-hydrogen-to-power, and

---

[20] Net zero power: Long duration energy storage for a renewable grid. https://www.rechargenews.com/energy-transition/between-25-35gw-of-long-duration-energy-storage-will-be-installed-globally-by-2025-report/2-1-1103860

Exhibit 26

Alternative battery technologies that could either compliment or compete with Li-ion technology; most are just getting off the ground

Battery Technology	Description	Pros (vs. Li-ion)	Cons (vs. Li-ion)	Commercial Viability
Flow (or Redox flow) (4–12 hours)	Flow batteries differ from solid batteries, as the electrolytes are stored in external tanks.	• Should theoretically offer high economy, long lifespan, high safety and low environmental load • Less reliance on scarce materials • Better suited to provide lower energy over a longer time period • Resilient rechargeable ability, low degradation	• Energy and power density of these technologies still needs to be developed further • Vanadium and Zinc based systems remain at the demonstration phase but remain some way off large-scale commercial production • Higher upfront investment (but longer lifespan)	• Several successful systems have been built and operated for a number of years • Optimistic market size estimates put this at $4.5B by 2028 vs. the Li-ion market forecast of $216B by 2028 (vs. $69B in 2021)
Lithium-Sulfur (<4 hours)	An alternative type of Lithium-Ion rechargeable battery, originally invented in the 1980's. Uses Sulfur Instead of using a cathode from Nickel, Manganese, and Cobalt, (NMC).	• Theoretical energy density 5x that of Li-ion batteries so last longer on a single charge • Abundant, environmentally friendly and low-cost, safer, and lighter	• charging causes a build-up of chemical deposits that degrade the cell and shorten its lifespan • Still some way off commercial scale, still high cost, and difficulties remain in recharge lives in mass production	• $0.4B market size in 2020 – projected to grow by a c.30% CAGR to 2030 as cost falls • Lyten has introduced the first Li-S battery for EVs in 2021 • Sion Power has partnered with Airbus for satellite application
Sodium-Ion (Na-ion) (<4 hours)	Similar to Li-ion except not using Lithium in the anode, using sodium instead.	• Sodium is the 7th most abundant material on the planet • Safer and easier to transport than Li-ion • Can operate at a much wider range of temperatures, in particular is efficient at low temperatures • Lighter	• Still remains some way off large-scale application, in part due to the chemical differences of a sodium ion (e.g., larger) • Low energy density and a limited number of charge-discharge cycles	• $1B in 2021 – forecast CAGR of c.19% through 2030 • Faradion is a UK-based leader in Na-ion technology but has yet to introduce on-grid storage or EV application
Zinc-air (<4 hours)	These are water-based batteries using a zinc, rather than Lithium, anode, and an oxygen permeable cathode.	• Longer lifespan, lowering the LCOS • More abundant raw materials, and less reliant on China's processing domination of Lithium • Safer, water-based system is ideal for residential and commercial storage • Initial productions favouring items that require longer lifespan for safety reasons e.g., traffic lights	• Still remains a Li-ion-like technology, with around four hours max discharge time • Theory remains far from practical output when it comes to full scale commercialisation	• Global market projected to reach $0.5B by 2026, a CAGR of 6% during 2021-2026. But most of these applications are outside of energy storage (hearing aids, other medical)
Liquid Metal (<4 hours)	Uses the chemical reaction of metals combining and then reversing the process, to release energy and then to recharge.	• Lower cost • Lower operating temperatures • More stored energy • Cannot be over- or under-charged • Much less degradation of capacity if "deep-cycled" i.e., charged to 100% and back to 0% too often • Higher safety • No ongoing maintenance required	• Price projected to fall to around a 1/3 of current Li-ion costs • Lower efficiency • Still not proven commercially	• Ambri, the company developing the technology has signed a deal for first commercial application at a Terrascale data centre
Solid State (4–12 hours)	Same ingredients as a lithium-ion battery but the liquid electrolyte is replaced with a solid electrolyte.	• Reduced risk of spontaneous combustion • Lighter weight, more compact leading to higher energy density • Can provide up to 2x the charge of a li-ion battery • Recharge at 5-6x the speed of a li-ion battery	• Costs still prohibitively expensive for large scale application such as EVs/grid battery • Batteries perform poorly when mixed with water • Faster degradation relative to li-ion batteries but researchers are said to be close to a solution	• All major auto manufacturers are investing heavily in the technology with Toyota said to be in the lead having released a prototype vehicle • Samsung SDI leading the way in grid scale application research
Iron Air (12–200 hours)	Technology originally developed by NASA in the 1960s which uses a "reverse rusting" process to discharge and recharge batteries with simple core ingredients of iron and fresh air.	• Form Energy, the primary patent holder, suggests that they will be just 10% the cost of a lithium-ion battery • The low cost is a function of readily available, easily accessible core ingredients of air and iron which significantly reduces supply side risks • Has the potential to be utilised for medium duration grid storage with discharge for up to 6 days	• Heavy weight so only suitable for grid scale applications; not suitable for EVs or smart devices • Yet to be proven at a commercial grid scale • Battery is designed to be a complement and not a replacement for lithium-ion batteries	• Form Energy has produced a prototype with a larger scale launch planned for 2023. Form Energy aims to get the cost of storage down to $10/KWh by the end of the decade

Exhibit 26
Alternative battery technologies that could either compliment or compete with Li-ion technology; most are just getting off the ground

Continued

Source: *Partners Capital*

power-to- synthetic gas-to-power. The first is the same as what we describe in the next section on green hydrogen. This involves using wind and solar power to electrolyse water into hydrogen when is then supplied to a hydrogen turbine or fuel cell. If the hydrogen is combined with CO2 in a second step to make methane, the resulting gas—known as syngas—has similar properties to natural gas and can be stored and later burned in conventional power plants. Similarly, hydrogen can be converted to ammonia for direct combustion.

Biggest unknowns:

- How will various battery and non-battery storage technologies evolve to create an "optimal mix" of storage mediums for difference discharge duration needs?
- Will Western governments promote alternative battery technology to avert an overdependence on China and the Congo for raw material sources? E.g., Sodium-ion, Solid State or Flow batteries?

Question 10: What role will hydrogen play in the transition?

Green hydrogen could be the most significant new technology in the green transition by being a scalable, high-energy density, low-cost solution to the problem of intermittent, unpredictable renewable energy (wind and solar) via large-scale, long-term hydrogen storage. Green hydrogen is produced from water via electrolysis where the process is powered by excess wind or solar power. Hydrogen can be used in place of natural gas in power plants, cutting emissions by 90-95%. Ultimately, both the European Union and China expect hydrogen to represent 10% or more of their respective power mixes by 2050 from a base of just 1-2% today.

How is hydrogen currently utilised?

Hydrogen is the most abundant element in the universe, but it does not exist freely in nature on this planet and is only produced utilising other, mostly high carbon emitting, energy sources as inputs. At present, the vast majority of hydrogen is produced using fossil fuels in a process known as steam reformation.

Hydrogen is produced out of the electrochemical reaction between water and the hydrocarbons (usually natural gas). This process creates carbon emissions because it requires the burning of fossil fuels. The hydrogen that is produced today is used primarily by heavy industry for refining petroleum, treating metals (steel), producing cement and fertiliser, and processing foods.

Exhibit 27 shows that traditional hydrogen, referred to as grey hydrogen, is produced using fossil fuels. When carbon capture techniques (discussed in the next section) are utilised to reduce emissions, this is referred to as blue hydrogen. Purple hydrogen is created by utilising nuclear power as an input. Turquoise hydrogen is produced out of methane which is transported via existing natural gas pipelines to the industrial user where the HiiROC technology converts methane to hydrogen gas with a solid carbon by-product which has commercial value. Finally, and most importantly, there is green hydrogen which is hydrogen produced from water using renewable energy via electrolysis. Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyser. Green hydrogen represents just 1% of all hydrogen produced today but is likely to be crucial to the success of the world's efforts to move to net zero by 2050.

The answer to which colour of hydrogen technology will win is very region specific as the costs vary by input cost. In most locations, green hydrogen is still two to three times more expensive than blue or turquoise hydrogen. However, if gaps in cost and performance are addressed, and a rapid scale-up takes place over the next decade, green hydrogen could begin to compete with blue hydrogen by 2030 in countries with electricity prices of $30/MWh. Green hydrogen is "already close to being competitive" in regions where favourable conditions align, IRENA noted, but these are usually at a considerable distance away from demand centres. For example, in Patagonia, wind energy could have a capacity factor of almost 50%, with an electricity cost of $25–30/MWh. This would be enough to achieve a green hydrogen production cost of about $2.50/kg, which is close to the blue hydrogen cost range.

What problems could green hydrogen solve?

- **Grid-scale energy storage:** The most important potential application for green hydrogen is as a storable form of energy produced from renewable energy.

One of the key issues with renewable energy is its intermittent nature and the inability of present-day batteries to store power over long periods of time and at large quantities. The specific properties of hydrogen mean that renewable energy can be converted to green hydrogen via electrolysis. This green hydrogen can then be used in place of natural gas in gas-fired power plants. Green hydrogen can be compressed and stored underground for months at a time. When the power grid experiences a deficit of power, this hydrogen can then be called upon to generate electricity via power cells or hydrogen gas turbines. Most active projects are looking at underground salt caverns, aquifers and abandoned coal mines as potential storage locations. The Clean Air Task Force estimate

Exhibit 27

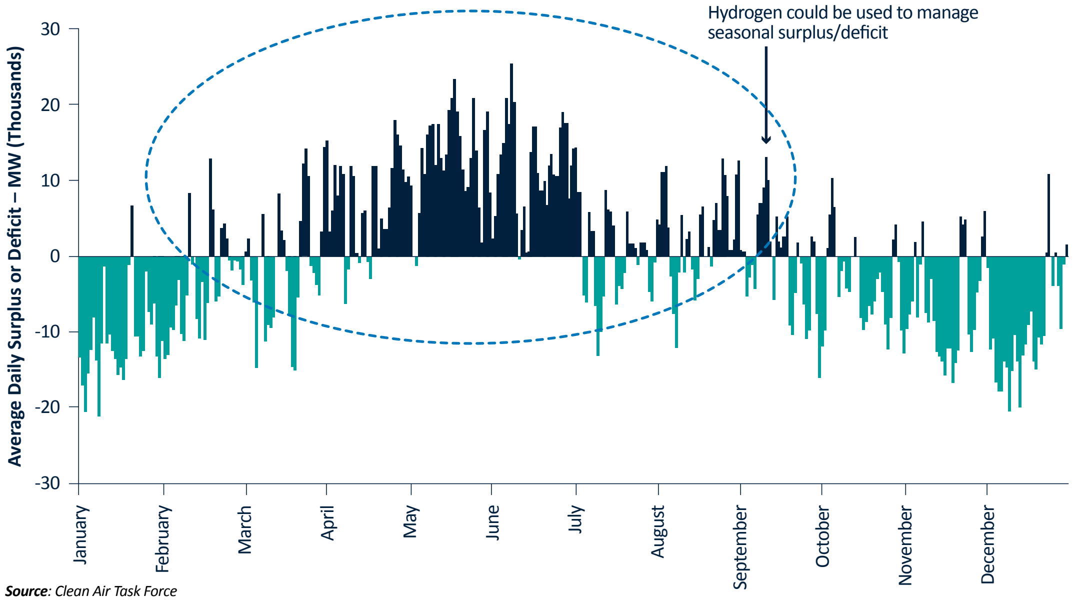
Classifications of hydrogen

Terminology	Technology	Feedstock/ Electricity source	GHG footprint	Projected $ cost excl cost of CO2 emissions / kg
Green Hydrogen	Electrolysis	Wind / Solar / Hydro Geothermal / Tidal	Minimal	$5-7
Purple/Pink Hydrogen		Nuclear		
Yellow Hydrogen		Mixed-origin grid energy	Medium	
Blue Hydrogen	Natural gas reforming + CCUS	Natural gas / coal	Low	$2
Turquoise Hydrogen	Methane Pyrolysis	Methane	Solid carbon (by-product)	$2-3
Grey Hydrogen	Natural gas reforming	Natural gas	Medium	$1

***Source**: Global Energy Infrastructure; Eric McFarland, Bulletin of the Atomic Scientists for costs/kg*

Exhibit 28

Modelled energy surplus/deficit estimate for California energy grid using 100% renewables



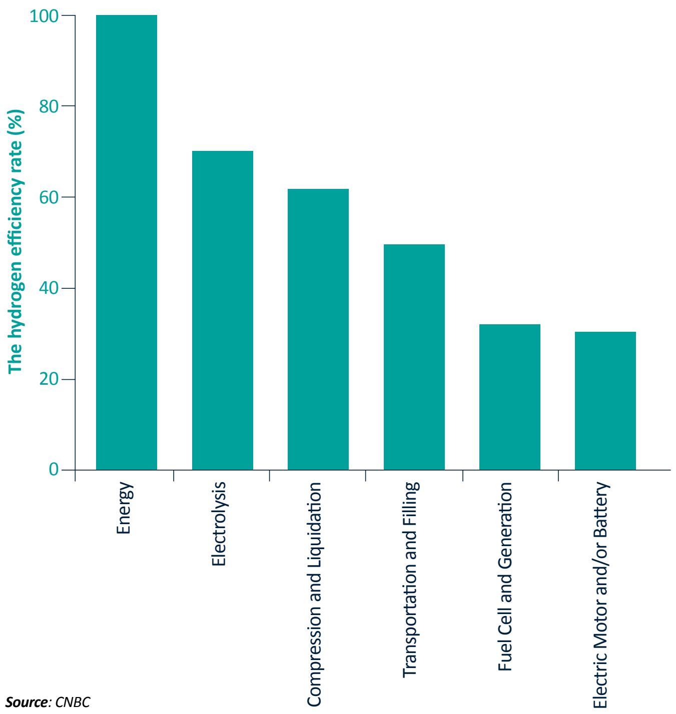
***Source**: Clean Air Task Force*

that if California's energy grid was supplied by 100% renewable energy sources, it would result in 36 million megawatt hours of surplus energy during the summer months. Hydrogen storage could allow for some of this, otherwise wasted, surplus energy to be captured and utilised when the grid experiences shortfalls in the winter as illustrated in Exhibit 28[21].

- **Heavy Industry:** Heavy industry has carbon emissions which will be much more challenging to abate than the electricity grid. For example, steel and cement production currently use grey hydrogen as a key input. Green hydrogen or indeed purple/blue hydrogen could be substituted for grey hydrogen to abate emissions from steel and cement production processes.
- **Transportation:** Hydrogen fuel cells may also provide a solution for long haul transportation such as shipping and aviation. Battery technology, in its present state is not feasible for these modes of transport at least over long distances due to the size and weight of the batteries required. Hydrogen fuel cells however are light weight due to the high energy density of hydrogen making it perfect for larger/longer scale transport.

Exhibit 29

Green hydrogen starts with renewable energy and water to generate hydrogen which may deliver only 30% of the electricity it consumed to the EV end user, but 50% to a gas turbine



Source: CNBC

What are the key issues with green hydrogen at present?

- **Low efficiency/cost:** One issue with green hydrogen as a fuel source is its low efficiency. Green hydrogen is made from water via electrolysis where the process is powered by a low-carbon source such as renewable energy (wind or solar). The hydrogen is then compressed and then transported to its final destination to produce power via a gas turbine or fuel cell. The gas turbine can be a retrofitted natural gas turbine located in a gas-fired power plant. Exhibit 26 illustrates the yield loss on hydrogen from creation to use in an electric vehicle. For power generation, which finishes at the transportation stage in Exhibit 29, there is a 50% yield loss from beginning to end, versus a 70% yield loss for hydrogen powered EVs. The IEA estimates that the current cost of producing a megawatt hour of electricity from green hydrogen is roughly $50/MWh. This compares to a range of $26-40 for wind energy and a range of $28-58 for natural gas. However, analysts at Wood Mackenzie estimate that the cost of electrolysers is set to fall by 35-50% in the next 6-8 years thanks to innovation and economies of scale. This reduction in cost will feed through to an expected cost of $30/MWh for green hydrogen making it competitive with all baseload energy sources (nuclear, natural gas and coal)[22].
- **Infrastructure buildout.** Hydrogen also requires a substantial build out of infrastructure. Older natural gas pipes may require retrofitting, salt caverns need to be prepared and natural gas power plants need to be retrofitted for hydrogen gas powered turbines.
- **Hydrogen gas storage is still in its infancy.** Today, most hydrogen storage facilities are still above ground and very limited in terms of their capacity. Hydrogen is stored underground, similar to natural gas. Both are mostly stored in aquifer reservoirs or salt caverns. The number of existing salt caverns in Europe, together with the potential to develop new ones, is already very significant compared to most hydrogen consumption scenarios for the coming decade. But not all countries are blessed with a good salt layer underground. This form of natural storage is mostly located in North-West-Europe and parts of the US.

Natural gas has been stored underground since 1916. Being able to store hydrogen in existing natural gas reservoirs may unlock greater potential for a strong rise in the role of hydrogen in Southern or Eastern Europe. Existing natural gas storage in Europe already amounts to capacity equivalent to 25% of national natural gas consumption. While not yet fully tested, experts believe that hydrogen could be stored in former natural gas storage locations (aquifers and salt caverns). The technology for storage (salt caverns or natural gas reservoirs) has only been deployed at small scale projects and there is still much to learn about the operational risks associated with it. Experts have noted that there are still uncertainties related to potential leakage, as well as other risks such as induced seismicity and the loss of hydrogen due to microbial activity.

There are examples of new functioning underground projects in the UK and the US with operational salt caverns storing pure hydrogen. The world's largest project in Salt Lake City aims to store 1,000 megawatts of clean power primarily via underground hydrogen storage in salt caverns. If successful, the storage facility would initially have enough capacity to power 150,000 homes for an entire year[23]. Mitsubishi Power, the operator of the project, suggest that this would equate to nearly 150x the current installed lithium-ion battery storage base in the US. That is just the starting point however, as the structure has the potential to create up to 100 caverns in the future, each capable of storing up to 150,000 megawatt hours if fully exploited.

Left:
German salt cavern. Europe has the potential to inject hydrogen in bedded salt deposits and salt domes with a total storage capacity of 85 PWh.
Image: Guilhem Vellut, flickr

---

[21] https://www.technologyreview.com/2018/07/27/141282/the-25-trillion-reason-we-cant-rely-on-batteries-to-clean-up-the-grid/

[22] https://www.rechargenews.com/energy-transition/producing-green-hydrogen-for-1-kg-is-achievable-in-some-countries-by-2030-woodmac/2-1-1118580

[23] https://www.cnbc.com/2020/11/01/how-salt-caverns-may-trigger-11-trillion-hydrogen-energy-boom-.html

Continental Europe's first hydrogen storage cavern, located in Saxony, Germany, is set to be operational in 2023-2024 if regulatory approval is granted. It will have the capacity to store roughly 150,000 megawatt hours.

A study by the International Journal of Hydrogen Energy noted that Europe has enough salt formations to theoretically store 85 petawatt hours of hydrogen power, which is enough energy to power Germany for an entire year.

At present, there are 359 announced large scale hydrogen projects around the world, 80% of which are in Europe. These projects are expected to cost $500B through to 2030 and are expected to generate 10M tonnes of hydrogen. Solar and wind will be the electrolysis energy source for 70% of the output, with the remaining 30% from fossil fuels with carbon capture systems (CCS). Assuming 80% of this hydrogen (based on project distribution) goes to Europe, it would represent roughly 8% of the expected European electricity demand in 2030. The European Commission's stated plan is to take hydrogen's share of the European power mix from 2% at present to 14% by 2050. Of the rest of the projects, 53 of the 359 projects are in China. China expects hydrogen will supply 10% of their total energy needs by 2050.

Green ammonia as a storage solution. As previously discussed, one of the key issues with hydrogen is that it is a very low-density gas at room temperature (about 1/3 of the density of natural gas). As a result of this low density, in order to store and transport hydrogen it must either be liquified or compressed. To liquify hydrogen it needs to be super chilled at -250°C or it has to be pressurised to somewhere between 100- and 300-times atmospheric pressure. Both of these actions are highly energy intensive which are part of the reason why hydrogen energy is considered to have a low energy efficiency. Another issue with hydrogen is that it is a highly reactive gas which tends to make steel containers, in which it is stored, become brittle over time. This makes it challenging, but not impossible, to store and transport hydrogen using existing infrastructure.

One solution that has been proposed to solve both of these issues is to convert the hydrogen into ammonia during the electrolysis process by adding nitrogen. This "green" ammonia could then be transported and stored far more efficiently with less energy loss. This is because ammonia only needs to be chilled to -33°C or compressed to 10x atmospheric pressure, thereby requiring far less energy intensive processes relative to hydrogen. Ammonia is also far less reactive with steel meaning that it could be transported and stored using existing infrastructure. This ammonia could be reconverted to hydrogen when power is required or potentially utilised as a fuel in and of itself, most notably for shipping.

The barriers to this at present are the efficient conversion of green hydrogen to ammonia. The technology in its current state is quite slow compared to the traditional Haber-Bosch method (standard process of converting hydrogen to ammonia) which is very carbon intensive. However, there are several promising solutions in the pipeline, such as a reverse fuel cell being developed by Monash University in Melbourne and a membrane reactor being developed by Australia's commonwealth scientific and industrial research organisation (CSIRO). The UK also launched a large-scale feasibility study to find solutions to speed and efficiency of conversion in 2021.

Biggest unknowns:

- How quickly can green hydrogen technology scale and become cost-effective? The first large scale projects open in the next 3-5 years, but how long will it be before stored green hydrogen truly changes the picture?
- Will there be significant bottlenecks with sourcing cost-effective electrolysers as demand grows?

Question 11: What role will nuclear energy play?

Most official forecasts, including the IEA's (Exhibit 30), suggest that nuclear power's contribution to the grid will remain stable at its current 10% or grow marginally over time. However, if the cost, waste disposal and safety perception issues can be improved, nuclear may well be the clearest path to net zero. Given the typical 15+ year construction period, nuclear is more likely to be a solution in the last decade running up to 2050 targets, unless small modular reactors reach commercial viability sooner. There are significant potential technological developments in the space, including nuclear fusion, which if successful, have the potential to contribute much more significantly than what is implied in the IEA forecasts below.

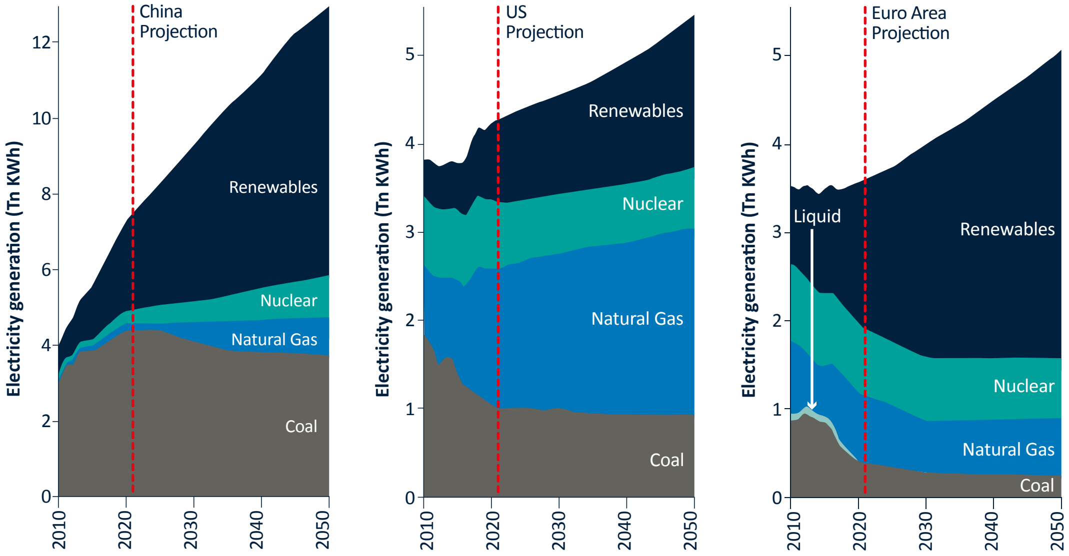
Nuclear reactors generate power through nuclear fission, a process where uranium atoms are split and release energy. In 1956 the world's first commercial nuclear power station was opened in the UK. By the end of 1960's, 78 reactors had been built across 14 countries. The oil embargo of the 1970's helped to further propel nuclear power capacity with capacity growing more than 20x out to 1990, as illustrated in Exhibit 31. Since then, however, the number of active reactors and generation capacity has hardly changed on a global basis. Nuclear power is responsible for roughly 10% of global electricity generation at present but this had been as high as 18% in 1996[24].

---

[24] EIA

Exhibit 30

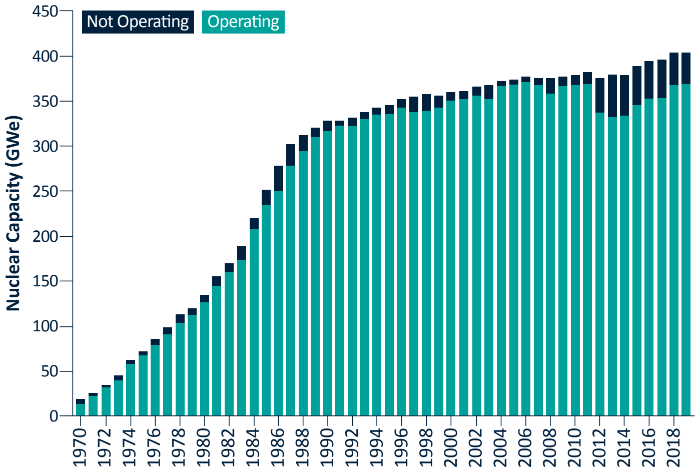
IEA forecasted electricity fuel mix out to 2050



Source: IEA

Exhibit 31

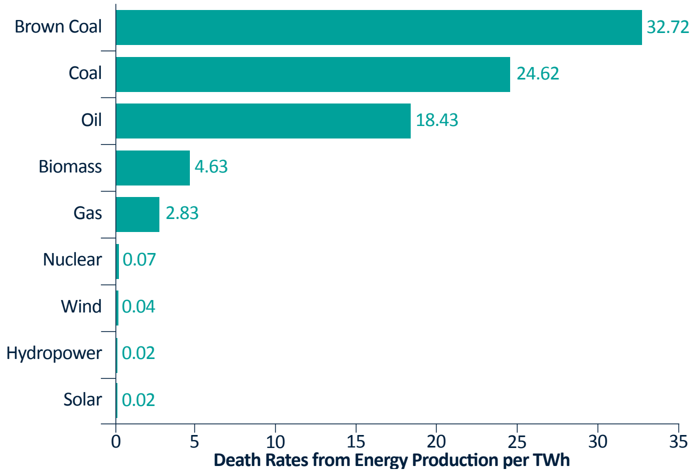
Global nuclear power capacity hasn't changed significantly since the late 1980s



Source: World Nuclear Association

Exhibit 32

Deaths from fossil fuel energy production are much higher than from nuclear



Source: ourworldindata.org

Why has nuclear power not become more widely utilised?

- **Risk perception:** Since the Fukushima disaster, nuclear energy has had the lowest public support of all energy sources (even lower than coal) according to a poll by IPOS MORI. Much of this is down to perception of risk as opposed to the actual risk. The relatively small scale accident at Three Mile Island, the infamous meltdown at Chernobyl and finally the Fukushima disaster in 2011 have created a perception of a high risk technology. Yet deaths related to nuclear power generation are far lower than other fuel sources as illustrated in Exhibit 32.
- **Environmental impact:** Like all industries and energy-producing technologies, the use of nuclear energy results in waste products. 3% of the waste produced by nuclear is classified as High Level Waste ("HLW" - classified according to radioactivity). This mostly comprises the "spent" fuel that is no longer usable to generate electricity. The amount of waste is very small, however. The generation of electricity from a typical 1,000-megawatt nuclear power station, which would supply the needs of more than a million people, produces only three cubic metres of high-level waste per year, if the used fuel is recycled. In comparison, a 1,000-megawatt coal-fired power station produces approximately 300,000 tonnes of ash and more than 6 million tonnes of carbon dioxide, every year. At present nearly all nuclear waste is stored on plant sites in dry casts awaiting long term storage facilities to be constructed. It is widely accepted that deep underground geological storage is the most satisfactory long term solution for future high level nuclear waste disposal. Deep underground geological storage has the potential for higher quantities of waste to be stored in what experts believe to be a far safer environment with less potential for issues such as leakage of waste. Deep geological disposal involves isolating radioactive waste deep inside a suitable rock volume to ensure that no harmful quantities of radioactivity ever reach the surface environment. Finland's Onkalo repository is expected to start operating in 2023. It will be the first deep geological repository licenced for the disposal of used fuel from civil reactors[25].
- **Cost:** The levelised cost of energy (lifecycle cost, including initial construction, of producing energy per megawatt hour) of a nuclear plant ranges between $29-105. This compares to a range of $28-58 for natural gas and $26-40 for wind projects. The range is highly dependent on the cost of capital for nuclear projects because of the significant upfront construction expenses and long buildout period.
- **Construction period:** Many experts believe the key reason why nuclear power has not been more widely utilised is the length of time for construction (which also impacts cost). For nuclear reactors completed between 2016 and 2019, the median time to completion was 17 years (delays have been a significant issue). This compares to just two years for a natural gas plant[27]. One potential solution to this, described below, is small modular reactors which take just two years to build.

What solutions does nuclear offer?

- **Reduced carbon emissions:** The obvious benefit of nuclear power is that its lifecycle carbon emissions are on a par with renewable energy and roughly 90% lower than a coal powered plant.
- **Reliable power source to balance the grid given the increasing amount of intermittent renewables from wind and solar:** Until large quantities of renewable energy can be stored for long periods of time in a cost-effective manner, the world will require reliable baseload power sources such as coal, natural gas and nuclear which have high-capacity utilisation factors (actual average output vs. theoretical output). Nuclear power has a capacity factor of 91% versus just 30% for intermittent sources such as wind and solar.
- **Land usage:** Relative to renewable energy sources, nuclear has a much smaller physical footprint. Roughly 85x more space is required for wind/solar infrastructure to generate the equivalent amount of power.

What are the most significant technological developments in nuclear power ahead of us?

Thorium reactors: China has begun tests using thorium instead of uranium as a fuel for nuclear fission reactors. The element has been trialled in small scale tests previously, but China is the first to pursue the technology at a commercial scale. Thorium is less radioactive than uranium but is more plentiful and has little competing industrial use at present. Its relative abundance, safety and crucially the fact that it produces far lower amounts of radioactive waste as a biproduct, means that it has the potential to be a significant upgrade to the world's current reactors[28]. Thorium reactors are not new. They were originally trialled on a small scale in the US in the late 1960s, but the cost of extracting thorium from rock formations was seen as prohibitive. China, as a biproduct of its rare earth mining, has significant quantities of thorium which at present have little use. This would appear to be a good development for Chinese nuclear, but may not be for the US and Europe.

Small modular reactors (SMR): Typical large scale nuclear power plants have a range of capacities from 600 MWs to 6,000 MWs, with

---

[25] https://world-nuclear.org/nuclear-essentials/what-is-nuclear-waste-and-what-do-we-do-with-it.aspx
[26] The industry standard metric for comparing across energy sources
[27] Undecided energy

an average of 2,000 MWs. SMRs range from 10-500 MW's. Many experts believe these reactors could become the future of nuclear with the potential to build these small reactors in factories in just two years. Effectively this means one can scale production, reduce costs and lower the risk of associated delays. It also allows the use of these reactors in remote locations which would not be feasible with a traditional nuclear reactor. Estimates suggest that these small modular reactors could cost 20% less per megawatt hour than a traditional large-scale reactor. The reactors often use helium instead of water and studies suggest that the risk of a meltdown is far lower. Bill Gates' Therapower is one of the leaders in the SMR space. At present there are 9 small reactors in operation around the world: 4 in Pakistan (Chinese made), 3 in Russia, one in India and one in China. There are 4 under construction: 2 in China, 1 in Russia, 1 in Argentina. These range in capacity from 11MWs to 300 MW's, with 300 MW's being what most industry experts think of as a good size for a SMR. In addition to the 9 in operation, there are dozens of SMRs with designs under approval including many in the US and one or more in the UK, Japan, South Africa and other nations. The most high-profile project in the pipeline at present is Nuscale's Idaho National Laboratory plant. The plant is expected to contain six 77 megawatt modules with the combined plant having an overall capacity of 462 MW's, roughly a quarter of a traditional nuclear plant. Exhibit 33 below, shows an artists rendition of the NuScale Power Modules being built in Idaho. The project has been beset with delays due to certification and licensing issues, but the first module is set to be operational in 2029 and the entire plant is expected to be operational by 2030. SMRs appear to be gaining the attention of the world with Joe Biden and Boris Johnson both committing to invest in SMRs. Rolls-Royce and EDF are also investing significantly in the concept[29].

Exhibit 33

Rendering of the NuScale Power Modules being built in Idaho.

Source: *NuScale Power, LLC*

---

28 https://www.nature.com/articles/d41586-021-02459-w

29 https://www.world-nuclear-news.org/Articles/Scaled-down-SMR-pilot-project-remains-on-course

Right:
Commonwealth Fusion Systems' SPARC, the world's first fusion device that produces plasmas which generate more energy than they consume. Started in 2021.
Image: cfs.energy

Fusion: Most experts suggest that this technology will not be ready to contribute meaningfully to achieving 2050 emission targets. The only place in our solar system that fusion successfully works is in the Sun. Creating a fusion reactor on Earth would be equivalent to producing a synthetic star, with the theoretical potential to provide near-limitless source of clean energy. It is no surprise that scientists have been experimenting with fusion technology for nearly a century. The technology is still only theoretically possible, not having been successfully completed practically. On 9 February 2022, a 24-year-old record was broken by scientists at the Joint European Torus (JET), creating the highest ever energy pulse from fusing atoms. However, no experiment yet has come close to generating more energy than is being put into the process. Progress is also slow. Fusion is famous for having been "twenty years away" for the past fifty+ years. One of our energy asset managers thinks fusion might now actually be ten years from a foundational reactor design that has demonstrated 'energy break-even' (i.e., it produces more energy than it consumes in the electromagnetic containment of the fusion reaction). A surge in private investment in fusion technology is now giving the small but prominent fusion community more ammunition for changing the prospects. Commonwealth Fusion Systems is the leading contender which is a spinout from MIT's Plasma Science and Fusion Center, leveraging decades of research. It recently received $1.8B in B-round financing from a long list of well-respected technology investors including Bill Gates, Tiger Global, John Doerr (Kleiner), Google, Temasek, Breathghrough Energy Ventures. CFS will use this capital to build SPARC, the world's first "commercially relevant" net energy fusion machine and to start building ARC, the first commercial fusion power plant.

Biggest unknowns:

- Will the public ever be sufficiently comfortable with nuclear as a larger part of the energy grid?
- What is the potential production capacity for small modular reactors and how fast can we scale over what time frame?
- Will the US DoE and other sovereign R&D funding sources step in to make fusion a reality sooner than expected?

Question 12: What role will carbon capture technology play in the transition?

Carbon capture technology will likely be crucial in decarbonising more difficult to abate emissions from heavy industry from 2030 onwards. Both carbon capture and storage of emissions at the point of industrial processes or fossil fuel electricity generation and direct air carbon capture (DACC) out of thin air, are still nascent developments. The means of making either technology cost efficient is still unproven. The IEA "pathway model" expects 15% of the contribution to NZE to come from carbon capture. At a global level, there are currently 31 commercial carbon capture facilities that are operational or under construction, with the capacity to capture 40M tonnes of carbon per year.[30] This includes 19 coal fired plants across the globe with CCS. This is very much a drop in the ocean given that the world currently emits 40-50B tonnes of carbon each year. Based on the limited progress to date and what we know now about the technology, we would put a low probability on this IEA goal being achieved.

Carbon capture is the process of capturing carbon dioxide either directly from the air (DACC) or capturing the carbon dioxide formed during power generation or industrial processes (Carbon Capture and Storage). The captured carbon is compressed, deeply chilled and transported to storage sites where it is injected into underground geological formations (a process known as mineralisation), to be stored long term, preventing it from entering the atmosphere. Storage sites include former oil and gas reservoirs, salt caverns and coal beds.

We describe the two forms of carbon capture in more detail below:

- **Carbon Capture and Storage (CCS):** There are three types of CCS. Post-combustion CCS, the primary method used in existing power plants, is where carbon is separated directly via a filter on the exhaust of the emitting facility. Pre-combustion CCS, the primary method used in industrial processes, involves gasifying fuel and separating out the carbon dioxide, but can only be applied to new facilities. Finally, there is oxy-fuel combustion where fuel is burned in a near pure oxygen environment which results in a more concentrated stream of carbon dioxide emissions which is easier to capture.

- **Direct Air Carbon Capture (DACC):** Industrial scale fans are used to draw in air across a filter that is soaked in potash. The potash absorbs the carbon dioxide, and this liquid is then mixed with calcium hydroxide which reacts to form limestone. The limestone is then heated until it decomposes releasing pure carbon dioxide which is then captured and stored[32].

The Intergovernmental Panel on Climate Change has explicitly warned that in order to limit global warming to just 1.5c by 2100, it will require the large-scale deployment of carbon negative technologies such as DACC. The latest modeling by the panel suggests we will need to capture 15% of total emissions. Obviously, the panel's estimate of what is needed has no relevance to what is technically and economically possible.

CCS potential applications

- **Heavy industry:** If we look at heavy industry such as chemicals and steel production, roughly 90% of the emissions could be reduced by switching to green hydrogen. The cement industry is different. Cement carbon emissions are not created primarily from burning fuels, they are emissions from the process itself as illustrated in Exhibit 34. This effectively means that carbon capture is likely to be the best method utilised to allow the cement industry to reach net zero. For context the cement industry produces roughly 3B tonnes of carbon each year (8% of global emissions).

- **Coal and gas fired plants:** Another potential use would be to allow coal and gas fired plants to continue to operate if they are retrofitted with CCS technology. The first large scale coal-fired power station was equipped with CCS in 2014 in Canada. As of 2020, there were 19 coal fired power plants across the globe operating with CCS. Coal gasification plants can more economically separate out the CO2, capture it and store it. Coal fired plants capture the CO2 from the exhaust which must be expensively separated from the nitrogen, oxygen and water in the exhaust. IEA analysis performed in 2018 put a cost of $110/tonne on carbon capture from the 2014 Boundary Dam plant and $64/tonne at the Petra Nova plant with CCS installed in 2017.

In November 2021, the La Porte Texas natural gas "test" plant delivered emissions-free electricity to the grid

Below:
Direct air capture technology
Image: Climeworks

---

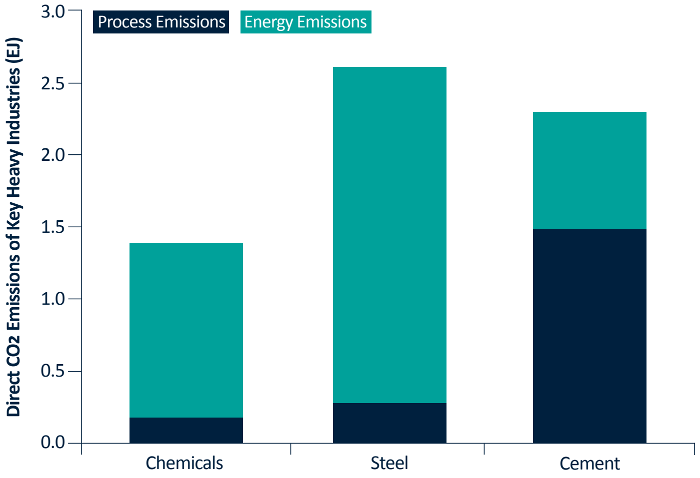
30 https://www.rff.org/publications/explainers/carbon-capture-and-storage-101/#:~:text=Carbon%20capture%20and%20sequestration%2Fstorage,CO%E2%82%82%20emissions%20in%20energy%20systems.

31 https://www.rff.org/publications/explainers/carbon-capture-and-storage-101/#:~:text=Carbon%20capture%20and%20sequestration%2Fstorage,CO%E2%82%82%20emissions%20in%20energy%20systems.

32 https://www.bbc.com/future/article/20210310-the-trillion-dollar-plan-to-capture-co2

Exhibit 34

The cement industry requires carbon capture due to its process emissions



Source: *Goldman Sachs*

for the first time anywhere in the world for this kind of technology. The plant operates using CCS technology which works by burning natural gas with pure oxygen, instead of air, and using "supercritical" carbon dioxide, instead of steam, to drive a turbine and generate electricity. Excess CO2 is captured and is "pipeline ready" for underground storage in geologic formations or use in industrial processes.

What are the key constraints?

- **Cost:** The largest costs of CCS are typically associated with the equipment and energy needed for the capture and compression phases. Capturing the CO2 can decrease the host plants' efficiency and increase their water use. The additional costs posed by these and other factors can ultimately render a CCS project financially nonviable.
In the US, there are national and state tax credits/offsets encouraging CCS investments. World R&D on CCS exceeded $1 billion per year over 2009 to 2013, then fell sharply.

An August 2020 research study published in the Royal Society, authored by Rutgers University academics Schmelz, Hochman and Miller, estimated the theoretical cost of CCS with coal and gas plants. The analysis suggests coal-sourced CO2 emissions can be stored in North Eastern US at a cost of $52–$60/tonne, whereas the cost to store emissions from natural-gas-fired plants ranges from approximately $80 to $90/tonne.

With current technology, DACC costs roughly $600/tonne to pull carbon from the air. In late 2021, the U.S. Department of Energy announced what it calls a "carbon negative shot" as part of its Energy Earthshots Initiative. This entails a significant investment in technologies meant to eventually take a billion tonnes of carbon from the air each year for the relatively affordable price of $100/tonne. The bipartisan infrastructure law that passed in mid-November has funded the effort with about $3.5 billion.

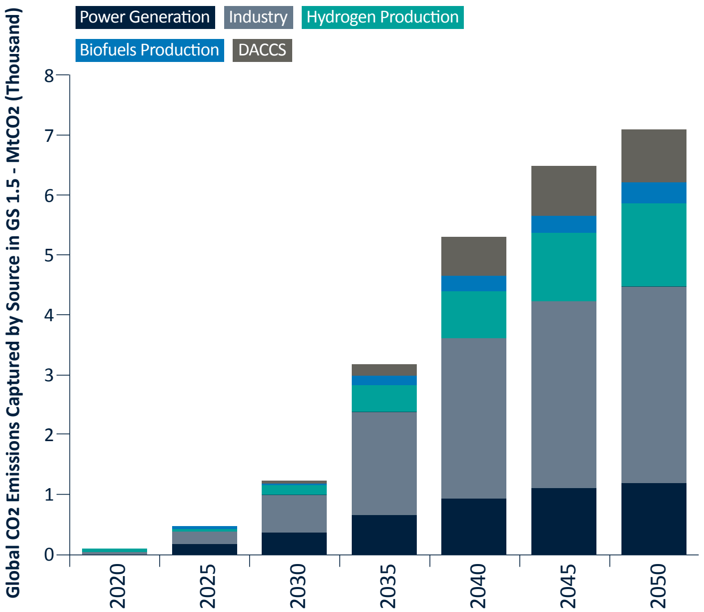
- **Transportation:** There is a significant input of energy required to compress and chill captured carbon dioxide to enable it to be transported. Existing oil and gas pipelines cannot be used for transportation. New pipelines must be specifically designed and built. This is not a significant issue if the carbon capture and storage occur in close proximity.

- **Storage Capacity:** The availability of geologic storage is generally not considered a barrier to widespread CCS deployment, at least not in the short to medium term. Experts suggest that there is more than sufficient storage worldwide for at least the next century. While some researchers have expressed concerns about the long-term ability of storage sites to sequester carbon without significant leakage, a 2018 IPCC report concluded that "current evaluation has identified a number of processes that alone or in combination can result in very long-term storage". There is also some potential for seismic activity caused by underground injection of CO2. Researchers continue to look at ways to minimise this risk, including considering above-ground carbon dioxide mineralisation[33] as an alternative to underground storage.

Where are we in the development of CCS and DACC? Of the 31 commercial carbon capture facilities around the world, 19 of these are DACC plants operating or being built across Europe, the US and Canada. None are operating at a significant enough scale to prove that the technology is viable on a global level. The largest DACC facility currently in operation is the Climework's ORCA plant in Iceland which is capable of filtering 4,000 tonnes of carbon out of the air. Climework's counts Microsoft, Spotify and Swiss Re amongst its customers who are seeking methods to reduce their carbon impact. Carbon Engineering and Occidental Petroleum are partnering to build the first large scale plant in Texas which they believe will be capable of capturing 1M tonnes per year at a cost of under $200/tonne and could be operational as early as 2024. If the larger scale projects prove to be successful, experts believe that by 2030 we may be able to capture 1B tonnes of carbon per annum and up to 7B tonnes per annum by 2050 (Exhibit 35). That would represent roughly 15% of present-day emissions. As for CCS, Heidelberg Cement, one of the world's largest building materials companies, is set to launch the world's first industrial scale carbon capture and storage cement production facility in Brevik Norway. The plant aims to capture 400,000 tonnes (50% of current emissions) of carbon dioxide annually and is expected to be operational by 2024. The current cost of CCS at existing global facilities ranges between $40-120/tonne of carbon which is far lower than DACC but the IEA note that this high cost and inappropriate pricing of carbon by policy makers is one of the key reasons for the slow uptake of the technology. Analysis from Goldman Sachs suggests that industrial demand for the technology will be driven by a combination of the cement, metals and chemicals sectors.

Exhibit 35

Global captured carbon emissions could reach 7B tonnes by 2050; most of which is from industrial process capture



Source: *Goldman Sachs*

Biggest unknowns:

- Is there a possibility that technological breakthroughs drive carbon capture costs down below $100/tonne and this changes the overall path to NZE?

---

[33] Captured carbon is injected into geological formations

Question 13: How will the substitution of various alternative sources of energy evolve and what will they cost?

There are huge uncertainties around the pace of the renewable energy roll out, with the largest obstacles being the transmission infrastructure upgrades, growth of grid storage batteries, production and storage of hydrogen, carbon capture technology and regulation – pretty much every dimension covered in this document. But relying on the pace of roll out modeled by the IEA and others, we arrive at a fairly dramatic reduction in the cost of energy. The current $82/MWh global average cost of electricity is forecast to decline to $68/MWh by 2030 and fall to $25/MWh in 2050 (in 2022 USDs). There may well be increases in cost in the 2023-28 time frame, before we see decreases. Based on the long-term climate objectives and the shorter-term technological constraints we believe that natural gas and nuclear, where available, will likely bridge the gap for the next decade until batteries and hydrogen storage technology reach the point of wide scale utility. At that point renewables will come to dominate the power grid supported by a combination of nuclear and natural gas plants fitted with carbon capture technology. Batteries will support day to day grid management and hydrogen will support the grid for seasonal management of surpluses/deficits.

What will drive the rate of substitution between baseload energy sources (coal, natural gas and nuclear) and renewables? The analysis below, summarised in Exhibit 36, illustrates that wind and solar are competitive on a cost basis today. The problem with these fuel sources is their intermittent nature or “capacity factor” which will require a storage solution either via batteries or hydrogen storage. Land usage is also a factor that must be taken into consideration given their lower energy density. The pace of substation will be determined by the following factors:

1. Streamlined regulations surrounding transmission line expansion
2. Developments in long term renewable storage technology most notably, lithium-ion batteries and green hydrogen storage.
3. Relative cost of energy sources including regulatory drivers (subsidies, carbon taxes), commodity input costs and the price of land.
4. The amount and availability of land needed to develop the required infrastructure.
5. The success of moon-shot projects in carbon capture and nuclear.

Our analysis below will highlight the areas we have yet to discuss, transmission line expansion, commodity prices and land mass requirements. Prior to this we summarise the tradeoffs across the five core sources of energy.

Exhibit 36

Summary of tradeoffs among the five core sources of power generation

Fuel Source	LCOE (Levelised Cost of Energy) (USD)	CO2 Emissions (1000 tonnes emitted/ GWh)	Capacity Factor (Reliability) (Actual operating time/ theoretical operating time 2011 - 2020)	Land usage (Land area required to power a flat screen TV)	Construction Time (Years)	Proposed Solutions
Natural Gas	58.5	499	61%	0.1m^2	N/A	Carbon Capture
Coal	112	888	54%	0.8m^2	N/A	Carbon Capture
Nuclear	105	29	91%	0.3m^2	>10yrs	Small Modular Reactors
Wind	26	26	34%	37m^2	<2yrs*	Batteries/ Hydrogen Storage
Solar	30.5	85	24%	14m^2	< 2yrs*	Batteries/ Hydrogen Storage

Note: *The levelised cost of energy (LCOE) is the standard metric used to compare the cost of generating power from each potential source. It takes into account the total lifecycle costs of each energy source, adds a cost of carbon ($30/tonne), includes government subsidies and a market weighted average cost of capital assumption.*

Source: *Partners Capital analysis.*

**Transmission line build outs can take up to 10 years in many areas.*

Exhibit 37

Renewables emit just 2-8% of what the worst emitting fossil fuel emits today

Fuel Source	CO2 (1000 tonnes) emitted/GWh	As a % Lignite Coal
Lignite Coal	1054	
Coal	888	84%
Oil	733	70%
Natural Gas	499	47%
Solar	85	8%
Biomass	45	4%
Nuclear	29	3%
Hydroelectric	26	2%
Wind	26	2%

Source: *world-nuclear.org*

As is summarised in Exhibit 36, CO2 emissions of wind and solar are a very small fraction of carbon-based fuels. Exhibit 37 shows the total lifecycle emissions associated with the fuel source, including carbon emissions in the construction phase (e.g., steel produced in building a wind turbine). Natural gas is the “least bad” fossil fuel emitter with half of what lignite coal emits.

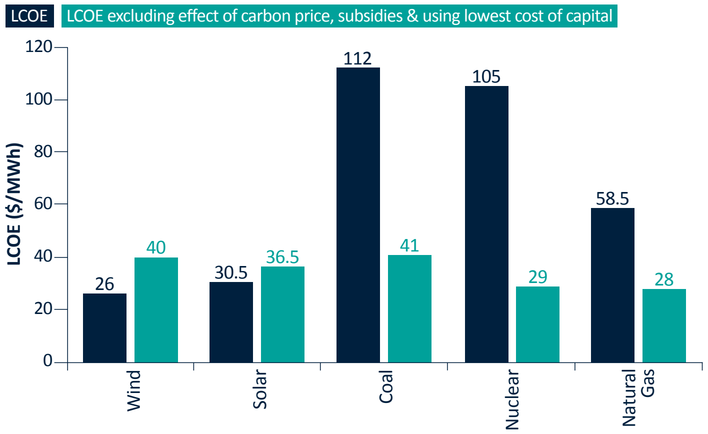
Renewables are competitive on a cost basis today once carbon taxes/credits and subsidies are factored in as you can see in Exhibit 38. The levelised cost of energy (LCOE) is the standard metric used to compare the cost of generating power from each potential source. It takes into account the total lifecycle costs of each energy source, adds a cost of carbon ($30/tonne), includes government subsidies and a market weighted average cost of capital assumption. As of December 2021, wind and solar are the cheapest energy sources once carbon pricing and subsidies are reflected. However, even without carbon pricing and subsidies, wind and solar are on a par with coal and only marginally more expensive that nuclear and natural gas. It should also be noted that the International Renewable Energy Agency (IRENA), in a study from May 2021, forecasts that by 2030 the weighted average cost of electricity in G20 countries from wind energy could fall by almost 50% from 2019 levels (Exhibit 39) and the cost of solar could fall by up to 55%[34].

---

[34] https://www.powerengineeringint.com/renewables/irena-wind-and-solar-costs-will-continue-to-fall/#:~:text=With%20the%20auction%20data%20suggesting,of%20an%20increasing%20number%20of

Exhibit 38

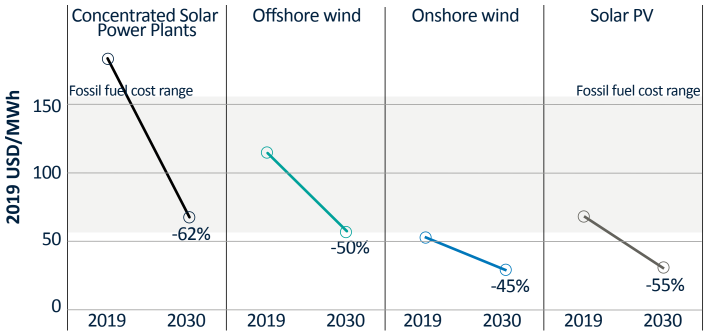
Renewables are competitive once carbon pricing and subsidies are accounted for



Source: *Lazard and IEA*

Exhibit 39

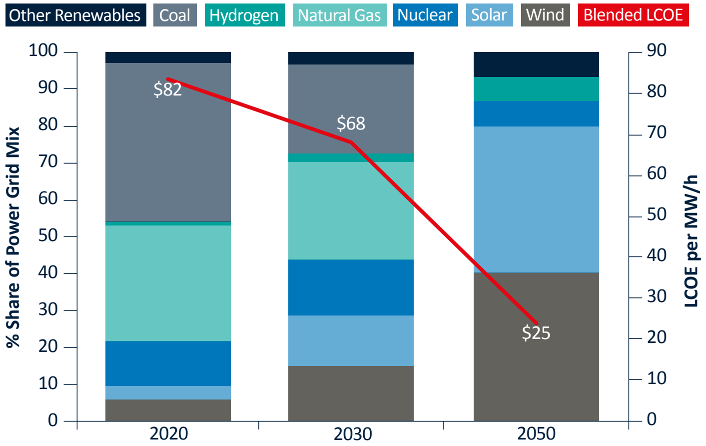
Weighted-average G20 levelised cost of electricity reduction potential, 2019-2030



Source: *IRENA*

Exhibit 40

The current $82/MWh average cost of electricity is forecast to decline to $68/MWh by 2030 and fall to $25/MWh in 2050 (in 2022 USD)



Source: *IRENA/IEA. Blended cost estimates exclude hydroelectric (14% in 2020) as it is a relative constant supply share and has prices that reflect costs of other energy sources. This reflects the expected costs in the US and Europe, ignoring the fact that China will still be relying on coal beyond 2050.*

The good news is that renewable costs have much further to go down the cost curve. IRENA has estimated the likely cost/MWh of both types of solar power (photo voltaic (PV) and concentrated solar power plants (CSP)) and both types of wind power out to 2030, with average further reductions from 2019 prices of 45-62%.

Reductions like those above have been projected out to 2050 as well. By 2050, IRENA estimate that 86% of global power demand will be facilitated by renewables. Using data from IRENA and the IEA, we estimate that the blended cost of grid power in 2050 will be in a range of $20-30/MWh (in 2022 USD). This assumes that the price of wind and solar power will fall by roughly -50% in real terms and that wind and solar power will come to represent 70-80% of the grid's power sources. The remainder of the grid will be powered by an equal combination of hydrogen, nuclear and renewables supported by battery technology. We also assume that the cost of producing green hydrogen energy falls by -40% in line with market forecasts, the cost of nuclear will fall by -20% with the adoption of small modular reactors and that battery storage costs will fall by roughly -60% in line with forecasts from Columbia University. In Europe and the US at present, data from the IEA suggests that the current blended power cost to be roughly $70-85/MWh[35]. Exhibit 40 provides a forecast of the power grid mix and the blended cost of power out to 2050. The move to renewables and their anticipated fall in cost is the key driver of the overall fall in the cost of power out to 2050. Fossil fuels sources such as coal and natural gas prices are expected to rise out to 2030 on the assumption that global carbon prices will increase.

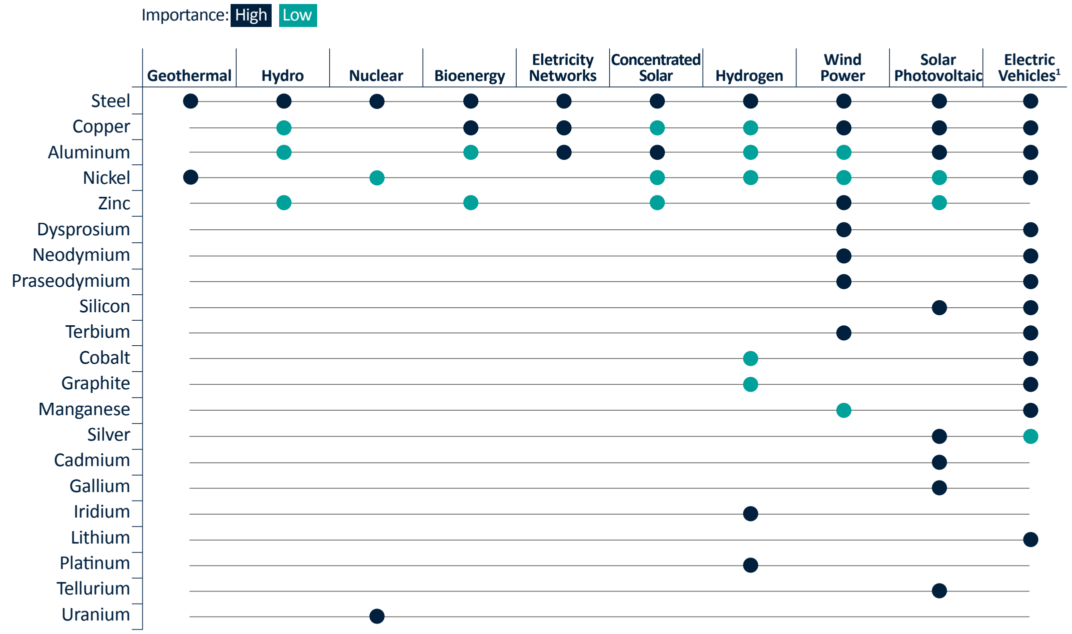
This trajectory of electricity costs ignores the likely spikes in cost between now and 2030. The sheer pace of growth will undoubtedly create commodity shortages and pressure on end products (wind turbines, solar panels, Li-ion batteries, nuclear reactors, transmission infrastructure, hydrogen electrolysers, etc.) that will create price rises for consumers. But by 2030, those inflationary pressures should subside as supply and demand is brought more into balance. Component and service suppliers to these producers who can unlock the bottleneck, should be one the most attractive investment areas in and around the energy transition.

The impact of commodity shortages and price inflation may impede renewable energy cost competitiveness and the pace of the transition to NZE. The cost of low carbon energy and electric vehicles is usually estimated using commodity input costs that may well be underestimated. The prices of steel and base metals such as copper, aluminium, nickel and zinc are likely to be pushed up to stratospheric levels by the scale of wind farms, solar PVs, EVs, EV charging stations, EV and grid batteries and other components of a low carbon energy infrastructure.

As you can see in Exhibit 41 below, after steel, copper is the most widely used mineral among energy technologies and is essential for all electricity-related infrastructure. It is a key component of power grids, wind and solar farms as well electric vehicles (EVs) and EV charging infrastructure. It is estimated that "green" demand for copper will more than double out to 2030 and overall copper demand will increase by 30-40%[36].

Exhibit 41

Materials critical to the transition to a low-carbon economy, by technology type



Importance: ● High ○ Low

	Geothermal	Hydro	Nuclear	Bioenergy	Eletricity Networks	Concentrated Solar	Hydrogen	Wind Power	Solar Photovoltaic	Electric Vehicles[1]
Steel	●	●	●	●	●	●	●	●	●	●
Copper		○		●	●	○	○	●	●	●
Aluminum		○		○	●	●	○	○	●	●
Nickel	●		○			○	○	○	○	●
Zinc		○		○		○		●	○	
Dysprosium								●		●
Neodymium								●		●
Praseodymium								●		●
Silicon									●	●
Terbium								●		●
Cobalt							○			●
Graphite							○			●
Manganese								○		●
Silver									●	○
Cadmium									●	
Gallium									●	
Iridium							●			
Lithium										●
Platinum							●			
Tellurium									●	
Uranium			●							

Source: *McKinsey*

---

[35] IEA

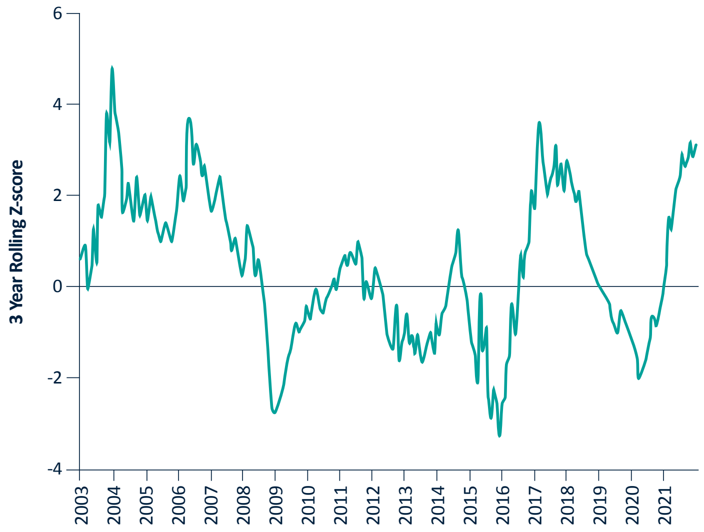
[36] https://www.visualcapitalist.com/visualizing-copper-demand-for-renewables/

McKinsey estimate that generating one terawatt-hour of electricity from solar and wind consumes two to three times more metals than generating the same terawatt-hour from a gas-fired power plant. Looking specifically at EVs, they will be another significant incremental demand driver for copper. They require four times as much copper as a traditional internal combustion engine (ICE) vehicle. The current batteries in EVs require lithium and cobalt as their core components and demand for these metals is expected to increase by 10x and 5x respectively out to 2030. While supply of copper is expected to increase significantly in the coming three years, it should also be noted that persistently low capex in the mining sector is expected to lead to a shortfall from 2025 based on this expected demand growth.

The supply of cobalt and lithium are also a concern. According to the 2021 BP Statistical Review, the majority of global lithium reserves are in South America and Australia. China has 7.9% of the world's lithium reserves and the U.S. has 4.0%. However, China processes 61% of the world's lithium. The Democratic Republic of Condo (DRC) holds 50% of the world's cobalt reserves. Amid the rise of EVs, China became the top producer of refined cobalt, accounting for about 65% of the global output in 2019.

Exhibit 42

A basket of the commodities most core to the buildout of green energy are already priced today at 3 standard deviations above the average price of such commodities



Source: Bloomberg

China's control of the lithium and cobalt processing industry gives it huge influence over prices and access. Exhibit 42 below shows that a basket of the commodities most core to the buildout of green energy are already priced today at 3 standard deviations above the average price of such commodities.

The biggest constraint on renewables is that they are intermittent and weather dependent. Their capacity factor, which is the average actual output versus the theoretical potential output, demonstrates the difficulty in fully transitioning the power grid to renewables. Natural gas, for instance, has a capacity factor of roughly twice that of a combination of wind and solar. This is illustrated in Exhibit 43. The average power outage duration per customer in the US has increased from three hours in 2013 to eight hours in 2020 as renewables have come to represent a greater proportion of the US energy mix. Grid operators have had to adapt to the challenges this provides[37]. Grid-scale battery storage can aid renewables by storing power sufficient to provide power for three to four hours once the solar or wind has stopped producing. But batteries are not a solution for long periods of low renewable output during the dark, cloudy and windless times of year.

Exhibit 43

The key issue with renewables is that they are intermittent

Power Source	Capacity Factor (avg. 2011 - 2020)
Nuclear	91%
Natural Gas	61%
Coal	54%
Wind	**34%**
Solar	**24%**

Source: EIA

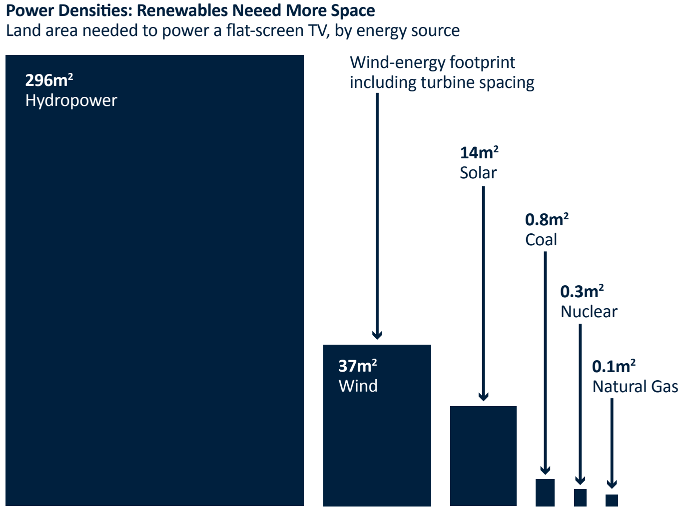
Land mass requirements may constrain wind and solar expansion. This switch will require a lot of land but it does appear to be feasible. Princeton University's Net Zero America project has looked specifically at the issue of the land usage required to produce the required scale of renewable energy for the United States. Exhibit 44 shows the land area required by energy source to power a flat screen TV. The US Department of Energy estimates that the US currently utilises 81M acres of land to generate its energy requirements, which is roughly 4% of the US landmass[38].

Princeton University proposes two potential scenarios to achieve net zero by 2050, one which relies nearly entirely on renewables (98% from wind/solar) and a more pragmatic approach that utilises a combination of wind, solar, nuclear and natural gas overlayed with carbon capture technology. They estimate that demand for electricity will triple out to 2050 but the efficiency of various technologies will improve over that time.

The first scenario is clearly far more land intensive and would entail a quadrupling of the land being utilised at present to approximately 300 million acres or roughly 16% of the US landmass (equivalent to coverage of Arkansas, Iowa, Kansas, Missouri, Nebraska and Oklahoma). In that first scenario, electricity would power all vehicles, warm/cool homes and power most industrial processes. Grid shortages would be supported by batteries and hydrogen powered turbines. They estimate that this would require building an extra 250M acres of windfarms, 17M acres of solar panel rooftops and solar farms together with the other associated storage infrastructure (batteries and hydrogen). This has raised questions of feasibility, but the US department of agriculture note that this would be possible as wind farms can be placed where it does not interfere with other agricultural purposes (pasture/cropland), unlike solar farms. The growth in solar panels would rely heavily on rooftop fittings in areas that enjoy high levels of solar exposure, such as California. Exhibit 45 illustrates that the current land usage in the US could support such a scenario given that there are 1.6 billion acres in forest, cropland and pasture.

Exhibit 44

Wind and solar require more space to generate energy relative to traditional fuel sources



Source: Princeton

Many European countries and Japan are of course not in a similar situation with respect to available land mass as the US. But huge emitters like China, Russia, India and Indonesia may have similar scope for massive rollouts of wind and solar.

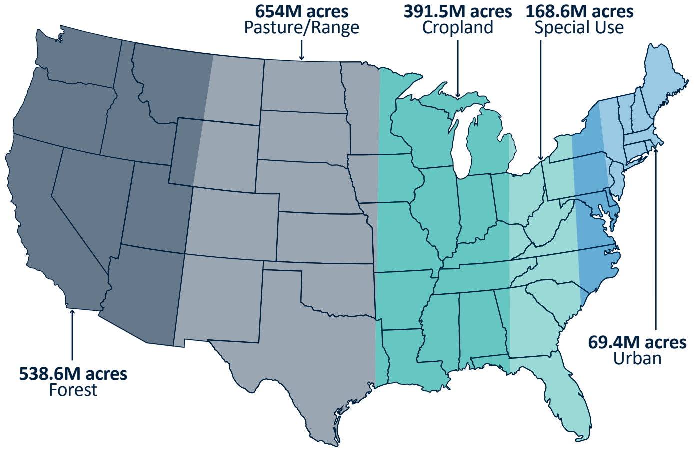
---

[37] EIA

[38] https://www.bloomberg.com/graphics/2021-energy-land-use-economy/?sref=ABA0JC7B

Exhibit 45

The most aggressive wind and solar roll out scenario (by Princeton) will require c 16% of the total 1.9B acres in the US lower 48 states. Forest, cropland and pasture offer 1.6B acres



Source: *Bloomberg/DOA*

In the second scenario, Princeton look at how the US could achieve net zero utilising the least amount of land (7% = 4% at present + 3% additional). This would entail building hundreds of nuclear power plants (250 standard plants or several thousand small modular reactors) and retrofitting natural gas plants with carbon capture technology. In this scenario, just over 60M acres of wind farms and 3.5M acres of solar farms would be added. Wind and solar would contribute just under 50% of electricity generation in this 2050 scenario, but it would require an unprecedented pace of adoption for nuclear technology and a significant reduction in cost for carbon capture. Furthermore, the captured carbon would require transportation infrastructure and carbon dioxide pipes spanning a length totalling 500,000 acres.

Given the possible negative response to 16% of the country having to host wind and solar infrastructure, we see this second scenario as much more likely where renewable energy sources are augmented with nuclear power with some support from natural gas fitted with carbon capture technology.

Exhibit 46

Estimated timeline for transmission line projects (US)

Approval process	Low Estimate (months)	High Estimate (months)
Environmental Assessment and Routing Study	9	12
Public Utility Commission Processing	12	15
Surveying, Right of way acquisition, Permitting	18	60
Construction Process	12	48
Total Time	**51**	**135**

Source: *ONCOR*

Transmission line buildout is another potential constraint on the renewable roll-out. Analysis from Princeton University suggests that the US must at least triple its transmission infrastructure in order to decarbonise by 2050. Steve Cicala, an economics professor at Tufts University, notes that solar and wind are now the cheapest forms of electricity generation in most parts of the US, but those lower costs will only matter if the largest power markets in the country are connected via new transmission networks. The entire process for a major transmission line project can take up to 11 years as shown in Exhibit 46. While the construction phase is challenging to expedite, up to five years is spent in the surveying, right of way acquisition and permitting phase that authorities believe can be curtailed with regulatory improvements. Most transmission line projects face pushback during the permitting and right of way process, including opposition from state regulators, established power providers and individual property owners. Companies that own nuclear and fossil-fuel plants, for example, often raise concerns about their ability to compete with wind, solar or hydropower delivered from other markets.

The Biden administration is attempting to speed up the permitting process for high-voltage power lines as part of its drive to promote renewable energy. Their proposed changes, which include giving the federal government more authority to intervene in state-level permitting decisions, are intended to expedite the approval of new transmission lines. The November 2021 infrastructure bill empowers the Federal Energy Regulatory Commission to issue permits for certain transmission projects even if a state has denied approval. Developers have suggested that they believe that the new measures will assist in streamlining approvals, but they might not go far enough.

The administration is seeking to replicate the success that has been observed with infrastructure projects for fossil fuels in the last decade. From 2010 to 2019, the US added 107,400 miles of gas pipelines. Companies are able to build pipelines quickly because the federal government has streamlined the process. Unlike other types of infrastructure, which typically require federal, state, and local approval, gas pipelines have, since 1938, only required the Federal Energy Regulatory Commission's (FERC) stamp of approval. The Supreme Court has repeatedly enforced the FERC's power, ruling that the FERC can condemn state-owned land if the agency chooses to do so. No such process exists for electricity transmission. As it stands if you want to build a new transmission line, you must secure the buy-in of multiple state and local agencies, in every state you pass through.

Putting all of these factors together, it would suggest that natural gas and nuclear will continue to be relied upon until adequate, cost-effective mediums of storage for renewables can be developed and until the transmission infrastructure is upgraded. Furthermore, given its far smaller impact in terms of land usage, nuclear may be a significant part of the long-term solution if issues with construction time, waste material and perceptions of safety can be addressed. The first, large scale, green hydrogen storage facilities are set to open in the coming 3-5 years and if they are successful, they will facilitate a large-scale transition to renewables.

Biggest unknowns:

- With the massive growth rates behind the core infrastructural components of the energy transition, where will the most critical supply constraints be and what will be the implications be for electricity inflation (especially in the 2023-2028 time frame)?
- Will policymakers step in to accelerate the pace of the transmission infrastructure upgrades required for solar and wind to get to the user?
- Will the public accept a scenario where 7 - 16% of the landmass is utilised for renewables? If not, does this point to a bigger role for nuclear?

SECTION 3: Investment Implications

Question 14: What are the most investible conclusions regarding the path to net zero emissions (NZE)?

The "so what?" of all of the discussion of the path to NZE are the key assumptions, on which investors should be able to rely when making investments. Very little we have written is certain, but the list below comprises our key conclusions about the path to net zero. These are the conclusions which we believe at this point in are the broadest reaching and most relevant assumptions that investors should factor into their range of possible scenarios for any given investment.

1. Based on the long-term climate objectives and the shorter-term technological constraints, we believe that natural gas and nuclear, where available, will likely bridge the gap for the next decade until batteries and hydrogen storage technology reach the point of wide scale utility. At that point renewables will come to dominate the power grid supported by a combination of nuclear and natural gas plants fitted with carbon capture technology. Batteries will support day to day grid management and hydrogen will support the grid for seasonal management of surpluses/deficits.

2. We believe the green transition will expose vulnerabilities in energy supply chains, prompting policy makers to accept a more pragmatic approach towards fossil fuels, in the near term, and nuclear power in the long term.

3. Technological breakthroughs in grid-scale battery technology, nuclear power and hydrogen electrolysis will be among the most powerful drivers of a successful energy transition. Expect to see major government R&D budget allocations in the US, Europe and China behind these three areas ahead of others. Nuclear fusion is also likely to receive significant additional funding, but with a longer timeframe before it contributes significantly to the energy transition.

4. The cost of carbon, as measured by the variable cost of capture and sequestration, will need to be factored into the cost of most financial assets, but with varying phasing of implementation. Many assets will become permanently non-viable which are what investors are dubbing "stranded assets." Insights into company/asset valuations based on moving carbon costs will be critical for any active asset manager to understand while investing in virtually any asset class.

5. Similar to the solar panel industry, China is likely to dominate the global lithium-ion batteries industry as a result of a more rapid transition to EVs and is also likely to dominate hydrogen electrolysis and small- and large-scale nuclear fission technology.

6. Scale, cost-effective carbon capture (whether CCS or DACC) is a long way off from reality. The technology needs much more public and private capital behind it for it to have a chance of making the 15% contribution toward NZE the IEA forecasts.

7. The price of green commodities (e.g., copper, nickel, zinc) which are perceived as crucial to the next phase of the transition may rise to such levels as to compromise the economic competitiveness against high carbon emitting alternatives (e.g., natural gas, ICE vehicles).

8. The largest area of investment, at an estimated $960B per year, will be building renovation and retrofitting for energy efficiency – making buildings "smart" about energy consumption. Micro power grids, HVAC efficiency improvements, energy monitoring and residential home management systems will be among some of the largest scale new opportunities supporting the overall energy transition.

9. The land required to build out renewable infrastructure is vast and may become quite valuable where its previous utility may have been limited. Investment in farmland and timberland trusts may become long-term sources of real asset appreciation and diversification.

10. Investors should watch for corporate demand signals in the market for some of these decarbonisation technologies and get out in front of the implied supply chain. For example, the big consumer goods players are resetting the fuel standards for trucking and the big auto makers are starting to reset the standards for steel decarbonisation.

11. Green power equipment recycling will become a massive new industry (wind turbines, solar PV cells, EVs, grid-scale batteries, etc.).

12. Investors need to match the cost of their capital with the investment. The cost of capital for different energy transition investments varies hugely from c. 3-5% for wind and solar infrastructure to 8-12% for project finance in building out early but proven technologies, to 20% or more for early stage technology investments.

Right:
Nickel mines, Thio, east coast, New Caledonia
Image: Alamy

Question 15: Where might investors be blindsided?

As mentioned at the outset of this document, the first burst of investment activity behind the energy transition, what is referred to as Cleantech 1.0, from 2005-15 was disappointing for all. Many private investors and public companies dove in with good intentions, but a poor understanding of the macroeconomic reality of clean energy. The very purpose of this paper is to guide investors in the energy transition to not end up in the same place as Cleantech 1.0. Investors in 1.0 were blindsided by regulatory U-turns, China's determination to dominate solar and other sectors, the capital intensity of many of the new technologies and the very slow pace of technological development.

From what we have learned in the process of answering the first 13 questions, we list below the top 10 major potential negative surprises or blindsides that investors in the energy transition investing space should watch out for.

1. Several or all of the pivotal technologies do not reach breakeven cost levels including storage batteries, hydrogen, carbon capture systems and small scale nuclear.
2. Populations rise up against the rising cost of energy and the general inflationary impact, curtailing the pace of the overall energy transition.
3. Transmission system bottlenecks (approvals, line installation) hold back wind and solar roll-out.
4. A reinvigoration of fossil fuel-based energy is required to build green sources of energy for many more years. The pace of fossil fuel substitution slows out of the needs of the EV and renewable energy infrastructure.
5. The pace of the energy transition buildout will create acute shortages in raw materials as well as core infrastructure components. Supply will be a bottleneck for many businesses that are core to the transition.
6. China dominates lithium-ion battery supply (and much of the raw materials), green hydrogen electrolyser technology and nuclear reactor technology.
7. Governments may invest in "moon-shot projects" backing rival technologies to the incumbents, which are game changers given the scale of resource they can supply. This could apply to grid-scale battery technology, nuclear fusion, hydrogen electrolysers or any area where a government feels they need to bring a foreign sourced component onshore, or there may be national competitive advantages sought, or they simply want to open up a potential bottleneck to the path to NZE.
8. As virtually all companies eventually set their own carbon emission targets, this creates excess demand for carbon offsets, driving up the cost of carbon to points not anticipated, increasing the universe of stranded assets and non-viable companies.
9. Carbon credits may not always be an acceptable means of companies achieving emission targets (it is viewed as passing the obligation off to others), thus forcing companies to dramatically alter how they operate and creating more stranded assets.
10. Popular protests by landowners, and citizens in general, extend to the pace of wind farm and solar farms and parks' land appropriation as large swaths of the country are covered with them.

There will be many other potential surprises and, even more, actual surprises.

Question 16: What areas would appear to have the most attractive risk adjusted returns and impact?

The answer is different for public equity investors and private equity or private debt investors. Investors in public companies want to invest in those companies who can have the biggest impact and the most to gain from the transition. This could be current fossil fuel producers, energy utilities, EV manufacturers, charging infrastructure or the smaller developers and builders of the critical technology. Private equity and private debt investors will want to very carefully pick their spots for their $20-40B of capital among the $3T or more being invested each year by governments and corporations with much lower return expectations and capital costs.

For both public and private equity investors, the most attractive investment opportunities in support of our sustainability investment theme are those which sit in pivotal positions on the path to net zero emissions. We expect that the highest returns will be earned where our managers, through their deep fundamental research and energy sector insights, are finding the companies who are advancing essential proven technologies that unlock the scale deployment of green energy, along with specialist product and service suppliers to the industries growing fastest on the back of the drive to net zero emissions.

Cleantech 1.0 investors were surprised by the capital intensity of the infrastructure buildout. Now many years later, the bulk of the development will be undertaken by large publicly financed energy utilities, energy commodity producers, auto manufacturers and technology companies. This is not a space for private equity investors who come with a much higher cost of capital. Public securities investors, like us, will seek to overweight allocations with those corporate management teams that have the means and capability to manage the transition within their own businesses, fully aware of the hurdles and potential surprises listed under question 15 above.

Buyout firms and growth equity firms classically invest behind well-proven stable cash flowing businesses and do not take business model risk or technology risk. The best place for buyout firms and growth equity investors is in proven businesses who are supplying the largest growth sectors with components or services ("picks and shovels") directly on the major thoroughfares of the energy transition map. Ideally, these are the components or services in short supply as a result of the rapid growth and these companies were early in and have market share advantages which will have them gaining a larger share of the growing profit pool. For example, one of our energy transition focused buyout firms, Ara Partners, owns Priority Power which has long been in the business of replacing diesel generators with clean power from the grid for various industrial users. This business is sufficiently niche that it should be protected from many of the big changes that may happen at a macro level behind the energy transition. We provide more examples of attractive energy pathway "picks and shovels" in the bottom half of the chart in Exhibit 47.

Venture capital (VC) firms, on the other hand, take business model and technology risk every day. The best ones will be well aware of what technologies are best developed by large public energy companies, or technology companies, as opposed to venture capitalists. The Energytech VC sector has always been challenging. Attractive investments will be defined as firms with proven breakthroughs, whose commercial success comes down to excellent execution and ample funding to take a leadership position, ideally in a protected niche or someplace where the total addressable market it so huge that it warrants the inherent technology and execution risk.

Below, we finish this document with our "framework for investing in the energy transition". These six sectors seem to be how the market is segmenting with the definition of each of the six sectors provided from the examples listed under each as core subsectors. We expect that our public equity asset managers will be focused on finding the winners in the subsectors listed in the top half. In contrast, our private equity managers, including venture capital, will be focused on firms who are energy transition enabling businesses, most operating in niche markets, listed on the bottom half.

Exhibit 47

The Energy Transition industry sectors include these six, defined by the core subsectors listed, most of which will be developed by large public energy companies with some support from government R&D

	Power	**Transportation**	**Industrial**	**Food & Ag**	**Smart Buildings**	**Recycling & Water**
Core Subsectors	• Wind, solar, renewable fuels, hydro, tidal and geothermal assets and their value chains • Green hydrogen electrolysis, distribution and utilisation • Renewable energy integration, optimisation and service • Grid battery storage systems • Grid management & demand response • Transmission infrastructure upgrades • Hydrogen electrolysers	• Battery & fuel cell optimisation, innovation, value chain and end-of-life management • DC charging infrastructure & service • Hydrogen fuel & infrastructure • Autonomous management, connected vehicles & free-flow tolling • EV battery micro-grid integration	• Electrification/ hydrogenation of Steel, Cement and other high carbon emitting industrial processes • Carbon capture, utilisation and storage (CCUS) including Direct Air Carbon Capture (DACC) machinery • Electrification, power & fuel switching • Green chemistry to produce low carbon materials • Factory water use & process management	• Indoor and vertical agriculture • Satellite imagery for crop management • No-till farming • Alternative proteins • Livestock feed & management software • Regenerative cropping • Targeted irrigation • Automation and electrification of processes • Crop enhancement chemistry • Soil diagnostics • Aerial application of pesticides and fertiliser	• Energy monitoring and management & efficiency • Electric heat pumps • Advanced insulation materials • More efficient Heating, Ventilation & Air Conditioning • Robotics • Advanced appliance efficiency (i.e., solar hot water, pumps, compressors) • Micro- power grid integration • Residential home energy management systems	• Chemical recycling of plastics • Enhanced sorting & robotics • Alternative packaging • Refrigerant collection, monitoring & destruction • Wastewater treatment & recycling • Water desalination • Water distribution • Circular product development & management
Examples of transition enabling investments in niche markets	• Grid storage system integration • Sensing, monitoring, analytics and control solutions for debottlenecking transmission. • Battery management systems • Nat gas pipeline methane leak sensors	• EV battery recycling • Freight logistics & fleet management • Mobility-as-a-Service (MaaS) • LiDAR technology for autonomous vehicles	• Aerial intelligence platform for industry-specific analytics. • CCS project management • HiiROC technology for Turquoise hydrogen production	• Farm machinery fleet management software/AI • Drone-based spraying systems • Electrification of fertilizer production	• Smart building retrofit services	• Fabric recycling • Construction materials recycling

Source: *: Partners Capital in concert with our climate impact private equity asset managers*

Conclusion

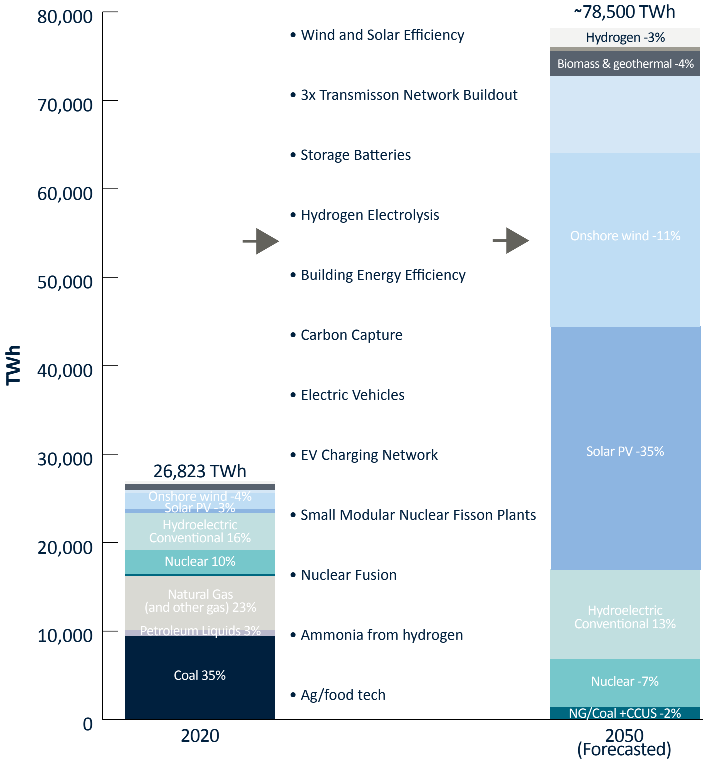
Net zero emissions by 2050 will not be easy. This is "putting a man on the moon" x 100. We admire the commitments being made by sovereign states, companies and institutions. The commitments will be what gets all of us to focus on the solution, but the path is far from clear. The IEA, US Department of Energy (EIA), Goldman Sachs, McKinsey, IRENA, Bloomberg, Lazard and many others that we have learned from in creating this document, have taken great leaps to put forecasts down on paper for what it will take. These are valuable "stakes in the ground," but we are very far away from having a confident route to NZE.

Most, but not enough, governments have made firm policy commitments to carbon reduction and even fewer have legislated emissions reduction actions. This makes sense if there is no clear means to achieving the targets. So we have a chicken and egg problem. It is hard to make commitments without a clear path and it is hard to invest to create a clear path without commitments. John F. Kennedy made a commitment to put a man on the moon way before he had the means and the Americans got there. The energy transition should be the same, but with more at stake. If we had to make a wager we would bet that the leadership will be there and that leadership will create the path. We will work hard to make sure we are investing in highly profitable and impactful ways along that path, mostly behind the critical enablers of achieving the NZE goal as we show in Exhibit 48.

Technology will be the key enablers beyond sovereign and corporate commitments. In particular, we are acutely focused on particular developments in hydrogen, carbon capture, grid-scale batteries and small nuclear power reactors.

Exhibit 48

Investments most critical to the success of the energy transition



Source: *energy data: Goldman Sachs. Enabling technologies: Partners Capital*

DEFINITIONS

Global Emission by Gas

What is Carbon Dioxide?

(Source: Climate.gov)

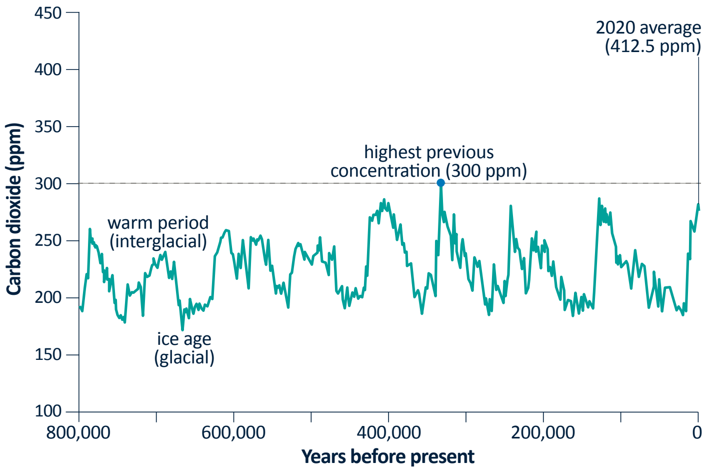
Carbon dioxide is a greenhouse gas: a gas that absorbs and radiates heat. Warmed by sunlight, Earth's land and ocean surfaces continuously radiate thermal infrared energy (heat). Unlike oxygen or nitrogen (which make up most of our atmosphere), greenhouse gases absorb that heat and release it gradually over time, like bricks in a fireplace after the fire goes out. Without this natural greenhouse effect, Earth's average annual temperature would be below freezing instead of close to 15°C. Increases in greenhouse gases are trapping additional heat and raising the Earth's average temperature.

Carbon dioxide is the most important of Earth's long-lived greenhouse gases. It absorbs less heat per molecule than the greenhouse gases methane or nitrous oxide, but it's more abundant, and it stays in the atmosphere much longer. Increases in atmospheric carbon dioxide are responsible for about two-thirds of the total energy imbalance that is causing Earth's temperature to rise.

Approximately 30% of all carbon dioxide emitted into the earth's atmosphere is absorbed into the ocean and reacts with water molecules, producing carbonic acid and lowering the ocean's pH (raising its acidity). Since the start of the Industrial Revolution, the pH of the ocean's surface waters has dropped from 8.21 to 8.10. This drop in pH is called ocean acidification. The pH scale is logarithmic, so a 1-unit drop in pH is a tenfold increase in acidity. A change of 0.1 means a roughly 30% increase in acidity. Increasing acidity interferes with the ability of marine life to extract calcium from the water to build their shells and skeletons.

Exhibit 49 shows the global atmospheric carbon dioxide concentrations (CO2) in parts per million (ppm) for the past 800,000 years. The peaks and valleys track ice ages (low CO2) and warmer interglacial activity (higher CO2). During these cycles, CO2 was never higher than 300 ppm. According to Climate.gov, the global average carbon dioxide composition of the earth's atmosphere in 2020 was 412.5 parts per million (ppm), setting a new record high amount despite the economic slowdown due to the COVID-19 pandemic. In fact, the jump of 2.6 ppm over 2019 levels was the fifth-highest annual increase in National Oceanic and Atmospheric Administration's (NOAA) 63-year record. Since 2000, the global atmospheric carbon dioxide amount has grown by 43.5 ppm, an increase of 12 percent.

Exhibit 49
Carbon Dioxide over 800,000 years

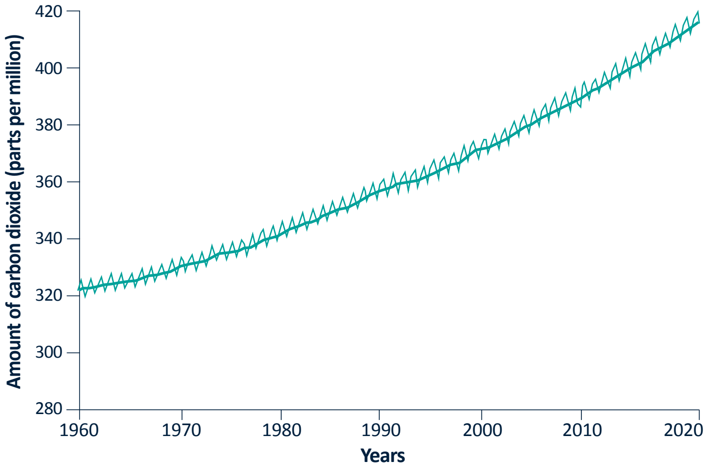


Source: *NDAA Climate.gov, NCEI*

The modern record of atmospheric carbon dioxide levels began with observations recorded at Mauna Loa Observatory in Hawaii. Exhibit 50 shows the station's monthly average carbon dioxide measurements since 1960 in parts per million (ppm). The seasonal cycle of highs and lows (small peaks and valleys) is driven by summertime growth and winter decay of Northern Hemisphere vegetation. The long-term trend of rising carbon dioxide levels is driven by human activities. NOAA Climate.gov image, based on data from NOAA Global Monitoring Lab.

At the global scale, the key greenhouse gases emitted by human activities annually are estimated to total 50 giga tonnes (GT): 38GTs from CO2, 8 GTs from methane, 3GTs from nitrous oxide and 1 GT from F-gases.

Exhibit 50
Carbon Dioxide over the last 50 years (1960-2021)



Source: *NDAA Climate.gov, NCEI*

Carbon dioxide (CO_2): Fossil fuel use is the primary source of CO2. CO2 can also be emitted from direct human-induced impacts on forestry and other land use, such as through deforestation, land clearing for agriculture, and degradation of soils. Likewise, land can also remove CO2 from the atmosphere through reforestation, improvement of soils, and other activities.

Methane (CH4): Agricultural activities, waste management, energy use, and biomass burning all contribute to CH4 emissions.

Nitrous oxide (N2O): Agricultural activities, such as fertiliser use, are the primary source of N2O emissions. Fossil fuel combustion also generates N2O.

Fluorinated gases (F-gases): Industrial processes, refrigeration, and the use of a variety of consumer products contribute to emissions of F-gases, which include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6).

Energy production or usage is usually measured in watts and joules

A watt-hour (Wh) is the amount of energy produced by a one-watt source running for one hour.

A kilowatt-hour (kWh) is a unit of energy equal to one kilowatt (1000 watts) of power sustained for one hour. This is the measure typically shown on our electricity bills. US average household pay 10c/kWh, in the UK 17p/kWh, but has gone up to 28p in 2022 due to the energy supply shortages.

A megawatt-hour (MWh) is one million Wh or 1000 kWh. Electricity source cost comparisons are usually expressed using MWhs.

Before carbon taxes or subsidies, the cost today averages between $25 and $40/MWh for various sources of energy including coal, solar, wind, and natural gas. This is 2.5 to 4c per kWh.

MW vs. MWh: A 582 MW Capacity Plant refers to hourly production. In 24hrs, this plant will produce 13,968 MWh's (24 x 582).

A gigawatt-hour (GWh) is 1,000 MWh.

A terawatt-hour (TWh) is one trillion Wh, or 1,000 GWh.

A gigawatt (GW) is equal to one billion watts. The light bulbs in our homes are typically between 60 and 100 watts. So 1.21 gigawatts would power more than 10 million light bulbs.

Joule (J): The joule is a derived unit of energy in the International System of Units. It is equal to the amount of work done when a force of 1 newton displaces a body.

I kWh = 3,600,000 joules or 1 joule = 2.77778-e7

Exajoule (EJ): 1 EJ = 10^{18} J

Most global emissions figures are shown in tonnes or billion tonnes of CO2 (GtCO2)

A Gigatonne (Gt) = 1 billion tonnes = 1×1015g = 1 Petagram (Pg)

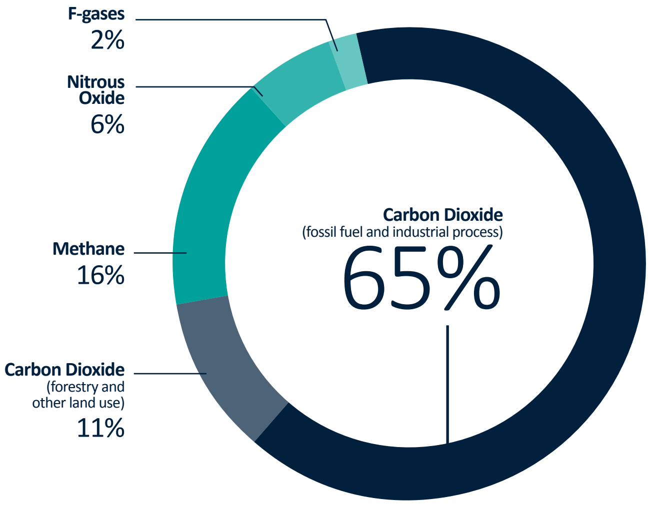
A kg carbon (C) = 3.664 kg carbon dioxide (CO2)

A GtC = 3.664 billion tonnes CO2 = 3.664 GtCO2

Discussions around the cost of carbon emissions often price it between $30 and $100 per tonne.

Exhibit 51

Global Greenhouse Gas Emissions by Gas



Source: IPCC (2014) based on global emissions from 2010

Concentrated solar power (CSP), systems generate solar power by using mirrors or lenses to concentrate a large area of sunlight onto a receiver. Electricity is generated when the concentrated light is converted to heat (solar thermal energy), which drives a heat engine (usually a steam turbine) connected to an electrical power generator or powers a thermochemical reaction.

Solar photovoltaic energy or PV solar energy directly converts sunlight into electricity, using a technology based on the photovoltaic effect. When radiation from the sun hits one of the faces of a photoelectric cell (many of which make up a solar panel), it produces an electric voltage differential between both faces that makes the electrons flow between one to the other, generating an electric current.

Building Heat Pump. These are expected to be the preferred replacement for coal and natural gas building heat. They work by having outside air blown over a network of tubes filled with a refrigerant. This warms up the refrigerant, and it turns from a liquid into a gas. This gas passes through a compressor, which increases the pressure. Compression also adds more heat – similar to how the air hose warms up when you top up the air pressure in your tyres.

The compressed, hot gases pass into a heat exchanger, surrounded by cool air or water. The refrigerant transfers its heat to this cool air or water, making it warm. And this is circulated around your home to provide heating and hot water. Meanwhile, the refrigerant condenses back into a cool liquid and starts the cycle all over again.

DISCLAIMER

Within the United Kingdom, this material has been issued by Partners Capital LLP, which is authorised and regulated by the Financial Conduct Authority of the United Kingdom (the “FCA”), and constitutes a financial promotion for the purposes of the rules of the Financial Conduct Authority. Within Hong Kong, this material has been issued by Partners Capital Asia Limited, which is licensed by the Securities and Futures Commission in Hong Kong (the “SFC”) to provide Types 1 and 4 services to professional investors only. Within Singapore, this material has been issued by Partners Capital Investment Group (Asia) Pte Ltd, which is regulated by the Monetary Authority of Singapore as a holder of a Capital Markets Services licence for Fund Management under the Securities and Futures Act and as an exempt financial adviser. Within France, this material has been issued by Partners Capital Europe SAS, which is regulated by the Autorité des Marchés Financiers (the “AMF”).

For all other locations, this material has been issued by Partners Capital Investment Group, LLP which is registered as an Investment Adviser with the US Securities and Exchange Commission (the “SEC”) and as a commodity trading adviser and commodity pool operator with the Commodity Futures Trading Commission (“CFTC”) and is a member of the National Future’s Association (the “NFA”).

This material is being provided to clients, potential clients and other interested parties (collectively “clients”) of Partners Capital LLP, Partners Capital Asia Limited, Partners Capital Investment Group (Asia) Pte Ltd, Partners Capital Europe SAS and Partners Capital Investment Group, LLP (the “Group”) on the condition that it will not form a primary basis for any investment decision by, or on behalf of the clients or potential clients and that the Group shall not be a fiduciary or adviser with respect to recipients on the basis of this material alone. These materials and any related documentation provided herewith is given on a confidential basis. This material is not intended for public use or distribution. It is the responsibility of every person reading this material to satisfy himself or herself as to the full observance of any laws of any relevant jurisdiction applicable to such person, including obtaining any governmental or other consent which may be required or observing any other formality which needs to be observed in such jurisdiction. The investment concepts referenced in this material may be unsuitable for investors depending on their specific investment objectives and financial position.

This material is for your private information, and we are not soliciting any action based upon it. This report is not an offer to sell or the solicitation of an offer to buy any investment. While all the information prepared in this material is believed to be accurate, the Group, may have relied on information obtained from third parties and makes no warranty as to the completeness or accuracy of information obtained from such third parties, nor can it accept responsibility for errors of such third parties, appearing in this material. The source for all figures included in this material is Partners Capital Investment Group, LLP, unless stated otherwise. Opinions expressed are our current opinions as of the date appearing on this material only. We do not undertake to update the information discussed in this material. We and our affiliates, officers, directors, managing directors, and employees, including persons involved in the preparation or issuance of this material may, from time to time, have long or short positions in, and buy and sell, the securities, or derivatives thereof, of any companies or funds mentioned herein.

Whilst every effort is made to ensure that the information provided to clients is accurate and up to date, some of the information may be rendered inaccurate by changes in applicable laws and regulations. For example, the levels and bases of taxation may change at any time. Any reference to taxation relies upon information currently in force. Tax treatment depends upon the individual circumstances of each client and may be subject to change in the future. The Group is not a tax adviser and clients should seek independent professional advice on all tax matters.

Within the United Kingdom, and where this material refers to or describes an unregulated collective investment scheme (a “UCIS”), the communication of this material is made only to and/or is directed only at persons who are of a kind to whom a UCIS may lawfully be promoted by a person authorised under the Financial Services and Markets Act 2000 (the “FSMA”) by virtue of Section 238(6) of the FSMA and the Financial Services and Markets Act 2000 (Promotion of Collective Investment Schemes) (Exemptions) Order 2001 (including other persons who are authorised under the FSMA, certain persons having professional experience of participating in unrecognised collective investment schemes, high net worth companies, high net worth unincorporated associations or partnerships, the trustees of high value trusts and certified sophisticated investors) or Section 4.12 of the FCA’s Conduct of Business Sourcebook (“COBS”) (including persons who are professional clients or eligible counterparties for the purposes of COBS). This material is exempt from the scheme promotion restriction (in Section 238 of the FSMA) on the communication of invitations or inducements to participate in a UCIS on the grounds that it is being issued to and/or directed at only the types of person referred to above. Interests in any UCIS referred to or described in this material are only available to such persons and this material must not be relied or acted upon by any other persons.

Within Hong Kong, where this material refers to or describes an unauthorised collective investment schemes (including a fund) (“CIS”), the communication of this material is made only to and/or is directed only at professional investors who are of a kind to whom an unauthorised CIS may lawfully be promoted by Partners Capital Asia Limited under the Hong Kong applicable laws and regulation to institutional professional investors as defined in paragraph (a) to (i) under Part 1 of Schedule to the Securities and Futures Ordinance (“SFO”) and high net worth professional investors falling under paragraph (j) of the definition of “professional investor” in Part 1 of Schedule 1 to the SFO with the net worth or portfolio threshold prescribed by Section 3 of the Securities and Futures (Professional Investor) Rules (the “Professional Investors”).

Within Singapore, where this material refers to or describes an unauthorised collective investment schemes (including a fund) (“CIS”), the communication of this material is made only to and/or is directed only at persons who are of a kind to whom an unauthorised CIS may lawfully be promoted by Partners Capital Investment Group (Asia) Pte Ltd under the Singapore applicable laws and regulation (including accredited investors or institutional investors as defined in Section 4A of the Securities and Futures Act).

Within France, where this material refers to or describes to unregulated or undeclared collective investment schemes (CIS) or unregulated or undeclared alternative Investment Funds (AIF), the communication of this material is made only to and/or is directed only at persons who are of a kind to whom an unregulated or undeclared CIS or an unregulated or undeclared AIF may lawfully be promoted by Partners Capital Europe under the French applicable laws and regulation, including professional clients or equivalent, as defined in Article D533-11, D533-11-1, and D533-13 of the French Monetary and Financial Code.

Certain aspects of the investment strategies described in this presentation may from time to time include commodity interests as defined under applicable law. Within the United States of America, pursuant to an exemption from the US Commodity Futures Trading Commission (CFTC) in connection with accounts of qualified eligible clients, this brochure is not required to be, and has not been filed with the CFTC. The CFTC does not pass upon the merits of participating in a trading program or upon the adequacy or accuracy of commodity trading advisor disclosure. Consequently, the CFTC has not reviewed or approved this trading program or this brochure.

In order to qualify as a certified sophisticated investor a person must (i) have a certificate in writing or other legible form signed by an authorised person to the effect that he is sufficiently knowledgeable to understand the risks associated with participating in unrecognised collective investment schemes and (ii) have signed, within the last 12 months, a statement in a prescribed form declaring, amongst other things, that he qualifies as a sophisticated investor in relation to such investments.

This material may contain hypothetical or simulated performance results which have certain inherent limitations. Unlike an actual performance record, simulated results do not represent actual trading. Also, since the trades have not actually been executed, the results may have under- or over-compensated for the impact, if any, of certain market factors, such as lack of liquidity. Simulated trading programs in general are also subject to the fact that they are designed with the benefit of hindsight. No representation is being made that any client will or is likely to achieve profits or losses similar to those shown. These results are simulated and may be presented gross or net of management fees. This material may include indications of past performance of investments or asset classes that are presented gross and net of fees. Gross performance results are presented before Partners Capital management and performance fees, but net of underlying manager fees. Net performance results include the deduction of Partners Capital management and performance fees, and of underlying manager fees. Partners Capital fees will vary depending on individual client fee arrangements. Gross and net returns assume the reinvestment of dividends, interest, income and earnings.

The information contained herein has neither been reviewed nor approved by the referenced funds or investment managers. Past performance is not a reliable indicator and is no guarantee of future results. Investment returns will fluctuate with market conditions and every investment has the potential for loss as well as profit. The value of investments may fall as well as rise and investors may not get back the amount invested. Forecasts are not a reliable indicator of future performance.

Certain information presented herein constitutes “forward-looking statements” which can be identified by the use of forward-looking terminology such as “may”, “will”, “should”, “expect”, “anticipate”, “project”, “continue” or “believe” or the negatives thereof or other variations thereon or comparable terminology. Any projections, market outlooks or estimates in this material are forward –looking statements and are based upon assumptions Partners Capital believe to be reasonable. Due to various risks and uncertainties, actual market events, opportunities or results or strategies may differ significantly and materially from those reflected in or contemplated by such forward-looking statements. There is no assurance or guarantee that any such projections, outlooks or assumptions will occur.

Certain transactions, including those involving futures, options, and high yield securities, give rise to substantial risk and are not suitable for all investors. The investments described herein are speculative, involve significant risk and are suitable only for investors of substantial net worth who are willing and have the financial capacity to purchase a high risk investment which may not provide any immediate cash return and may result in the loss of all or a substantial part of their investment. An investor should be able to bear the complete loss in connection with any investment.

All securities investments risk the loss of some or all of your capital and certain investments, including those involving futures, options, forwards and high yield securities, give rise to substantial risk and are not suitable for all investors.

Below:
Mega Ampere Spherical Tokamak (MAST) in Culham Centre for Fusion Energy, Oxfordshire, UK. Bright glowing plasma inside the vessel.
Image: Eye Steel Film

Europe

5 Young Street
London
W8 5EH
United Kingdom
T +44 (0)20 7938 5200

28 Cours Albert 1er
75008 Paris
France
T +33 (0)1 7038 1054

North America

Federal Reserve Plaza
600 Atlantic Avenue
30th Floor
Boston, MA 02210
United States
T +1 617 292 2570

1330 Avenue of the Americas
22nd Floor
New York, NY 10019
United States
T +1 212 951 1288

One Embarcadero Center
Suite 3500
San Francisco, CA 94111
United States
T +1 415 862 7100

Asia

50 Raffles Place
Level 13
Singapore Land Tower
Singapore 048623
T +65 6645 3733

10/F Champion Tower
3 Garden Road
Central, Hong Kong
T +852 3614 0230