KEELING
CAPITAL

ENERGY TRANSITION DISTILLED

2023

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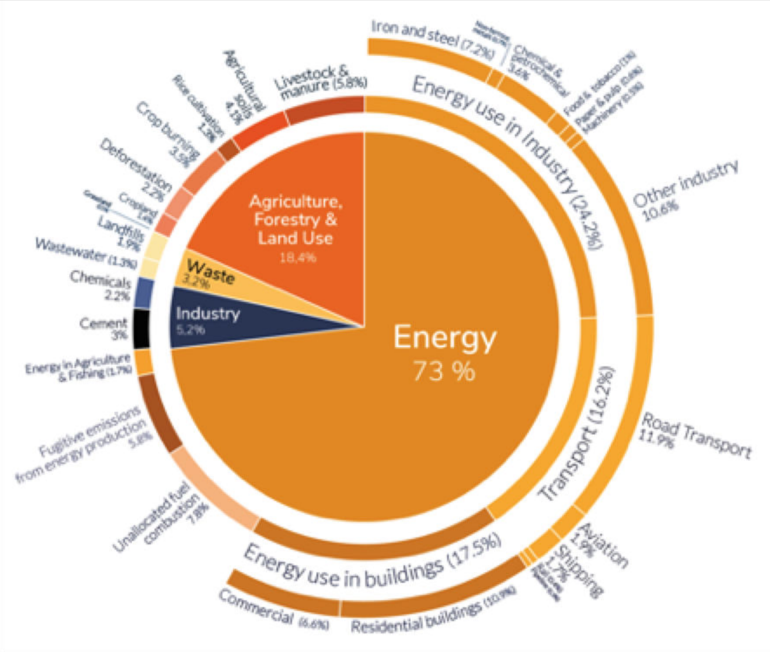
Introduction and Executive Summary

A core part of our mission at Keeling Capital is education and engagement. We provide our investors and partners with the conceptual frameworks to allow them to make better allocation decisions over time, whether that be allocation of time or capital. The sheer breadth of the "climate" investment theme, means that it can be challenging for new entrants (or even not-so-new entrants) to stay properly orientated. Decarbonising our economy over time requires that we collectively focus on the big levers for emission reductions (in the words of David MacKay "if everyone does a little, we'll only achieve a little"). We also need to minimise, insofar as possible, time spent going down technological blind alleys that are unlikely to ever be truly scalable due to the limitations of physics, economics or politics.

The thing that lies at the heart of greenhouse gas emissions, and therefore climate action, is energy. Specifically, it is the production and consumption of fossil fuels, which accounts for three quarters of the emissions pie. Whilst we are aware that three quarters is not 100%, decarbonising our energy system is the principal challenge and opportunity for stabilising the climate. Additionally, from our perspective at Keeling, what we call the *energy complex* (the production and distribution of electricity and heat, together with its end uses) represents a richer opportunity set for venture than food and agriculture, as it revolves around the creation and management of physical infrastructure, as opposed to land management practices and behaviour change, which is more pertinent in the agriculture, food and land use sectors. It's for this reason that this document is focussed specifically on energy transition.



The thing about the Energy Complex is that, well, it's a complex complex. Our intention for this document is that readers will come away with fresh clarity on what the energy transition entails, an understanding of the cross-sectoral vectors for decarbonisation, and some ideas for the most exciting areas for impact and financial returns. It was originally published on Béla's Substack, as a five part series, comprised of the following instalments:

1. Defining the challenge

Starting with the end in mind, we set the scene with today's energy landscape and offer a working definition of Energy Transition: To supply the energy we need to fulfil the needs of society (including bringing billions of people out of poverty) whilst reducing net emissions to zero (and then negative). Note that we do not define it narrowly as constraining fossil fuel supply. The Energy Transition cannot happen without continued supply of energy, to the tune of about 70,000 TWh of useful energy, almost 80% of which today comes from fossil fuels. Also, we provide some clarity on the difference between primary, final and useful energy, as these terms are variously used in publications without the authors drawing attention to the different implications.

2. Reduce demand for fossil fuels

The reduction in fossil fuel use has got to come from the demand side. The way we do that is in part by constraining the growth of useful energy required as much as possible, but mostly it is through greater efficiency - reducing the gap between the amount of energy inputs and the amount of useful energy services (e.g. mechanical energy) that we consume. The other major, and related lever, is electrification. This has inherent efficiencies because electricity can more easily be converted to other forms of useful energy than can fossil fuels via combustion, but it also enables more parts of the economy to be powered by low-carbon power sources.

3. Decarbonise electricity supply

The electricity sector is the only sector to make meaningful progress on decarbonisation, but there remains a lot of work to do to fully decarbonise existing electricity use, even before we get on to powering all of the other sectors that are in the early stages of electrification. We might say that abundant, cost effective near-zero-carbon electricity (nothing is *truly* zero carbon) is the killer app for the energy transition. With sufficient low carbon electricity, we can afford to decarbonise things higher up the marginal abatement curve, either doing things that aren't very thermodynamically efficient (like green molecules) or powering carbon capture and removal (carbon management). The two main focus areas here are a) scaling wind and solar as much as possible, and b) starting to scale up low-carbon dispatchable power - nuclear, geothermal, hydro, oxy-combustion with capture.

4. Green molecules

We can break molecules into two categories. First, are those where the value is in the molecule itself, such as with materials, plastics, fertiliser, etc. Second, there are the molecules that only serve as energy carriers, releasing energy when broken apart by combustion. The former are the ones that we truly cannot do without. The latter should be confined only to those things that fiercely resist electrification (e.g. aviation). The most economic low-carbon alternative is using bioresources, but the supply is limited and should be prioritised for those higher value applications. Hydrogen as a fuel or e-fuels (combining H2 with captured CO2) is incredibly inefficient from an energy perspective, so would take a staggering (and implausible) build out of low-carbon electricity to make a serious dent in emissions. In this section, we also touch on "super GHGs" like HFCs used as refrigerants.

5. Carbon management

Even if, through herculean efforts, we succeed with deep decarbonisation on the above pathways, we will need extensive build out of carbon management infrastructure. This involves carbon capture for those things where there is extensive existing infrastructure and that have process emissions as well as energy emissions (think cement, chemicals), as well as carbon removal to deal with the trillion-tonne problem of legacy carbon that we've moved from the earth's crust into the atmosphere since the industrial revolution. This industry is still in its infancy, but it has orders of magnitude more attention and capital than it did even a few years back. We look at the state of these markets and the various technologies. Additionally, since we know that we will need some amount of fossil fuels for a long time to come, it is critical that we minimise methane leaks from oil and gas production. As methane is both a very potent greenhouse gas (~80x warming of CO2) but is short lived, it represents one of the highest leverage climate mitigation pathways.

Whilst this document isn't exactly short, we have heavily distilled the information on the various pathways to give readers as succinct an overview as possible without neglecting any major factors and introducing key concepts (we've attempted to adhere to Einstein's maxim to "make everything as simple as possible, but not simpler"). We hope that readers will come away feeling both enlightened, and empowered to navigate this complex space and conduct independent exploration on those topics most of interest to them.

As always, we welcome discussion, feedback and further questions and look forward to continuing to learn together and get towards better answers and outcomes.

Part 1:

Defining the Challenge

Energy Transition, a simple definition

To supply the energy we need to fulfil the needs of society (including bringing billions of people out of poverty) whilst reducing net emissions to zero (and then negative).

We might break this down into “the energy that we need” and “whilst reducing net emissions to zero”. One useful way to look at the component pieces for energy emissions and, hence, decarbonisation levers is the Kaya Identity. The Kaya Identity states that global (energy) emissions are a function of:

- **Population**
- **GDP per capita**
- **Energy use per unit of GDP**
- **Emissions per unit of energy**

The first three factors define “the energy that we need”, or the demand side. Let’s take these one by one. First up, population control is (obviously) fraught ethically and history has a few examples of unsavoury regimes having a go. The early environmental movement had an unfortunate depopulation element to it, driven by worry of Malthusian collapse and generally not giving humanity enough credit to be able to innovate our way to greater efficiencies. Second, GDP / capita we want to generally go higher, drastically so in developing countries (“degrowth” might be advocated by some people but, outside of a few well-heeled European urbanites, pretty much nobody wants that). And, incidentally, economic growth reliably results in a reduction of the birthrate, so population and GDP / capita are intertwined, especially in developing countries.

That leaves “energy intensity of GDP” as the lever we want to focus on to reduce overall energy demand. This we address through energy efficiency including dematerialisation of the economy (less physical stuff), avoiding wasted energy (e.g. by insulating buildings) and lifestyle choices like taking trains rather than planes or working from home, and also through electrification. We’ll get more into these in Part 2.

The final term of the Kaya Identity - emissions per unit of energy, or the supply side - is where most of the heavy lifting needs to be done.

First, a few basics:

Units

The basic unit of energy is a "joule". A "watt" is one joule / second, and so refers to a flow of energy. A "watt hour" puts us back into stock rather than flow of energy, referring to one joule / second for an hour, or 3600 joules. This then scales to kilowatt hours (kWh) or 3,600,000 joules, which is what residential energy bills are generally denominated in. For context, in my modest home for a family of 4, we use about 3,000 kWh of electricity and about 4,000 kWh of natural gas per year. From there it jumps to MWh (1,000 kWh), GWh (1,000,000 kWh) and TWh (1,000,000,000 kWh). With that last one we finally have a unit that we can sensibly use for national or global scale energy consumption.

Electricity ≠ Energy

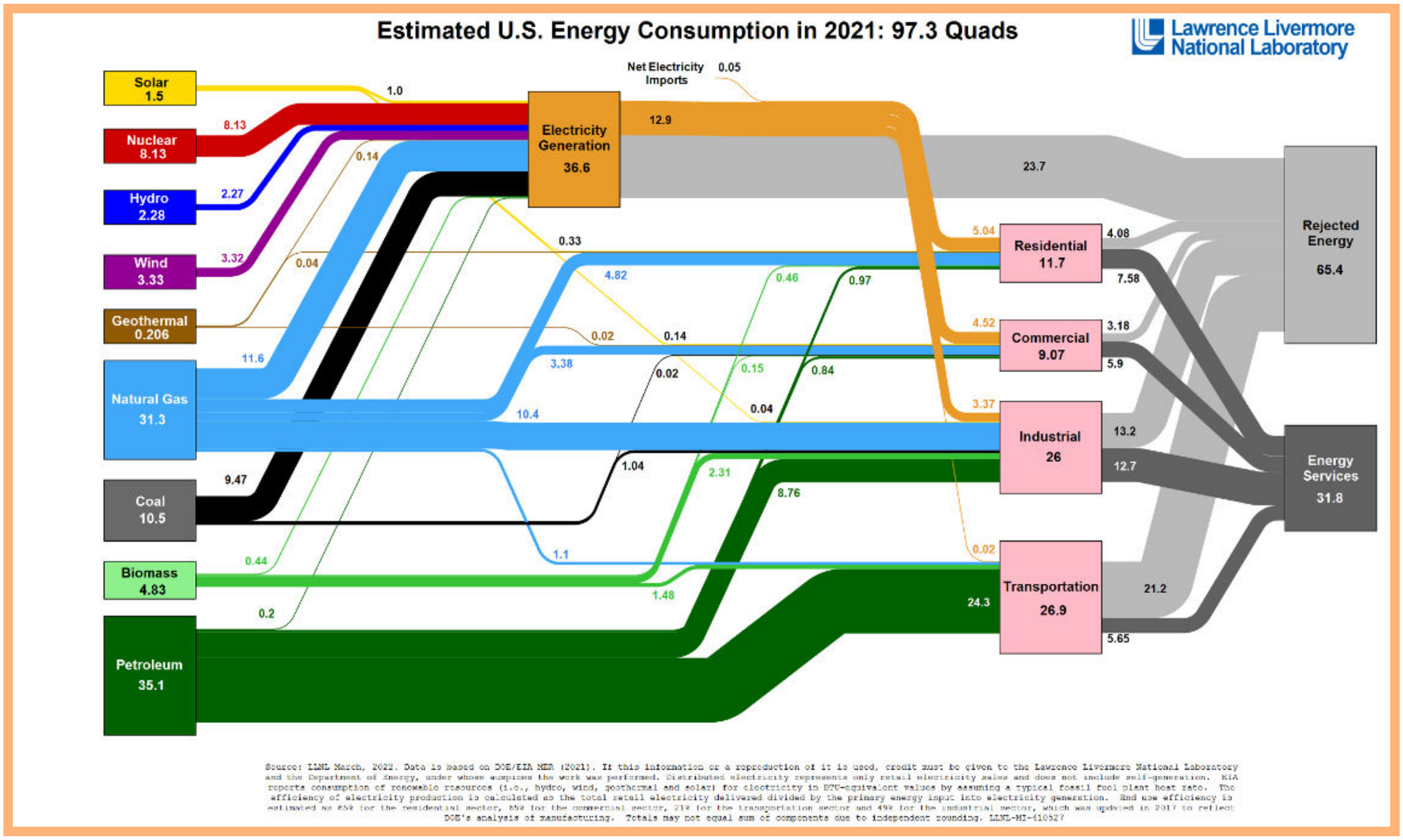
This might seem like an extremely basic point, but electricity (also called "power") is not the same thing as energy, and the terms are often used incorrectly, for example on the Irish grid operator's otherwise excellent dashboard describing "energy demand" when they mean "electricity demand". Electricity is an extremely high-value form of energy as it is easy to transform it into other forms of energy (it has high "exergy") and is easy to transport. Heat energy, on the other hand, is "low-grade" energy (low exergy) and is more difficult to transport. (Yes, of course, heat via high temperature steam is used to create a lot of our electricity, but not very efficiently, about 3:1 thermal: electric.)

Primary / Final / Useful Energy

There is another important concept to cover, which isn't popularly understood and can be easily used to obfuscate or otherwise bamboozle readers. That is the difference between primary, final, and useful energy. Different analyses will use different measures, making it challenging to get an apples-for-apples comparison.

- Primary energy refers to the embedded energy in whatever the fuel source is; for example the chemical energy within coal.
- Final energy refers to the energy in its final form as delivered to the end consumer, be it refined fuel for a car or electricity to a home.
- Useful energy refers to the energy consumed in doing the actual thing that we want it to do - kinetic energy moving a car, lighting our homes, etc.

Losses are incurred at each step so that there is a big gap between primary energy input and useful energy consumed. The biggest losses occur with combustion of fuels. That can either be at the gap between primary and final energy, like burning coal in a power plant, or between final and useful as petrol in a car and kinetic energy moving the car forward. There are also smaller losses incurred in the transmission and distribution of electricity, AC/DC conversion and inefficiencies in appliances. The best visualisation of these losses comes from the energy flow diagram from Lawrence Livermore showing US energy consumption. Converting the units to TWh, it shows about 28,000 TWh of primary energy input delivering about 9,000 TWh of useful energy, or “energy services”.

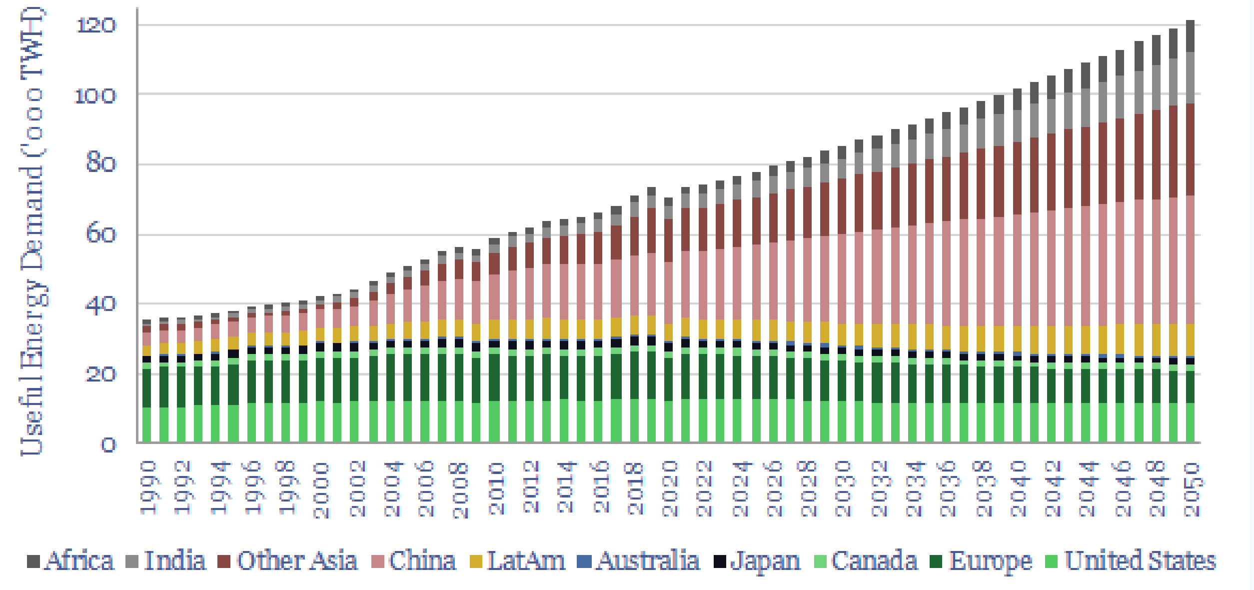

Estimated U.S. Energy Consumption in 2021: 97.3 Quads

Source: LLNL March, 2022. Data is based on DOE/EIA MER (2021). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector and 49% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Lawrence Livermore National Laboratory

Global demand

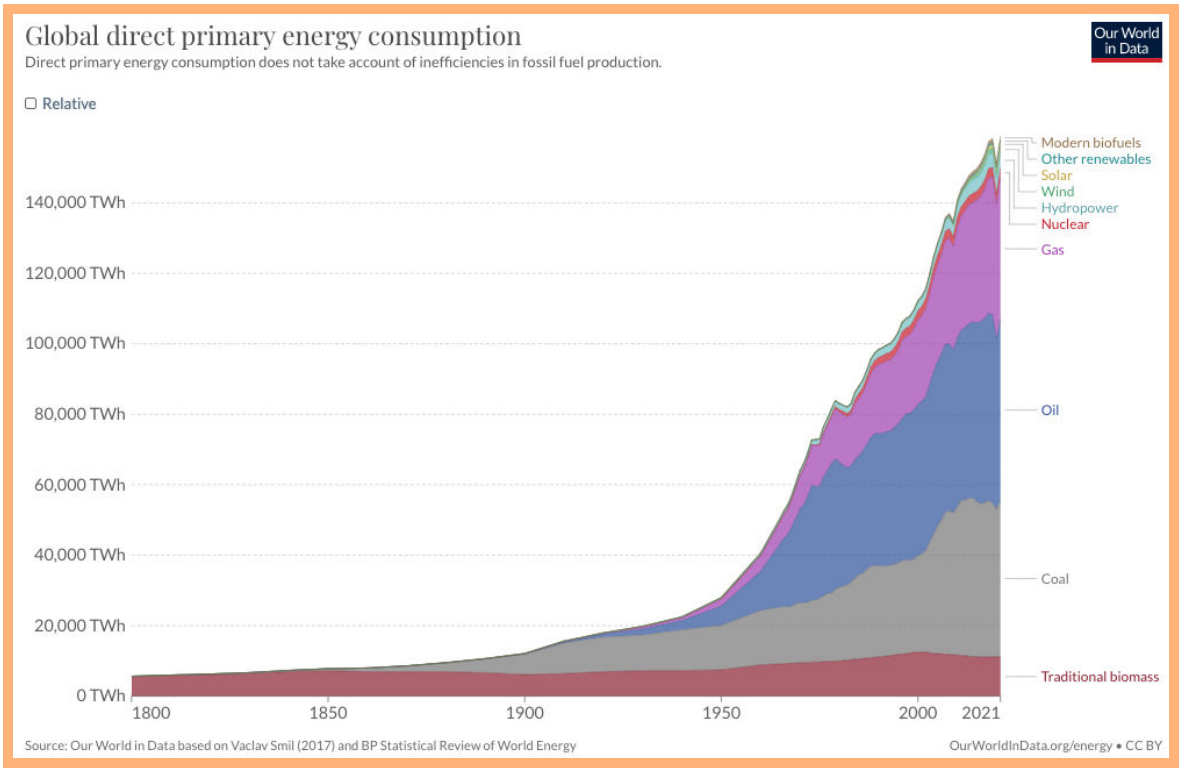
Since what we really care about is the utility that we get out of our energy, *useful energy* is the underlying demand metric that we need to solve for and is not sensitive to the assumptions on the mix of energy sources. Today globally we use about 70,000 TWh of useful energy, with per person consumption varying from about 20MWh per person per year in Europe to 40MWh in the US and 2.5MWh in Africa and India (more here). Because of population growth and increasing GDP (the first two inputs in the Kaya Identity), that is expected to increase to something like 120,000 TWh by the middle of the century along current trajectories.



Thunder Said Energy

How do we deliver 70,000 TWh of useful energy today?

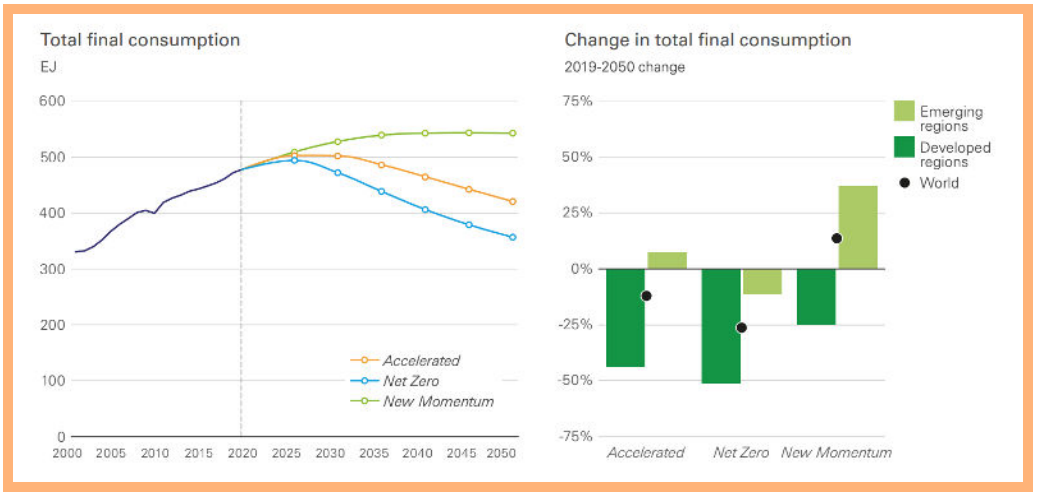
With 140,000 TWh of primary energy. In the chart below, the zero carbon bit starts with the red of nuclear below. Pretty small, eh? The good news is that wind and solar have a much smaller gap between primary and useful energy so their importance is under represented here. I have deliberately chosen a version of this chart below that doesn't gross them up to the equivalent of fossil fuels because this difference between fossil energy and renewable electricity is part of the transition narrative. Where we move to electrification and renewables, the gap between primary / final energy and useful energy shrinks drastically, with the consequence that we don't need to replace the same amount of primary fossil energy with low-carbon electricity.



Our World in Data

Final energy demand

Going forward, we can see final (and primary) energy demand plateau and shrink, even as we deliver an increasing amount of useful energy or energy services due to electrification and efficiencies. BP in their latest energy outlook see final energy demand plateauing at about 150,000 TWh along current trajectories, up from about 135,000 TWh currently (converting from exajoules in the chart below). Their more aggressive scenarios imply basically no growth in useful energy demand at a global level, which doesn't seem realistic or, frankly, desirable.



BP

Decarbonisation vectors

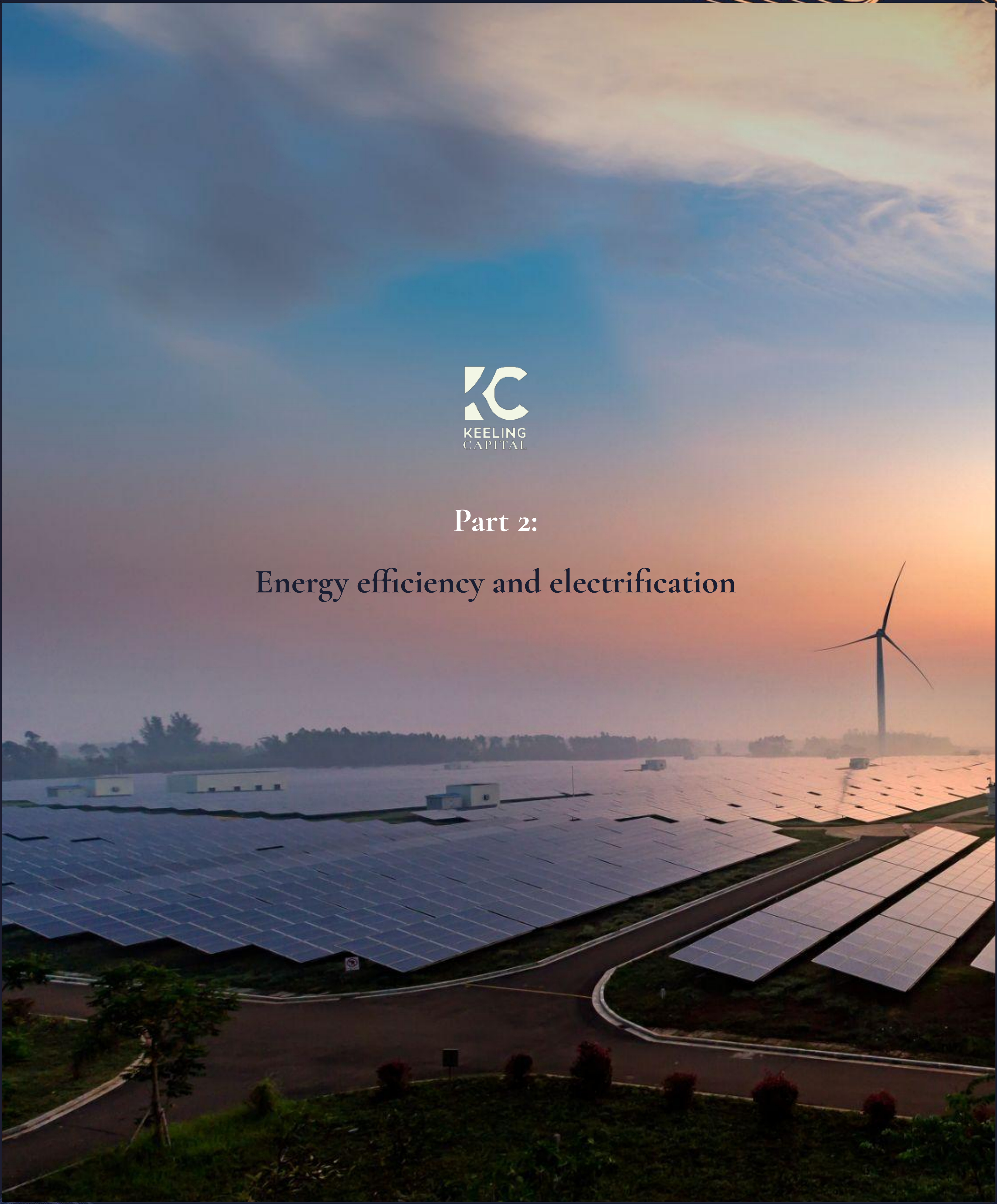
In order to get to Net Zero across the energy system there are a few broad vectors for decarbonisation, addressing the energy / GDP and emissions / energy terms in the Kaya Identity. This particular cat has been skinned a few different ways by different analyses, but this is how I'm breaking it down and will make up the subsequent sections of this piece. In rough order of priority:

1. **Energy efficiency and electrification** - reducing useful energy demand through efficiency and increasing renewables' addressable market through electrification is in many ways the low-hanging fruit, easing the supply challenges and mostly resulting in net savings and better outcomes (e.g. more comfortable homes, lower total cost vehicles).

2. **Generation of zero carbon electricity and heat** - This is arguably the killer app for decarbonisation. Taken to an extreme, if we had sufficiently abundant zero carbon electricity, we could do whatever we wanted, including sucking CO2 from the atmosphere and either sequestering it or combining it with zero carbon hydrogen to make net zero emission liquid fuels. Unfortunately we're a long way from that point of super abundance!

3. **Green molecules** - really for tackling the trickier parts of transport or industry, either through biofuels or starting with low-carbon hydrogen.

4. **Carbon management (capture and removal)** - inevitably there will be some residual emissions either from mobile emissions or areas that are inherently difficult to decarbonise (e.g. cement) that will require either point-source capture or taking carbon out of the atmosphere through natural or engineered pathways.



Part 2:

Energy efficiency and electrification

Whilst energy efficiency and electrification might be considered two different decarbonisation vectors, they share common ground as the two major levers for reducing fossil fuel demand and they are also intertwined, as we shall see.

Energy efficiency in two forms

We might think of energy efficiency as falling under two broad categories. First, is reducing the amount of *useful* energy that we require as a society; that is to say, the end amount of energy services we need to achieve our desired standards of living, whether that is in the form of kinetic energy for transport or thermal energy to heat our homes or drive industrial processes. Second, we can think of efficiency in terms of reducing the wasted energy that makes up the gap between primary energy inputs and useful energy services. These two categories work in tandem to reduce the demand for primary energy inputs and, therefore, fossil fuels since they make up 80% of primary energy globally. Because it tends to pay for itself and places less demand on the system, the IEA refers to energy efficiency as the “first fuel” of the energy transition.

“No other energy resource can compare with energy efficiency as a solution to the energy affordability, security of supply and climate change crises.” - IEA

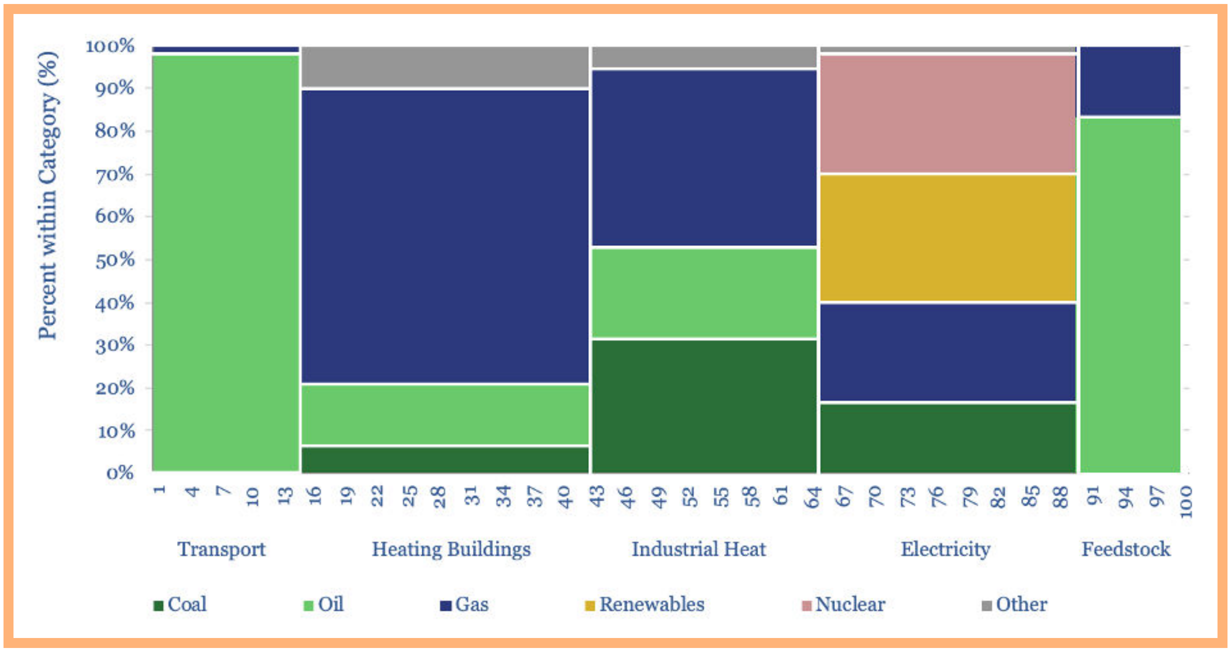
Electrification as efficiency

Electrification meanwhile delivers inherent efficiencies as electrical energy can be converted to useful energy services with low losses, narrowing the gap between final energy demand (the energy that is received by the consumer via whatever form, electricity, liquid fuels, etc) and useful energy. For example, an EV is something like 80% efficient at turning electrical energy into motion, vs around 20% for an ICE turning the chemical energy in petrol into motion. However, the decarbonisation benefit is marginal where the primary energy input is a fossil fuel in the power plant producing the electricity to run the EV, especially if it’s coal.

Electrification - power to decarbonise

The real reason that electrification is so crucial to the energy transition is that we have the ability to produce extremely low carbon electricity. By electrifying transport and heating (both buildings and industrial), we effectively expand the addressable market of solar, wind, nuclear, geothermal and hydro.

Below is one of the most arresting energy charts I’ve come across. This is (once again) from Thunder Said Energy and shows where Europe gets its energy from, shown as proportions of useful energy.



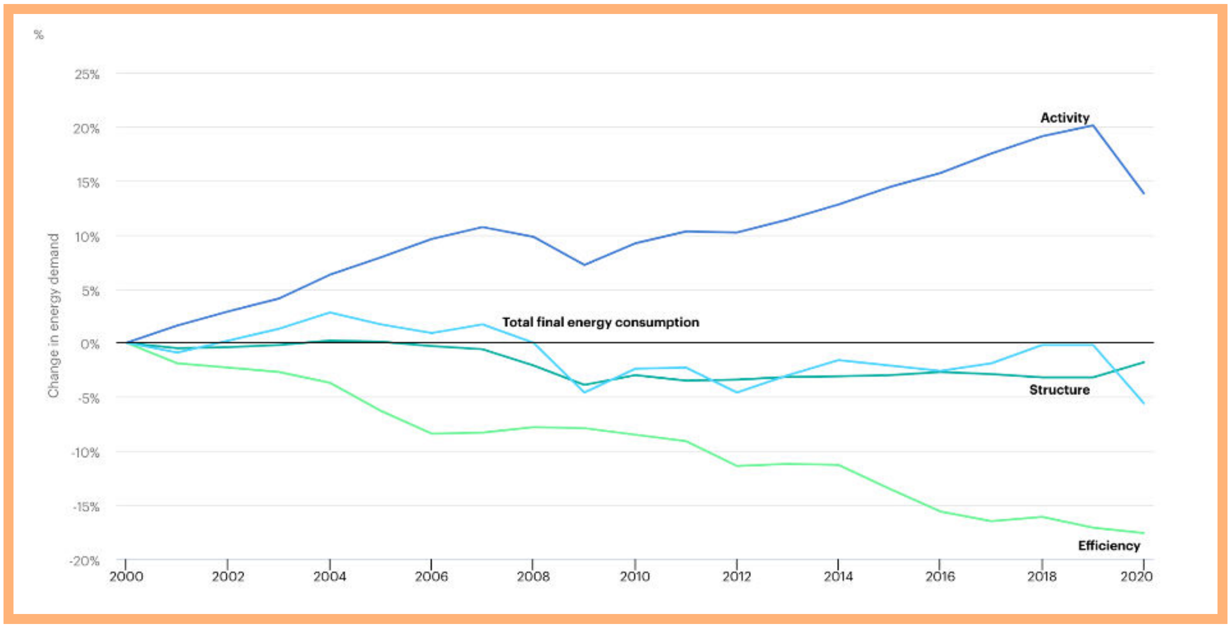
Thunder Said Energy

What is blindingly obvious from this is that the only sector to have any meaningful low-carbon penetration is the electricity sector. By electrifying end uses, we effectively move TWh out of the fossil fuel-heavy columns and into the increasingly low-carbon column of electricity generation.

So what progress is being made within energy efficiency and electrification and what are the main paths available to us to push them forward?

Energy efficiency - the progress

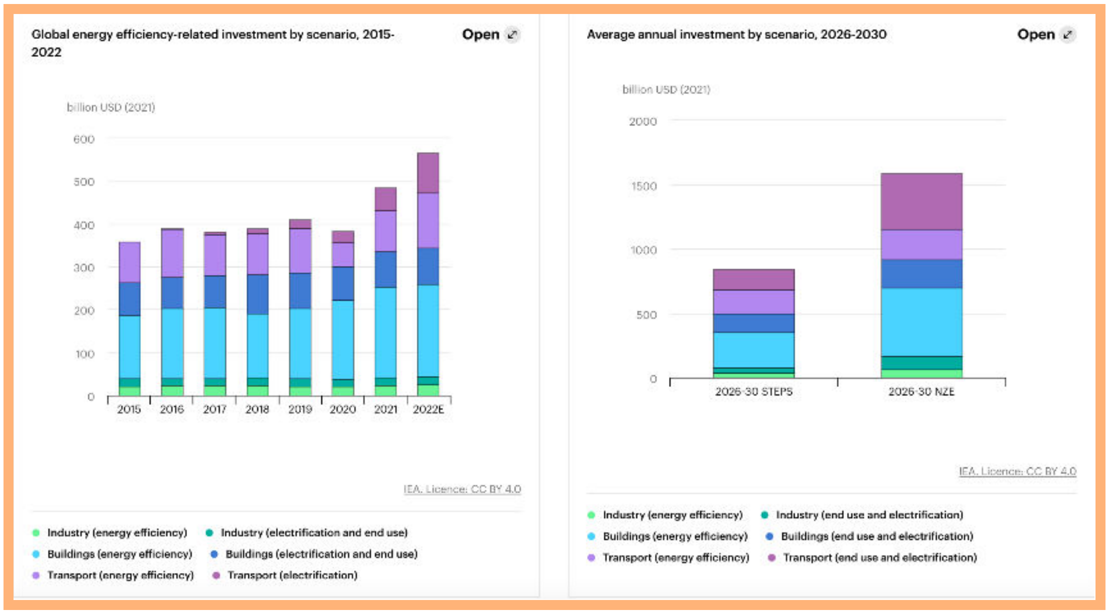
In its latest Energy Efficiency report, the IEA suggests that 4% annual reduction in "energy intensity" (energy / unit of GDP, which you might recognise as the third term in the Kaya Identity from Part 1) is required under its Net Zero scenario. It estimates improvements in energy intensity of 2% this year as a global energy crisis creates urgency, but that progress had slowed almost to a standstill over the pandemic. Still, energy efficiency improvements meant that over the last 20 years final energy demand stayed pretty much flat in IEA countries, which include both developed and developing economies, even as the economies grew 40% in real terms. This is entirely down to energy efficiency as the structure of the group of economies stayed pretty stable, meaning that they didn't pivot away from energy intensive activities.



IEA

Investment in efficiency

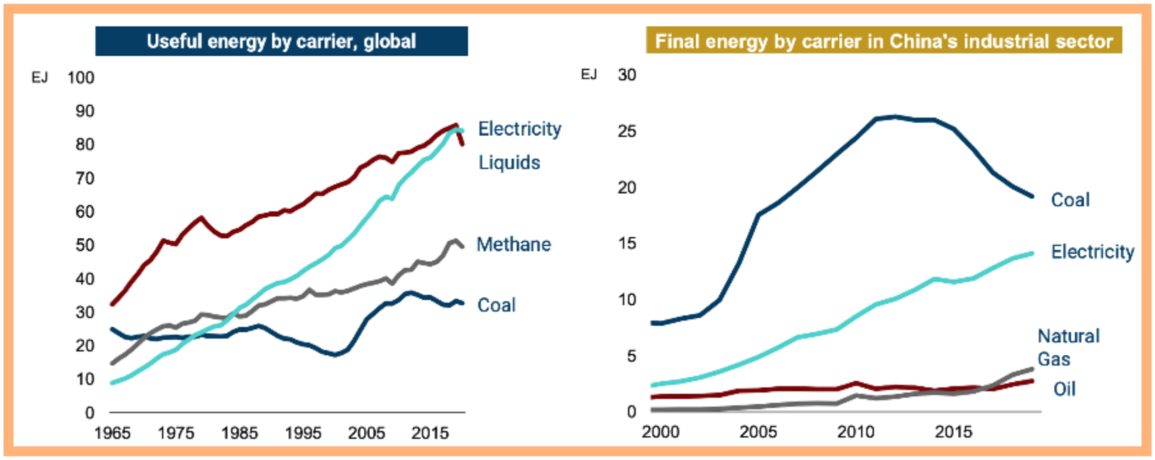
Encouragingly, a lot more capital is being mobilised towards energy efficiency, rising 16% to USD 560bn this year and expected to average USD 840bn in the second half of this decade. However, that is still only half of where it would need to be to get us on a Net Zero path. Note also that the IEA captures both efficiency and electrification in their numbers as both contribute to reduction of final energy intensity.



IEA

Electrification - the progress

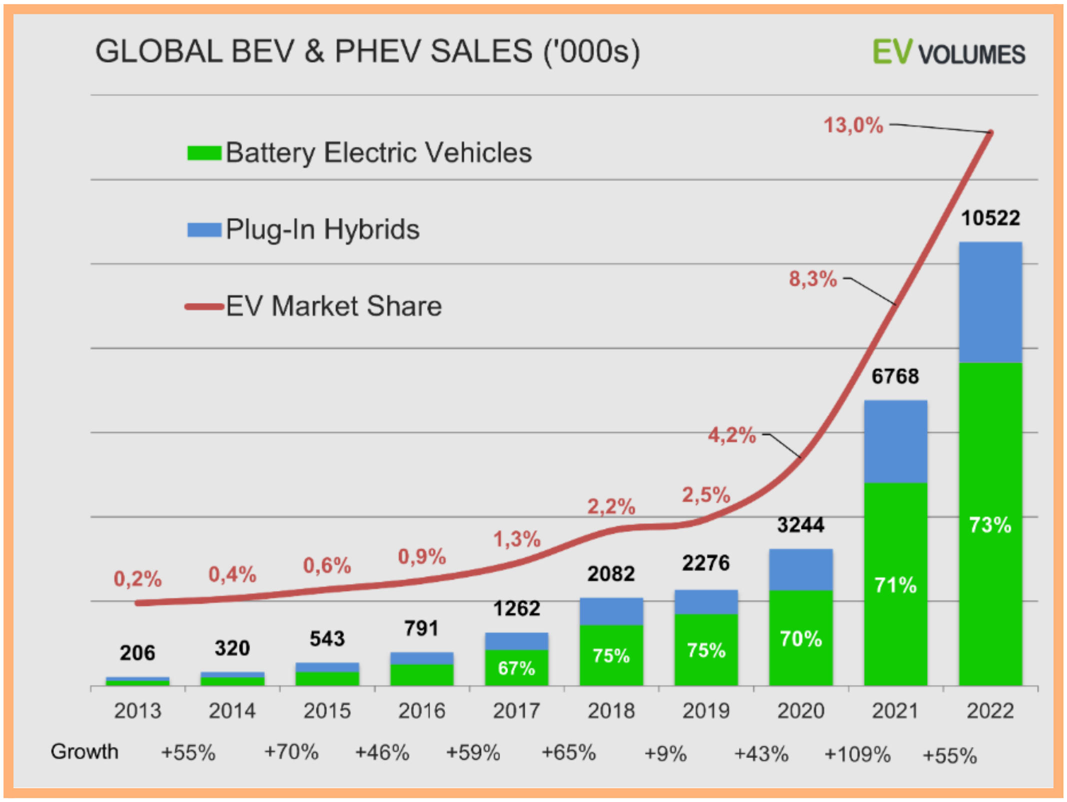
Here, honestly, it is pretty difficult to tell. Most of the data available is on primary energy, which doesn't tell us that much about the end use. The below charts from RMI's Energy Transition Narrative document suggests significant progress but it looks more dramatic on a useful energy basis rather than final energy basis (note the numbers on Chinese industrial sector are *final* not *useful* - complicated, I know). Also, it seems at odds with numbers from TSE that has electricity's share roughly stable at 40% of useful energy over the last 30 years.



RMI

Electrification of light vehicles

What is indisputable is that we are in the early part of the exponential adoption curve for electrification of some sectors of the economy, most notably light vehicles. Market share for EVs continues to increase radically, driven by Europe and China, but with the US also having crossed the 5% market share threshold last year (the market share threshold often cited as a tipping point). However, this trend will take a while to materialise as a meaningful share of electrification as cars are relatively long lived assets and ICEs still represent 98% of light vehicles on the road globally.



EV Volumes

Electrification of domestic heat

Similarly electrification of space heating via heat pumps is coming from a low-ish base, representing just 9% of global heating demand today. In their recent report on heat pumps, the IEA sees this doubling to 19% by 2030 with very rapid adoption particularly in some European companies looking to get off natural gas. Heat pumps, it should be noted, offer a double whammy of efficiency and electrification. Because they are not turning electricity into heat, but using electricity to *pump* heat from one place to another by turning a refrigerant back and forth from a liquid to a gas, heat pumps deliver more useful heat energy then they consume in electricity. In normal conditions, residential heat pumps will deliver something like 3-4x the amount of heat as they consume in electricity.

Energy efficiency vectors

Behaviour change

This is where we all have the ability to contribute and reduce demand for energy services or useful energy. It entails switching from more energy intensive to less energy intensive habits - taking a train instead of a plane, public transport or a bike instead of a car, heating or cooling our homes less aggressively, and consuming less material stuff.

More efficient use of fossil fuels

Whilst ultimately the goal is to move away from fossil fuels entirely, improved efficiency in turning primary fossil energy into energy services has delivered massive energy (and carbon) savings while meeting society's needs. For example, replacing old, inefficient coal plants with modern coal plants was a huge lever in China achieving carbon intensity reduction targets and resulted in a cumulative saving of 1.5GT of CO2 over 10 years. Much more useful energy can be squeezed from fossil fuels by using the heat by-product from electricity production through combined heat and power systems.

Design

A greatly overlooked lever for reducing energy demand as it isn't a technology per se. For example, something that cropped up in a podcast with Amory Lovins of RMI that I covered here is that using fatter, straighter pipes and ducts drastically reduces friction and hence the electricity needed to drive the motor. More on integrative design in Lovins' paper here. Design also contributes towards less material use, including use of steel and concrete in buildings, and lighter, more aerodynamic cars and aeroplanes.

Building insulation and HVAC (heating, ventilation, air-conditioning)

HVAC is the biggest chunk of building energy demand globally at about 40% of the total and responsible for 5GT of CO2 emissions. The amount of energy required is heavily impacted by the envelope of the building (glazing ratio, air-tightness, insulation). In Europe, it takes 3-4x more energy to heat the least efficient homes than the most efficient homes. Then the heating and cooling systems themselves vary wildly in efficiency. Scaling up activity in this area is challenging, but several groups are tackling this through either integrated delivery, financed options or both. Redaptive, focussing on commercial buildings, recently raised an additional $200mm to fuel expansion. Sealed is focussed on energy efficiency of residential buildings, whilst Woltair again focuses on providing more integrated delivery, operating in European geographies. There is an urgent need for more efficiency in cooling also, given that it represents one of the largest growth areas for electricity demand (3x globally over 30 years) as more people in developing countries can afford it and as the world warms. There are several companies working on more efficient systems (Gradient, Mojave HVAC), but the biggest lever here is really energy efficiency standards in emerging markets and particularly Asia where the demand growth is coming from (4x over the last 20 years).

Electrification vectors:

Transport

Transport accounts for 30% of final energy demand and is currently almost 100% powered by liquid fuels. The most tractable areas are those that are less energy intensive because of smaller vehicles and operate over shorter distances. The obvious area of progress, as noted earlier, is in light vehicles. EVs are on a clear path to dominate within the next few years. The areas of transport that are deemed eligible for direct electrification have been expanding as battery technology has been improving and costs falling. However, the boundaries will ultimately be constrained by energy density, both "gravimetric density" (energy per unit of mass) and "volumetric density" (energy per unit of volume). For example, jet fuel has a minimum energy density of 42.8 MJ/kg, which compares to about 1 MJ/kg for the best batteries used by Tesla. This puts long-distance flights out of scope for direct electrification, ditto long distance shipping. Hence we will still require molecules for these applications and others (covered in Part 4).

Heat

Heat represents about half of final energy demand according to the IEA. Of that, it is split roughly evenly between heat use in industry and in buildings. Heat pumps have already cropped up a couple of times here as both an efficiency and electrification vector for decarbonising space and water heating. However, the technology is increasingly able to tackle certain industrial applications that require higher levels of heat. Even for processes that require much higher temperatures, a range of electrification technologies are available from electric boilers to arc furnaces and induction. Work by Dr Silvia Madeddu has found that >90% of industrial heat can be electrified (presentation here and excellent podcast with Michael Liebreich here). I also covered the work of Rondo Energy in a previous post here.

But, of course, for electrification to play its role in the energy transition, it needs to be fed with low-carbon electricity. Supplying enough low-carbon electricity to cover existing uses and all of the expanded requirements through electrification is a daunting task. And that brings us onto Part 3.

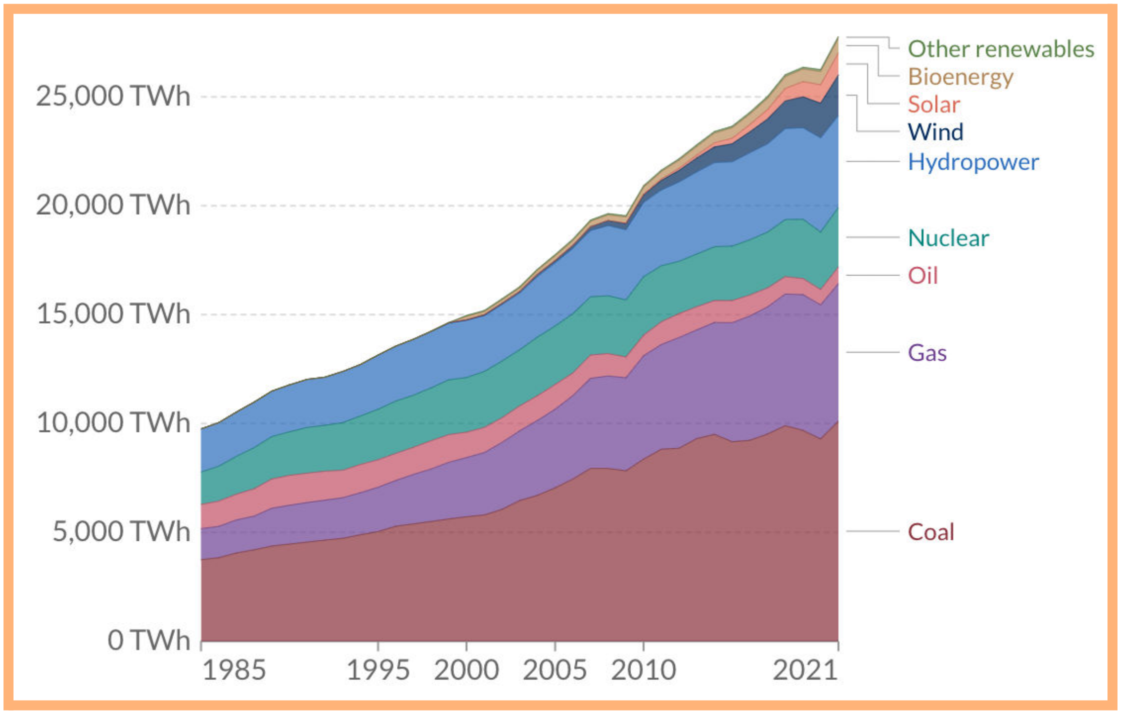
Part 3:

Decarbonise Electricity

Decarbonised electricity is the killer app for Net Zero. Energy efficiency may be the "first fuel" of the energy transition, but we can't efficiency our way to zero. On the other hand, there is very little we couldn't do with sufficiently abundant and cheap (near) zero carbon electricity, including, in extremis, removing carbon from the atmosphere via direct air capture and either sequestering it underground or combining it with low-carbon hydrogen to make net zero liquid fuels. We are still quite some ways from that sort of abundance, but, as per the sector chart in Part 2, the electricity sector is the one area where real progress is being made on decarbonisation. Here, we'll take a look at how we are doing so far and how we might think about the different ingredients for a zero emission power sector that meets not only today's electricity demand, but the vastly expanded electricity sector of the future; one that has subsumed transport, residential heating, industrial heating, etc, plus met the growing energy demands of developing countries. For more on this, you can check out the IEA's Electricity Market Report.

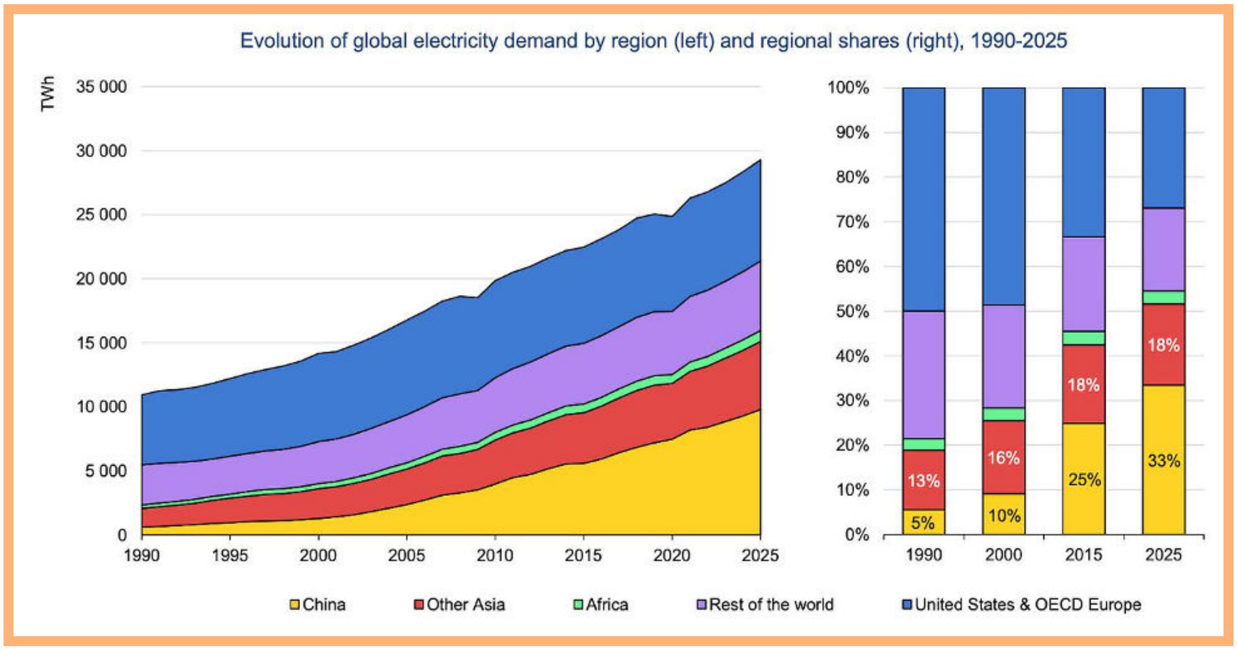
Where are we at?

- Currently the world uses about 28,000 TWh of electricity annually.
- Coal is still king in the electricity sector, accounting for about 35% of global electricity generation, ahead of gas as the next biggest source at a bit over 20%.



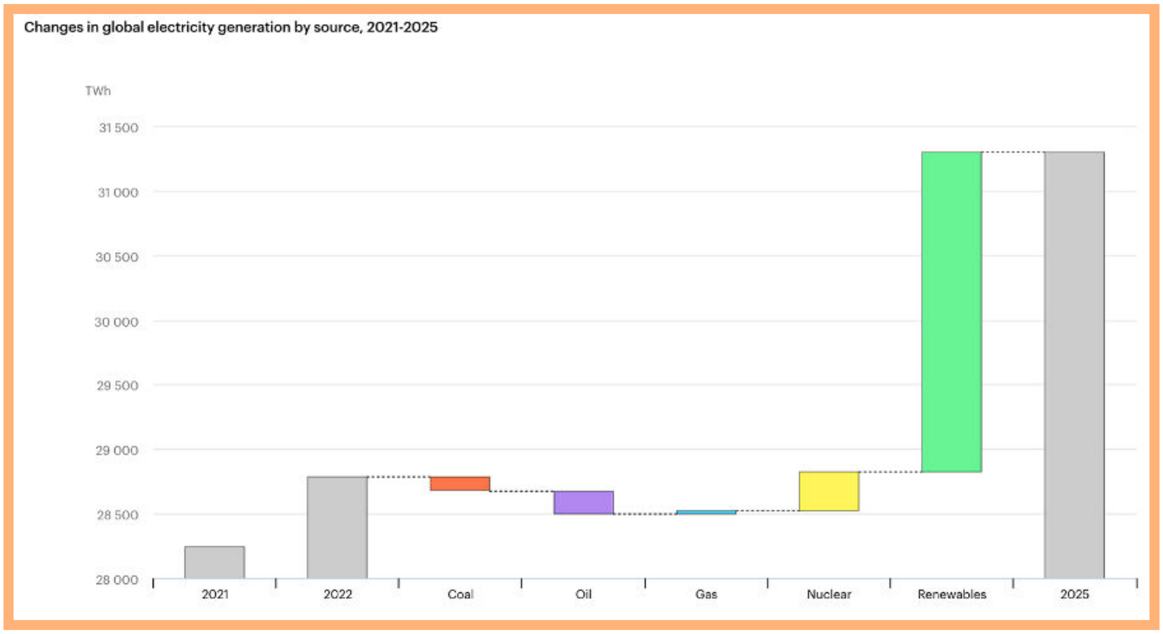
Our World in Data / BP

- Hydro is still the largest source of low-carbon electricity, followed by nuclear. However, both have experienced pretty meagre growth rates in recent years, compared to the exponential growth of wind and, particularly, solar.
- **Demand growth:** Although developed market electricity systems will need to expand to account for greater electrification of end-uses, the immediate demand growth will (continue to be) driven by Asia and China in particular, which is expected to represent a third of all electricity demand by 2025.



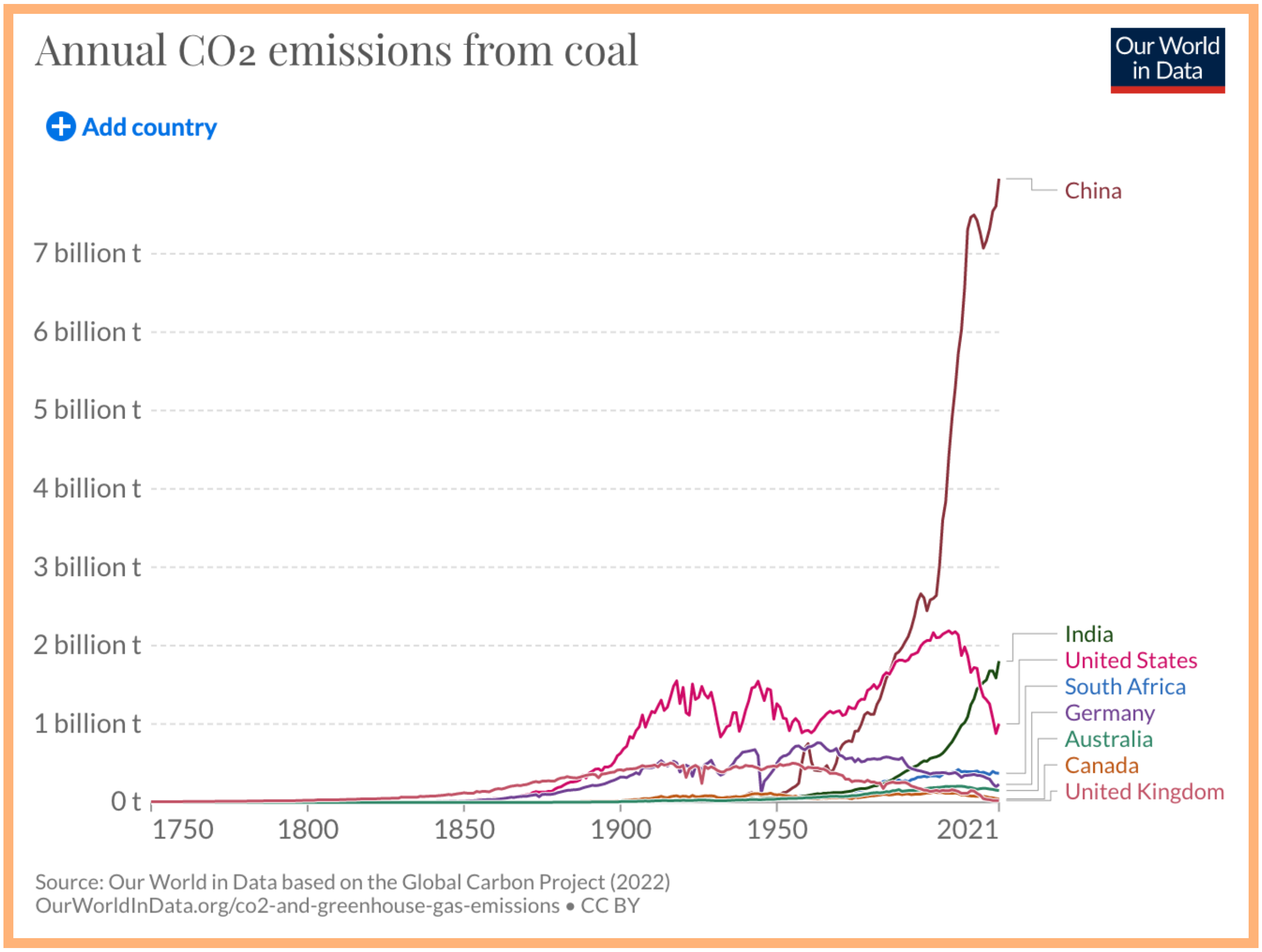
IEA

- The good news is that, now that wind and solar are the cheapest forms of electricity in most places, we are collectively doing a pretty good job of meeting incremental electricity demand with low-carbon sources (new coal in Asia being offset by closures in US and EU). The IEA estimates that about 90% of demand growth over the next few years will be met by wind and solar with most the rest coming from nuclear.



IEA

- The bad news is that low-carbon sources, whilst edging out fossil fuels on a relative basis, still aren't yet putting much of a dent in the absolute level of fossil generation and, hence, emissions in the global power sector. The IEA expects emissions from electricity generation to be broadly flat through to 2025. BUT, where incremental demand is being driven by electrifying end uses, and that incremental demand is being met by low-carbon electricity, then it still reduces emissions of the energy system as a whole.
- The clear priority for reducing absolute emissions from electricity is to phase out coal. Coal is responsible for about 10GT of the 13GT of annual emissions from the power sector, which is, once again, mostly China, followed by India and other Asian countries. If we look at emissions from coal use *in total* (not only the power sector), China's role in pretty striking:


Annual CO2 emissions from coal

Source: Our World in Data based on the Global Carbon Project (2022)
OurWorldInData.org/co2-and-greenhouse-gas-emissions • CC BY

Our World in Data

Before we get into the pathways for driving electricity towards zero carbon, it's worth touching on a few concepts.

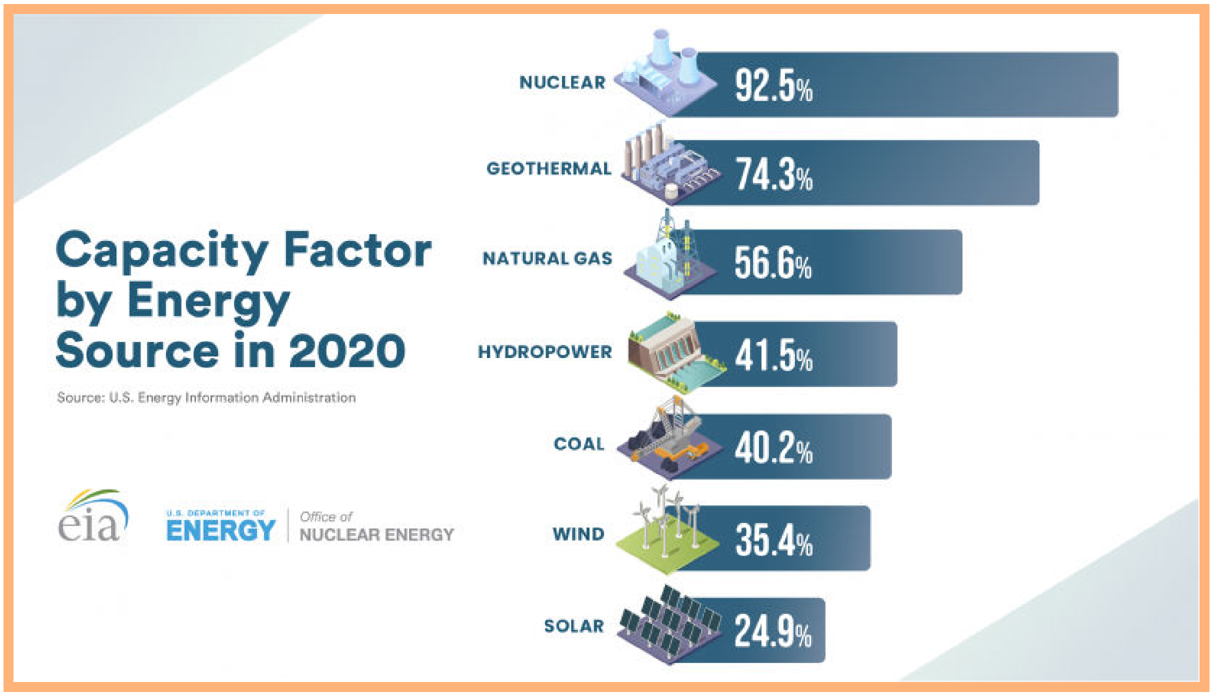
Levelised Cost of Electricity (LCOE)

This is the measure that is meant to capture the overall cost per unit of electricity delivered. A good report to dig around on to get a sense of competing technologies is Lazard's LCOE Report. One important qualifier is that the LCOE metric only captures the isolated costs of the generation. It *does not* capture the system costs of integrating that generation into the system. When these are included, the actual costs for variable renewables are shown to be much higher than the LCOE would suggest and increasing with increased grid penetration. The calculation for LCOE can be split different ways, but is essentially made up of three components:

- **Capital costs** - There are two inputs into this. Firstly, the capital outlay - how much does it cost to build the generation capacity per MW of potential output, whether that be a gas CCS plant, wind farm, etc. Secondly, the cost of capital - what is the interest rate you are paying on the financing to fund the capital expense. The perceived different risk profiles between fossil and renewables here gives renewables a distinct advantage as investors demand a lower return on wind and solar.

- **Operating costs** - for fossil power plants this is mostly the cost of the fuel - gas or coal. Nuclear operating costs include fuel, but it is a smaller portion as they also include waste disposal and decommissioning. Operating costs for wind and solar are a smaller portion of the LCOE as they get their 'fuel' for free.

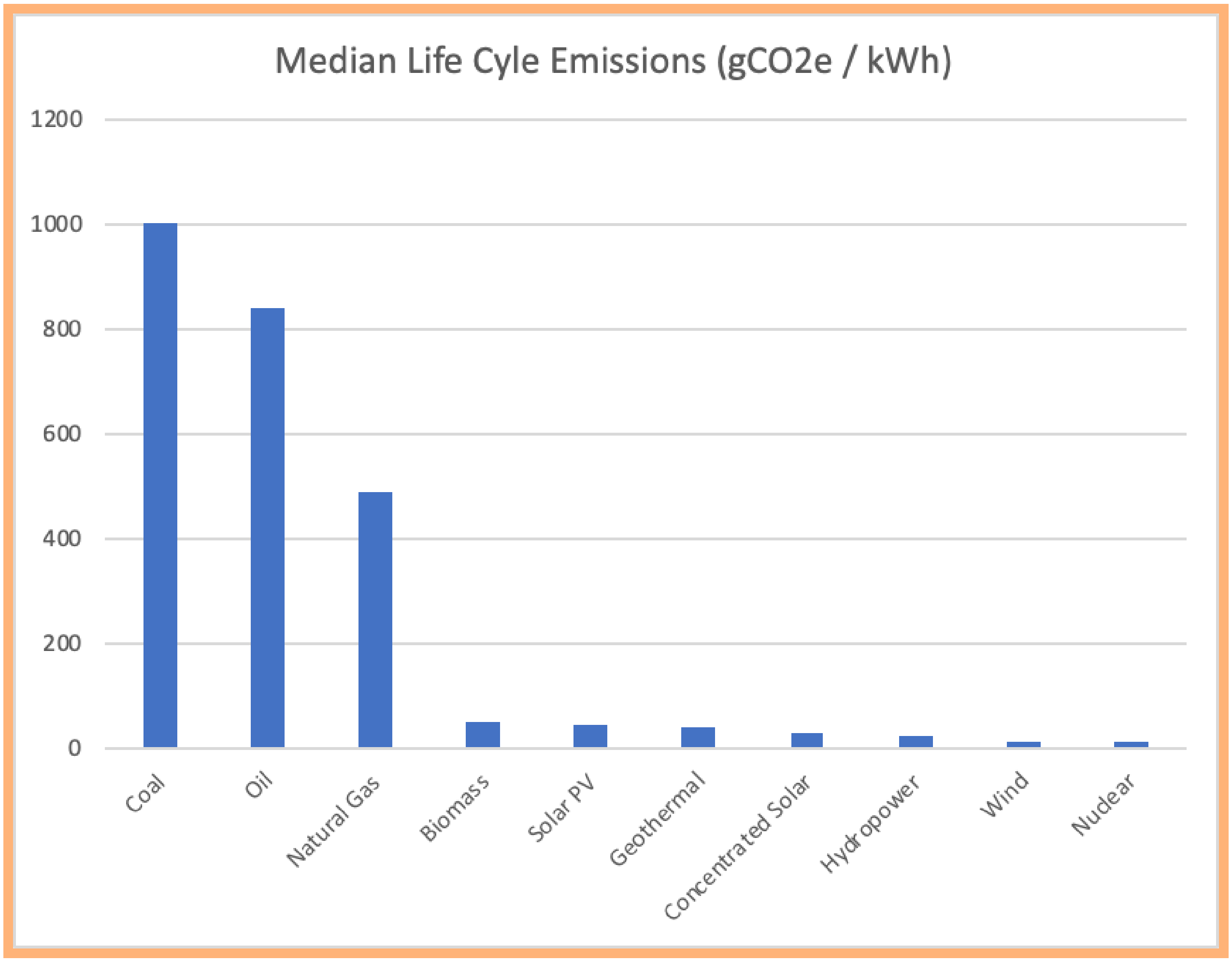
- **Capacity factor** - this refers to the amount of time the generating source is running and therefore the amount of energy the capital costs can be amortised over. This is an important concept that is often glossed over as the press so often reports changes in installed capacity. Installed capacity doesn't reflect the overall contribution to the grid, as, for example, solar farms don't produce any power at night. The capacity factor of different technologies varies radically between different countries or regions, but the below from the US gives a sense - you need 3-4x installed capacity of renewables to produce the same amount of electricity as nuclear:



US Energy Information Administration

Life-cycle emissions

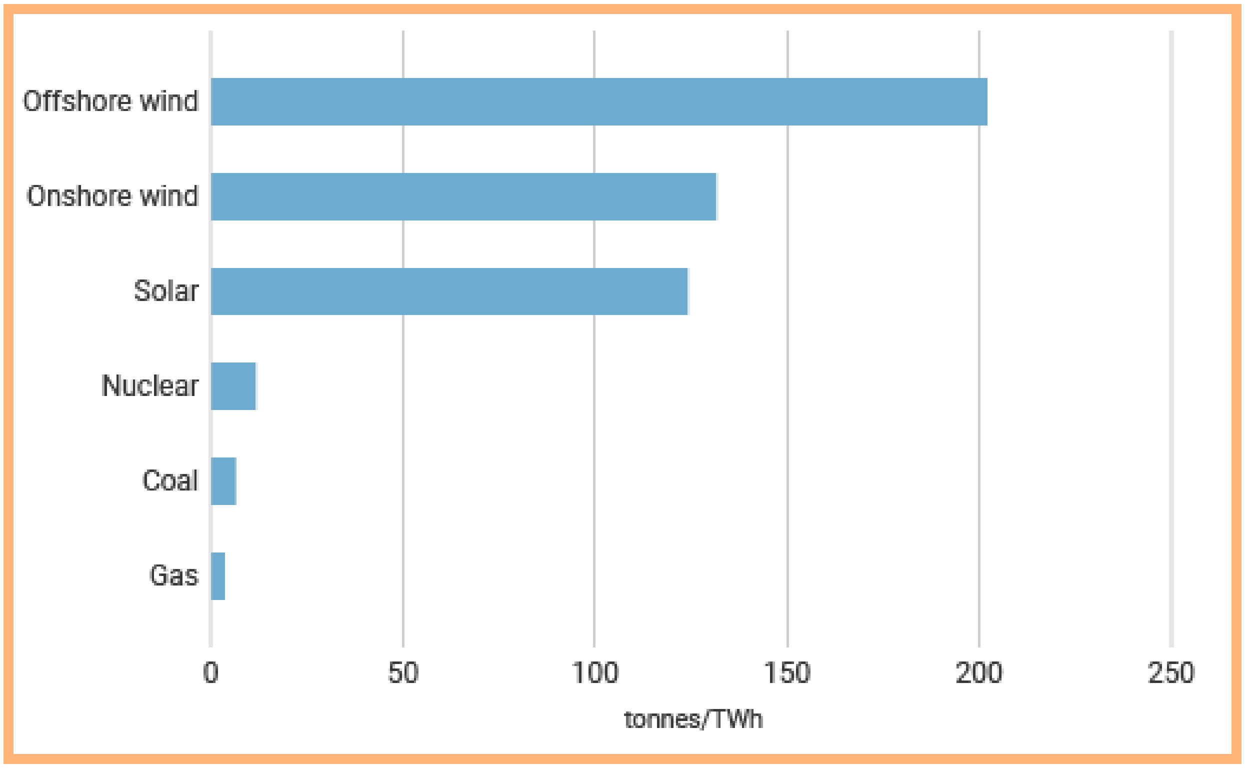
No electricity source is truly *zero* carbon as they all involve emissions at some point during their lifecycle. Solar panels require energy intensive manufacturing, wind turbines require copper and steel, hydro dams require steel and cement. According to NREL, the absolute lowest lifecycle emissions are jointly wind and nuclear, but everything not fossil fuel based is such a vast improvement on fossil that differences between them fade to insignificance.



Data from NREL

Material Requirements

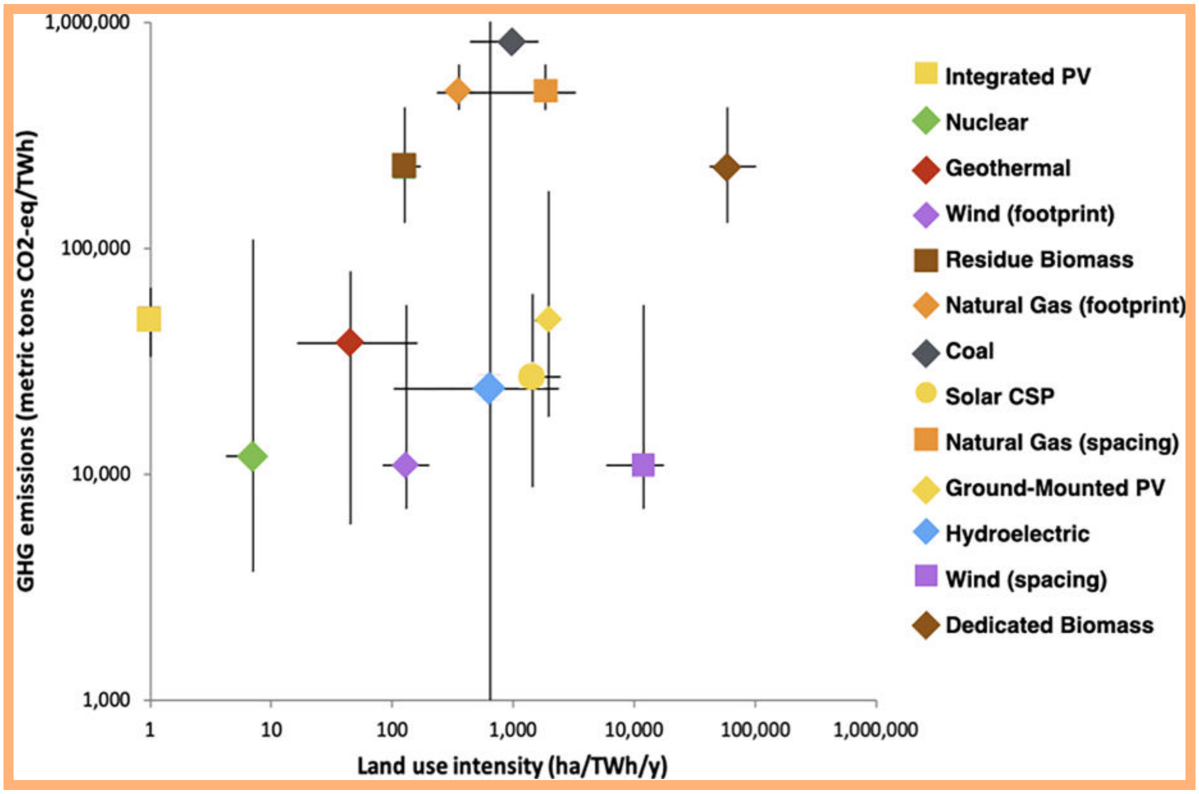
Supply chains in general and for critical minerals in particular have really swung into focus in the last year. The energy transition is going to require a lot of stuff. The IEA recently flagged copper and nickel in particular as having large investment gaps. You can see from below that nuclear has much lower requirements of critical minerals per unit of energy than wind or solar, and that isn't even accounting for associated requirements for batteries.



IEA / World Nuclear Association

Land use

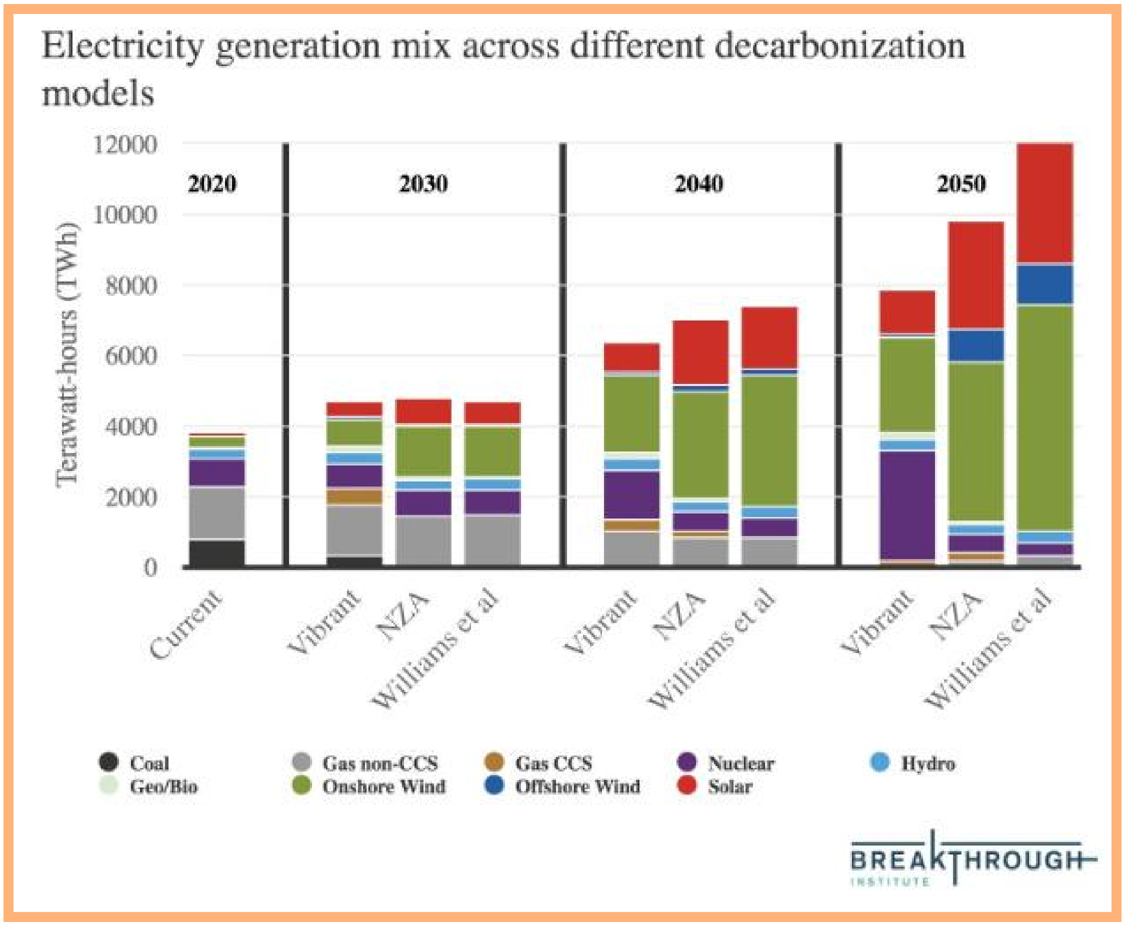
The question of land availability to date hasn't been very pressing, whilst wind and solar remained smaller portions of the grid. However, we are starting to see this become more of an issue, not necessarily due to an absolute dearth of suitable sites, but has areas with high development become saturated from a public approval and permitting perspective. Additionally, any scale application of energy crops has very serious land-use implications. As it stands already fully a quarter of US corn production covering almost 9mm hectares (21.5mm acres) are used for ethanol production. The below chart plots land use against carbon intensity. Note that it is plotted on a log scale! Also note that whilst wind farms take up vast amounts of land, the area between the turbines can be used for other purposes, like grazing land.



Breakthrough Institute

So how do we get there?

There is no one way to decarbonise electricity supply. The path taken will depend not on technology only, but also on political, public and industrial support and will be place-dependent. The most work has been done on modelling the decarbonisation of the US grid, for which there are multiple detailed studies, each of which have multiple viable pathways to get to the end goal. The Breakthrough Institute does a good job of comparing the central scenarios of three credible studies - Net Zero America, Vibrant Clean Energy, and this one by a team from Evolved Energy Research and others. There is also another detailed study by NREL released last year.



Breakthrough Institute

Almost all scenarios have on-shore wind as the biggest contributor to an expanded and clean electricity grid, with solar making up most of the rest and then nuclear playing a stable or expanded role, depending on the capacity to deploy renewables. In any case, we are looking at something like 70-80% combined for wind and solar, up from about 12% today. From here on out, there are two main areas we need to focus on. Firstly - expand wind and solar as much as possible. Secondly - build out low-carbon firm generation.

Expand wind and solar

Wind and solar deployment is really hitting an inflection point where they will start to make up a meaningful portion of generation in the coming years. But their variable nature means that we need to make a lot of system adaptations to maximise their integration. We'll take a look at these below. In addition to these integration measures, there are now lots of companies working on reducing the costs on the generation side by tackling those different components of LCOE - capex, opex, and capacity factor - to make renewables cheaper.

Transmission

Renewable resources are very often not located close to demand centres and the land use requirements can be challenging in densely populated regions. This requires the transport of electricity over long distances. Transmission across regions also allows much greater flexibility in the grid to draw supply from different generation sources. There are various ways to squeeze more out of the existing grid including upgrading the wires with higher-capacity conductors (e.g. those being developed by TS Conductor) and better optimisation of existing hardware (e.g. LineVision, SmartWires). There are also a couple of companies working on high-temperature superconductors for long-distance transmissions - BEV-backed VEIR in the States and SuperNode, based here in Ireland. But, whatever the tech, there needs to be a vast expansion of long-distance transmissions capacity. In NREL's high-wind and -solar scenarios, they have transmission increasing by 2-3x compared to less than 10% increase in the reference scenario. Tackling the permitting challenge is critical if we are to achieve this. I wrote more about the topic of transmission here.

Grid balancing

- **Utility-scale storage:** Already around half of new wind and solar projects applying for grid connections are paired with batteries generally with 4-8hr of storage to balance supply and demand over the day. New utility scale storage will be dominated by lithium-ion batteries in the near future given the momentum and build out of the industrial base, although (underreported) pumped hydro still accounts for 90% of storage today. BNEF estimates a 15x increase in energy storage up to 2030, with most of that (60%) for utility-scale shifting of energy supply.

- **Distributed Energy Resources (DERs)** - can be used to either reduce demand or increase supply (more on those here):
    - Demand side response (reduce demand): reducing demand at times of lower electricity supply has been around a long time, traditionally involving the utility picking up the phone to a commercial or industrial customer. Increasingly this will be digitised as more smart devices are managed with software to allow them to shift the demand according to the grid's needs - e.g. heatpumps / AC or EV charging (see recent announcement from Sonnen).
    - Virtual Power Plants (increase supply): VPPs cover the broad category of aggregating many distributed generation sources to provide electricity back to the grid. This generally will draw on rooftop solar, home batteries and eventually vehicle-to-grid (V2G) enabled EVs. Recently it was announced that Lunar Energy teamed up with SunRun to operate its VPPs across 10s of thousands customers with home batteries. Other companies in the DER area -

Leap Energy, Camus Energy, Octopus Energy, Therma (using cold chain assets) and Arcadia.

Long-duration storage

- **Multi-day:** Renewables penetration isn't yet high enough for this to be a burning need, but we need to start work on it now so eventually we can cover multi-day lulls in wind, for example. Even a lot of the energy storage companies branding themselves as "long-duration" are really only reaching 10-12 hours of storage. The company that seems to have the most momentum for multi-day storage is Form Energy, which has contracts to deploy two 100hr batteries with a power output of 10MW and capacity of 1000 MWh. One to watch closely, but that is at an earlier stage of development is Noon Energy. A few other companies that get out past the 4-8hrs of li-ion but aren't quite multi-day - Energy Dome, Hydrostor, Quidnet Energy, eZinc.
- **Seasonal storage:** Energy demands, particularly in densely populated northern latitudes, have large seasonal disparities for energy needs, as anyone closely watching Europe's weather and gas storage levels last winter will be acutely aware. Ultimately we will want to be able to shift abundant summer solar to cover gaps in winter energy demands. Again, we won't hit this level of dependence for some time, but it will be a challenge. This very long-term storage will likely take the same form that we currently store most of our energy in - molecules (we normally refer to them as oil / gas / coal). This could be hydrogen, or if we are happy to trade energy efficiency for ease of storage and transport, we could turn hydrogen back into synthetic fuels. This will be expensive energy, but will only form a small part of our energy use, if we go this way at all. However, it's possible (probable even) that we'll stick with natural gas to cover seasonal shortfalls. (I was surprised to see a pretty significant chunk of H2 seasonal storage in 3 of NREL's four scenarios.)

Clean baseload / firm generation

Whilst the backbone of future clean electricity grids might be wind and solar, the majority of low-carbon electricity historically, and still today, come from hydro and nuclear. The only developed economies today with very low carbon intensity of electricity are heavily dominated by hydro and / or nuclear - Sweden, Norway, France, Canada, Switzerland. So there is a demonstrable path to having a very low carbon grid with little or no variable renewables, whilst the reverse has not yet been demonstrated. Additionally, a number of baseload technologies create heat, which represents 50% of final energy demand, so can be used to provide that directly rather than going through the medium of electricity. Let's take a look at the different options - now and in the future.

Hydropower

Currently delivers 15% of global electricity and is about equivalent to all other low carbon generation put together. However the outlook doesn't suggest that hydro will be a major source of new generation over the next decade and beyond as it is very site-specific and most of the best resources have already been developed. There are some people working on electrifying existing dams (Rye Development) and trying to extract power out of man-made water infrastructure (Emrgy), but it will be a relatively marginal contributor.

Nuclear

Ah, nuclear. Joint lowest lifecycle emissions, lowest land use, safest form of generation per unit of energy delivered, and, in many large economies (e.g. US) still the biggest source of low-carbon electricity. Nuclear energy is swinging back into favour as the global energy crisis underscores the necessity for energy security and resilience as well as decarbonisation. However, a long period out of vogue and a culture of excessive caution has allowed supply chains and skills to atrophy and left the nuclear industries with precious few successes to celebrate.

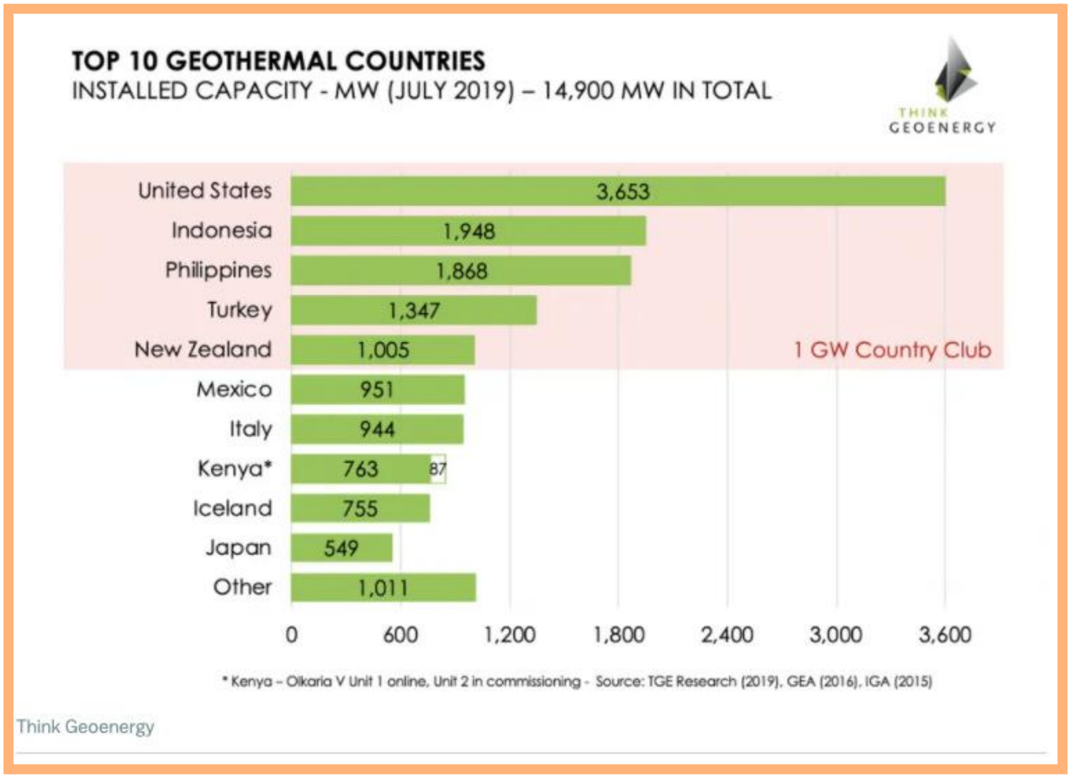
Currently, most of the planned construction is in China (as usual) and India, but with the UK committed to expanding its fleet, along with France, Romania, Poland, Netherlands, Sweden, Estonia, etc, it looks like we're on the cusp of a broad renaissance. There has also been a flourishing of new innovation in the space. SMRs that look like smaller versions of traditional reactors such as NuScale and GE-Hitachi's BWRX are the furthest ahead. GE-Hitachi's design looks like it will be the first to be built in the West, in Canada (why, yes, China does already have one well under way), with NuScale having advanced talks with multiple countries and recently fully completing US licensing of its design. There are other designs of similar scale but newer designs, mostly using a high-enriched fuel (known as HALEU) and different coolants, such as molten salts or gas. These include, amongst others, X-Energy and Bill Gates' TerraPower (both in the US's Advanced Reactor Demonstration program), Terrestrial Power, and Moltex (headed by a fellow Irishman and Trinity College alum!). These new designs also tend to have the capacity to be ramped up and down to compliment a renewables-heavy grid. Then there are others pursuing micro-reactors in the 1-20MW range, including Radiant, Ultra Safe Nuclear Corp and Oklo (going public via a SPAC led by Sam Altman), that could replace diesel generators in remote areas like mining operations or military bases, or serve large single users like university campuses. Another company in this last category with a design that utilises all existing technology is Last Energy, looking to build 20MW reactors to supply behind-the-meter electricity to industrial customers. One of the most exciting potential applications for advanced nuclear is to repower coal plants, allowing them to reuse the site, the grid connection and, depending on the age of the coal plant, some of the balance of plant. More about coal-to-nuclear here.

Natural Gas with CCS

What if we could get the benefits of fossil fuels without the negative externalities of emissions? Previous attempts to do post-combustion capture on power plants have ended in failure due to the expense of capturing the CO2 in a relatively dilute flu gas, needing to separate out the nitrogen and other pollutants. NET Power have developed an oxy-combustion technology where natural gas is burned in pure oxygen, creating a pure stream of CO2 which is then easy to capture and sequester. They also use the hot CO2 as the working fluid to drive the turbine, which has advantages over steam, but also complications (as Rob West of TSE explains here). More on NET Power here. Another company using an oxy-combustion technology is Clean Energy Systems, although they envisage using a classic steam turbine. We have a massive task to decarbonise energy and need all the levers available to us, including fossil fuels where we can make them compatible with our climate ambitions.

Geothermal

Today, geothermal represents a teeny-tiny portion of the global energy mix as it is extremely location dependent, requiring heat near the surface, permeability and water. There is only 14GW of installed capacity, with only 5 countries having more than 1 GW.



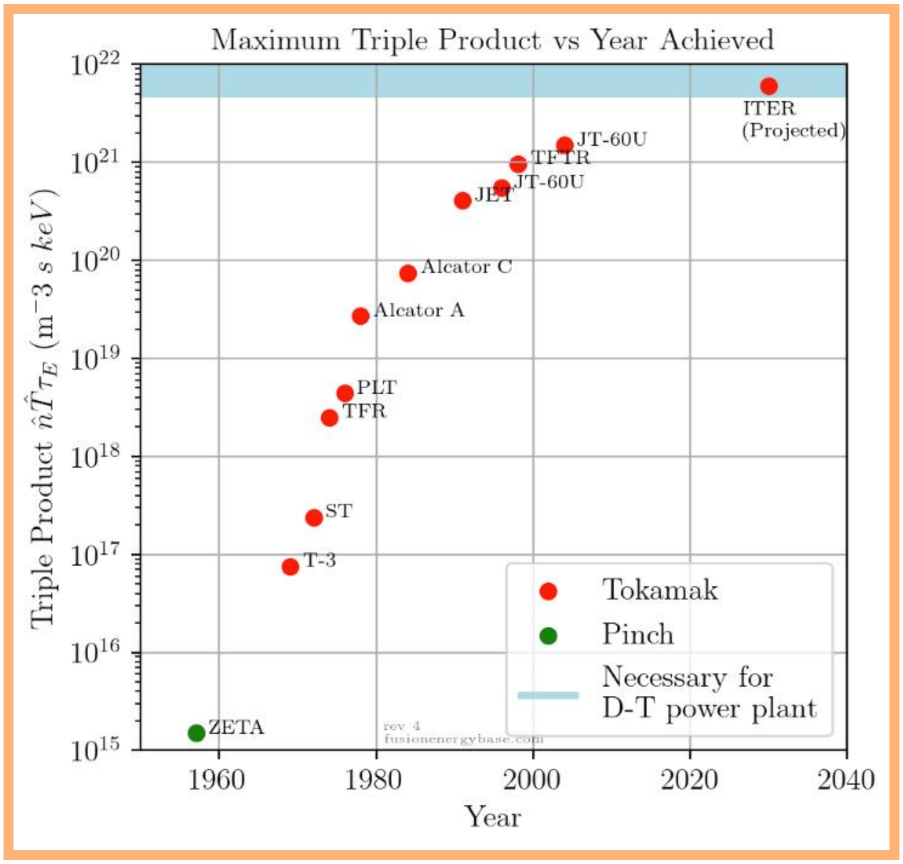
* Kenya – Olkaria V Unit 1 online, Unit 2 in commissioning - Source: TGE Research (2019), GEA (2016), IGA (2015)

Think Geothermal

- But advances in drilling technology in the oil and gas industry are opening up the prospect of economically accessing new heat resources. A few companies using techniques from the O&G industry are Fervo, Sage, and Eavor. However, the most compelling, if technologically difficult, approach is to try to drill much deeper to access higher temperature heat. This has the dual benefit of being able to access geothermal energy anywhere, and allowing much more efficient conversion of the heat to electricity (more on that here). The challenge is that, at those depths and temperatures, mechanical drilling equipment melts. Slovakian company (recently relocated to the US) GA Drilling and Quaise Energy (spin out from MIT) are respectively developing plasma and millimetre wave drilling techniques. If they are successful, they could unlock functionally limitless energy, and also be in a position to provide heat to repower coal plants. Whilst still early days, it's exciting stuff!

Fusion

Just because something is hard or far away, doesn't mean it isn't worth doing. Fusion definitely falls into this category. It won't have a short term role in grid decarbonisation, but successful realisation would have huge implications for clean energy abundance and humanity's long-term ambitions. Fusion technology has been making steady progress over the last several decades, but the inflection point where it starts to become interesting has only recently swung into view. Below shows the progress on the "triple product" conditions of heat, density and time of confinement that allow for fusion conditions in plasma. Note that it is on a log scale so these are exponential gains and also they don't include the latest improvements including the recent milestone (*not* breakthrough) of ignition at Lawrence Livermore.



Fusionenergybase.com

There has been a proliferation of startups taking on the challenge of commercialising fusion energy, supported by the advances of enabling technologies ranging from power electronics to computer modelling to material science. The two broad approaches to fusion are magnetic confinement and inertial confinement. The first, as the name suggests, uses super powerful magnets to contain the plasma to fusion conditions. Companies using that approach include CommonWealth Fusion Systems (to date the highest funded company), Tokamak Energy in the UK, and Renaissance Fusion, which is using a stellarator design. Inertial confinement relies on higher densities to create fusion as inertia holds together the plasma for tiny amounts of time. Prominent startups taking that approach include General Fusion and First Light Fusion, both of which are building pilot facilities at Culham in the UK. Another company of note is Helion, which has a slightly different approach using different molecules for its fusion reaction and a way to directly extract the electricity (rather than producing heat + steam). CFS and Helion are talking about net electricity this decade (with Helion as the first fusion company with a PPA, ostensibly for 2028), but it remains to be seen.

There is a lot to take in here, but hopefully we've made clear why low-carbon electricity is really the key to our climate goals and broader long-term ambitions and identified the main levers for getting there. As it stands today though, our energy system is mostly made of molecules (hydro-carbons) and there will be certain applications that we'll struggle to electrify, which brings us onto Part 4: Green Molecules.

Part 4:

Green Molecules

We often say to people that ultimately climate is a molecules game. The end game of climate action is to reduce the flow, and eventually the stock, of global warming gases in the atmosphere. The biggest opportunity to reduce emissions is through energy efficiency, and switching away from molecules and towards electrons for energy (whilst decarbonising electricity production). However, there are certain areas where electrons just won't do, and we need to tackle these also. We use molecules in two main ways - as ends in themselves, for making stuff (like plastics) or for their chemical inputs (like fertilisers), where their chemical composition matters; or as energy-carriers (oil, gas, coal, wood) where we are really just interested in releasing energy from breaking apart the bonds via combustion.

We'll divide this part into these two sections, tackling green chemistry first. This represents a smaller share of total emissions than emissions from fossil fuels used as energy carriers, but it takes priority as an end use for green molecules. We then look at the main options for green molecules as energy carriers and the (relatively few) use-cases where electrification will fall short and molecules will still be required.

Even by the standards of this high-level document, this part requires industrial-strength distillation, due to the highly heterogeneous nature of chemicals and fuels. Hopefully, it can serve readers as a reference and jumping off-point for further investigation, but, at minimum, readers should leave with the following takeaways:

1. Round trip efficiency is a challenge

For both chemicals and fuels, decarbonising effectively requires pushing molecules energetically up-hill, so we need to be very mindful of allocating clean electricity generation to that endeavour where it might otherwise be used more effectively for decarbonising the grid or expanding electrification.

2. Harness nature

Bioresources are the cheapest way to get many green molecules (allowing photosynthesis to do the work), but sustainable supply is limited and, once again, shouldn't be squandered on things which can otherwise be directly electrified.

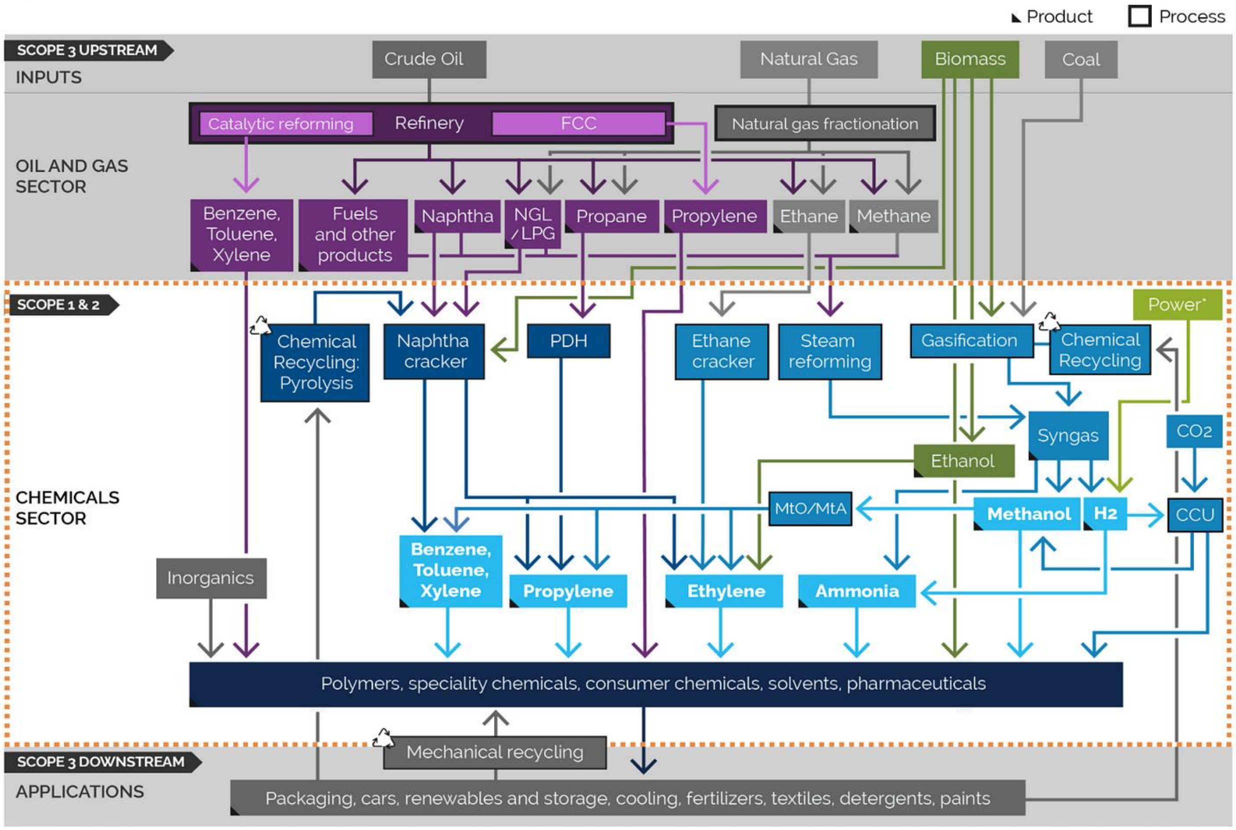
3. External factors matter

Whilst we should aim for the most cost- and energy-efficient transition possible, ultimately it will evolve according to what people are willing and able to build. For example, green electricity might be the lowest hanging fruit from a technical perspective, but if new transmission can't be permitted and interconnection queues are too long for renewable projects, whilst subsidies for molecules are generous ($3 / kg for low-carbon H2 under the IRA), then we'll see hydrogen get a bigger role than it "should". (I expand further on this, but it's important context.)

Green chemicals

Whilst it isn't very visible in our everyday lives, we are dependent on the chemical industry and the molecules it produces for many of our most basic needs, not least of all for fertiliser production, which is responsible for feeding half the people on the planet. The chemical industry is vast and its boundaries - and hence emissions - are difficult to define. Whilst the study cited by the IPCC in its latest report puts it at 2.8 GT, as the IEA defines it, it is just shy of 1 GT per year. The IEA figure includes ammonia, methanol, and what it terms "high-value chemicals" which are ethylene, propylene, benzene, toluene and mixed xylenes - all organic chemicals, or ones that are carbon-based and currently obtained from fossil fuel feedstock. The IEA leaves out big chunks of hydrogen production that are used for refining, and in steel production (a good use of green H2, but no climate benefit if it's made the traditional, high-emission way). Hydrogen production alone represents almost 1GT of CO2 emissions / year. What we can definitely say is that there are significant emissions related to the molecules we need to make stuff, but it's complicated - see below from SBTi's Chemicals program, yikes!

Figure 1: Visualization of Chemicals Sector Components and Boundaries



Notes: CCU = Carbon capture and utilization; FCC = Fluidized catalytic cracking; H_2 = Hydrogen; NGL = Natural gas liquids; LPG = Liquified Petroleum Gas; MtO = Methanol to olefins; MtA = Methanol to aromatics; PDH = Propane dehydrogenation. *Power denotes selected electricity use. Note discussion below on classification of chemical recycling.
Source: SBTi.

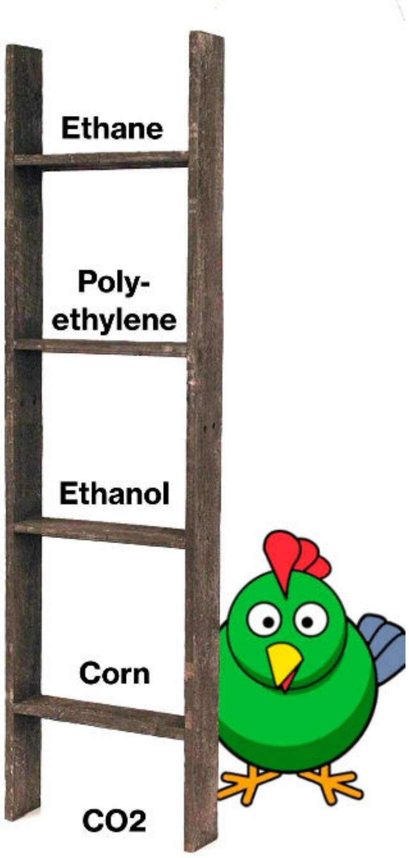
SBTi

Fossil feedstock

According to the IEA, fossil fuels are used as the feedstock for 70% of chemicals and the petrochemical industry (the bit that uses fossil feedstocks) accounts for 14% of oil demand and 8% of natural gas demand globally. As demand for stuff continues to rise whilst demand for oil in particular as a fuel drops because of electrification of transport, that proportion is likely to rise. As it happens, chemicals are a pretty good use of fossil fuels, much better than fuel. Why is that?

Inherent value of molecules and energy ladder

Unlike with fuels, which can be replaced in most cases with electrons (see exceptions in below section), when it comes to *stuff* the molecules are the point. When we are producing stuff we want to start with flexible feedstocks that can be relatively easily converted to valuable end uses. Here, I'll borrow a simplified visualisation from Doomberg:



Doomberg

The implication of the above ladder is that where we want to produce high value organic molecules with higher energy content from very low energy CO2 or sugars, we need to inject extra energy to push them up the ladder. Whilst the linearity suggested by the Doomberg ladder is not absolutely accurate (it still takes a lot of energy to crack ethane into ethylene - the precursor to polyethylene), it still usefully visualises the broader point around fossil feedstock being an easier starting point to get to complex hydrocarbons. Plastics and materials are a better use of our fossil energy endowment than using them for fuel!

So how do we go about decarbonising the valuable molecules we currently get from petrochemicals? The short answer is - with great difficulty. (Check out the complexity of tackling just a single value chain - work on decarbonising PVC from Center for Houston's Future.) However, there are a couple of broad areas that we might consider.

Biological pathways

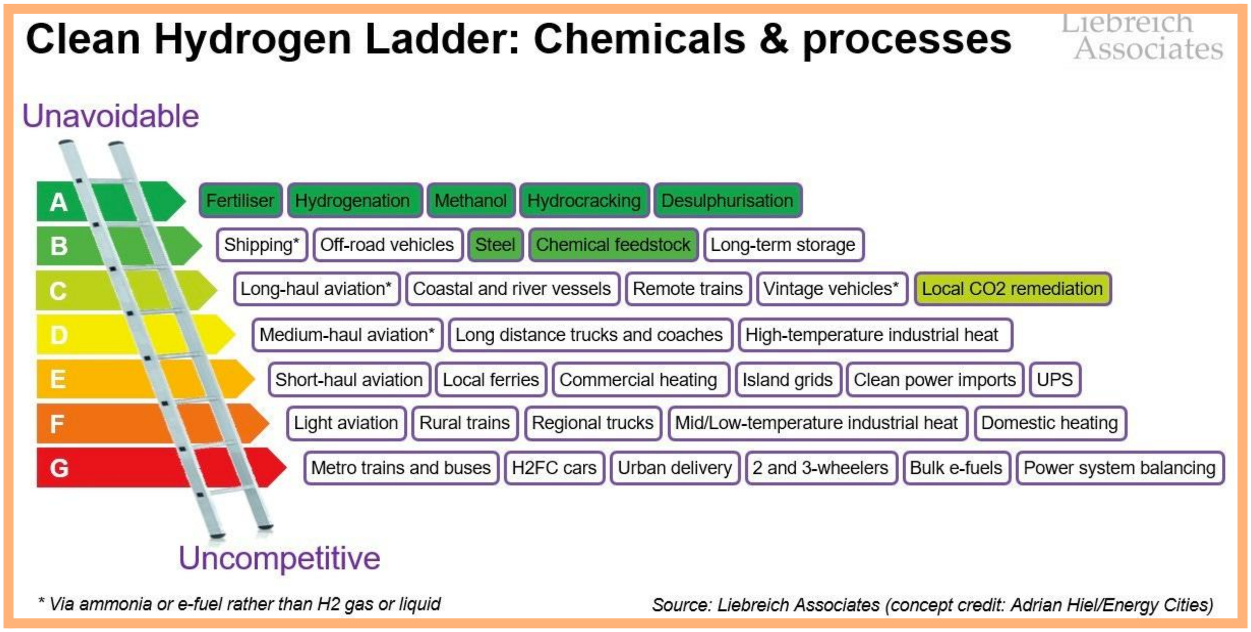
Whilst it is energetically expensive to push molecules up the ladder from CO2 or sugars (e.g. corn), it is relatively efficient via biological processes using enzymes (biological catalysts) or microbes. There are a number of companies looking to move either CO2 or sugars up the ladder to alcohol or beyond. To name a few - Lanzatech, Solugen, and Cemvita, each at various stages of development. Additionally, the Energy Transition Commission's report on bioresources clearly states that bioresources should be prioritised not as fuel but as feedstock, both for timber and wood materials as well as an input for bioplastics to replace some petrochemical demand (although it notes that this technology needs to be advanced).

Energy efficiency

This might technically fit into the earlier post on efficiency and electrification to reduce the demand for fossil fuels, but there are a couple of companies worth mentioning specifically in the context of chemicals. The chemicals industry uses vast amounts of energy creating heat and pressure. There are companies looking to replace those processes with either membranes (Via Separations, Osmoses) or light (Syzygy Plasmonics - efficiency / different feedstocks).

Hydrogen - decarbonising supply for existing uses

The current hydrogen market is about 90mm tons per year, and almost all of it is produced from fossil fuels (mostly steam methane reforming) producing almost 1GT of CO2 / year. It is used entirely for its value in chemical reactions and not at all as a fuel. The two biggest uses of hydrogen today are for ammonia production (the vast majority of which is used for fertiliser) and for refining, with some going to methanol production and to direct reduction of iron in steel making (more below). Hydrogen seems to be a weirdly emotive topic, but the top priority is replacing current uses with the low-carbon kind. For more on the priorities of low-carbon hydrogen, I'll defer to Michael Liebreich's [Hydrogen Ladder](), only to note that the entire top row and ⅔ of the second is for existing chemical processes:



** Via ammonia or e-fuel rather than H2 gas or liquid*

Source: Liebreich Associates (concept credit: Adrian Hiel/Energy Cities)

Liebreich Associates

Hydrogen in steel production

Hydrogen use for iron and steel production should be one of the higher priorities for new green H2 capacity. The sector is responsible for about 2.5GT of emissions, which includes both emissions from the heat sources and process emissions. According to the IEA, about 5 million tons of H2 is currently used in 7% of steel production, where it is mixed with carbon monoxide in various concentrations (syngas) to reduce iron ore to sponge iron. ("Reduce" in this context means removal of oxygen atoms, opposite of "oxidise".) Emissions from this reduction process can be basically eliminated by using 100% hydrogen, which bonds with the oxygen from the iron ore to form water (H2O) instead of having carbon bond with it to make carbon dioxide. The most prominent project underway is H2 Green Steel in Sweden, which is going to take advantage of abundant local clean electricity (hydro & wind) to use hydrogen for the reduction and electricity as the heat source. Just to note, one other (non-hydrogen) potential pathway to decarbonise steel is through the direct electrolysis process that is being developed by Boston Metal. Chris Goodall of Carbon Commentary did a useful comparison of Boston Metal's approach and the hydrogen DRI approach. Rob West also recently looked at it here.

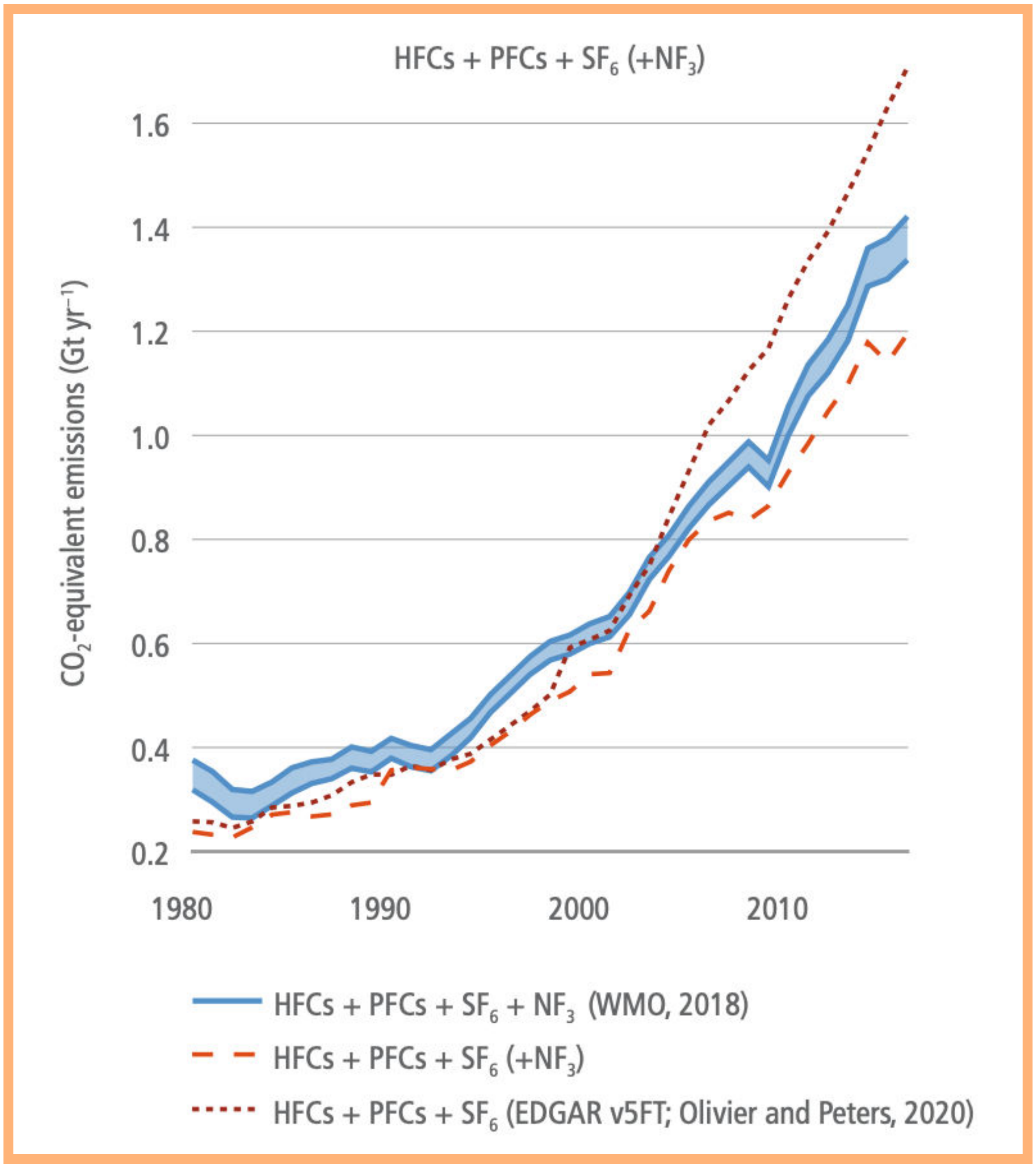
Reducing ammonia demand

aAs well as replacing high-emitting chemical fertiliser with a low-carbon equivalent, we should make efforts to reduce overall demand for chemical fertilisers either with regenerative ag practices that put nitrogen back in the soil (e.g. rotating crops with legumes) or using biological additives for putting nitrogen in the soil (as yet unproven, but plenty working on it - Switch Bio, Pivot Bio, Kula Bio, etc), or other novel ways of adding nitrogen (e.g. Nitricity - non-ammonia fertiliser). Judicious use of fertiliser is also critical because it creates nitrous oxide (NO2) which represents roughly 3GT CO2e and also is messing up the earth's natural nitrogen cycle.

Refrigerants and other super-GHGs

Whilst not a major contributor compared to carbon dioxide or methane, fluorinated gases (or F-gases) still represent about 1.5 GT CO2e emissions per year and that number has grown about 5x since 1990 (see below chart). Their growth represents a classic case of humanity replacing one problem with another when hydrofluorocarbons took over following the ban of ozone-depleting CFCs under the Montreal Protocol. As usual, The Simpsons have a quote for that.

Whilst F-gases are used in small quantities, their global warming potential runs to thousands of times that of CO2 and they tend to be long-lived. The vast majority of F-gases are used as refrigerants but also in industrial processes like making of foam. Replacing these gases would have a massive climate impact - Project Drawdown estimates there is something like 45GT of CO2e worth of abatement on the table over the 30 years to 2050. Climate-friendly cooling deserves (and will get) its own dedicated post, but there are a number of people working on alternatives that don't use F-gases such as Gradient. Luckily, there are lots of alternatives available including ammonia, propane and even carbon dioxide (longer list here for anyone interested). In this group of F-gases is also sulphur hexafluoride (SF6), which is the most potent greenhouse gas there is at about 23,000x the global warming potential of CO2. It is currently used in components of the electrical grid, but there are people working on it, including both incumbents and German start-up Nuventura.



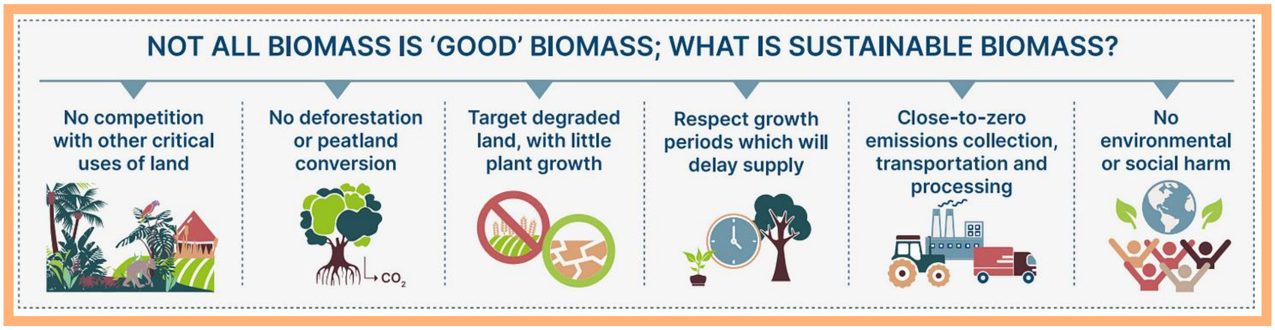
IPCC

Green molecules for carrying energy

The vast majority of the molecules we use today are in the form of hydrocarbons as energy carriers. Whilst the first order of business is to reduce the demand for them through energy efficiency and electrification, there will remain some energy end-uses that are resistant to electrification. This is usually down to the requirement for energy density - either volumetric (energy / unit volume) or gravimetric (energy / unit weight). For these we will ultimately need to be able to decarbonise these energy-carrying molecules. We can produce these through a few principal pathways.

Bioenergy / biofuels

These represent pretty much the entirety of non-fossil molecule energy use today. However, whether or not that bioenergy is low-carbon depends on the particular case. Biofuels have the capacity to be low-carbon because, whilst carbon is put into the atmosphere when they are combusted, it was only recently taken out through photosynthesis. But this requires that the feedstock is sustainably sourced. Still today the largest use of biomass for energy (about 35%) is what the IEA calls "traditional use", i.e. burning wood for cooking. According to the Clean Cooking Alliance, cooking with wood and charcoal represents 1 GT of carbon emissions and about a third of that is sourced unsustainably, i.e. by chopping down forests, with the associated biodiversity impacts on top of the climate ones. Whilst the IEA estimates that the world currently uses about 70 EJ of bioenergy, the Energy Transition Commission suggests that there is only about 65 EJ worth of sustainable bioenergy available, of which 40 EJ should be prioritised for materials and feedstock for chemicals (as noted above), leaving only 25 EJ for energy. That is about 7000 TWh of primary energy or around 5% of today's primary energy use. These should be prioritised for those applications that require liquid fuels. Bioenergy is turned into energy-dense liquid fuels for those niche applications that require them, either through fermentation (e.g. corn or sugarcane ethanol), or through gasification and then through a fischer-tropf process to turn it from gas to liquid. The other way bioresources can contribute to the energy mix is via biogas. This can be produced via agricultural residues, animal manure, or gases from landfill or waste water treatment. The European Biogas Association estimates that by 2050 Europe could produce the equivalent of 40% of its 2022 natural gas demand via biogas. To be sustainable, biomass (as feedstock or energy carrier) should be sourced adhering to the below principles:



Energy Transition Commission

Hydrogen as fuel

The appropriate role for hydrogen as an energy carrier has been vastly overstated in the press and, unfortunately, in some government policies. As already mentioned (but merits repeating), we already have a 1GT abatement opportunity to replace the 90mm tons of today's high-emission hydrogen with the low-emission variety. Hydrogen does have the advantage of being energy dense on a gravimetric basis (joules / kg), but the other side of that coin is that it is not dense at all on a *volumetric* basis. That makes it very expensive to transport, along with other factors such as leakage and high-boil off rates when it is liquified (which also takes a huge amount of energy). Michael Liebreich's piece *The Unbearable Lightness of Hydrogen* covers this well. Really the core underlying challenge with hydrogen as a fuel is that, with production and all of the other steps around making it useful, it is really inefficient, coming out at something like 3-5x less efficient than using electricity directly, depending on the application. Very briefly on the supply side, it is easy to get lost in the hydrogen rainbow of different hydrogen production pathways. The key thing is *low-carbon*! Generally that means using renewable electricity, but it could also mean methane pyrolysis (turning natural gas into H2 and solid carbon) like Monolith or Modern Hydrogen, using heat + power from nuclear fission, mining natural hydrogen reservoirs, using fossil fuels with carbon capture (although methane leaks make this challenging to be truly low carbon), or training microbes to eat crude oil to produce hydrogen like Cemvita is doing.

Electro-fuels / e-fuels / synthetic fuels

Most often these refer to hydrocarbons synthesised from low-carbon hydrogen and CO2, from point source capture (ideally from sustainable biogenic sources if it is to be truly low-carbon) or, eventually, direct air capture (DAC). The inefficiency of using hydrogen applies to e-fuels, only more so, as there are additional steps. However, whilst e-fuels have a disadvantage compared to hydrogen on energy efficiency, their big advantage is drop-in compatibility with existing infrastructure and ease of transport / storage.

Ammonia

Somewhere in between hydrogen and e-fuels sits ammonia - somewhat more efficient than e-fuels, somewhat easier to transport than hydrogen - but it comes with its own drawbacks of being highly toxic and emitting nitrous oxide (a potent GHG) when burnt. Carbon Direct recently put out a report on ammonia's role for decarbonisation.

As you can garner from the above, scaling green molecules as energy carriers is no mean feat. We quickly run into issues around availability of sustainable feedstock (biofuels) or major challenges around energy efficiency and infrastructure buildout. That reality seems to be sinking in, as we observe the putative jurisdiction of green-molecules-as-energy-carriers gradually shrinking. Hydrogen cars are dead. Hydrogen for residential heating is a non-starter. Hydrogen for long range trucking seems to be on the out also - Scania publicly ditched their hydrogen efforts a couple of years ago, hydrogen truck companies Hyzon and Nikola have both flamed out, and Tesla is gradually starting to ramp up production of the Tesla Semi. Remaining end applications will (or at least *should*!) be confined to the relatively narrow cases where a lot of energy needs to be carried over very long distances - shipping and, in particular, aviation.

Aviation

Only about 5% of aviation emissions are going to be able to be abated through electrification as the range of electric planes will cap out at about 400km over the next 10 or so years, extending maybe to 600km by 2050. This means that the vast majority will need to be addressed with green molecules. Liquid fuels that can be blended with conventional jet fuel ("jet-A") are broadly referred to as sustainable aviation fuel ("SAF"), which could be either biofuels or e-fuels. All of the SAF produced today falls into the biofuel bucket and currently pretty much all of that is converting used cooking oil. Another option is to use household rubbish (municipal solid waste or "MSW"), which is what Fulcrum is doing. SAF is also being pursued by the synbio companies mentioned above, again, because it is the highest value fuel. The e-fuels side is further behind, but a number of companies are working on it including MetaFuels, Infinium and Ineratec. Using hydrogen directly with fuel cells to power electric drive trains is another option (e.g. Zero Avia). This is less profligate from an energy perspective than e-fuels but it does require new infrastructure and, critically, redesigned planes. Because hydrogen is less volumetrically dense than jet-A, it requires planes with longer fuselages to store it. However, because it is more *gravimetrically* dense, it gives something back on the amount of weight that needs to be lifted from the ground. Another potential advantage of alternative fuels other than fossil Jet A is the potential to reduce contrails. Amazingly, the climate impact of contrails, which occur in about 1 in 20 flights and last for half a day, is about equivalent to the 100-year impact from the CO2 released by all flights. (This surely means that finding a way to reduce contrails must be one of the highest leverage climate actions out there?) I covered the challenge of decarbonising aviation in more detail in a previous post, and I would highly recommend this recent podcast with Rob Miller of Cambridge's Whittle Laboratory.

Shipping

Like aviation, there is low-hanging fruit for electrification on shorter routes but a much greater challenge electrifying long-distance shipping. There is though one company that deserves a special mention that is taking an innovative approach to long distance electrification, which is Fleet Zero. Long distance shipping's challenge is a bit different from aviation in that space rather than weight is at the greater premium. It is also used to paying very little for fuel as shipping uses fuel oil or bunker fuel, which is quite literally the bottom of the barrel, the tar-like residual that is left from crude oil after refining, so everything else is much more expensive by comparison. In general though, the discussion is centred around either ammonia or methanol, both of which are more volumetrically dense than hydrogen. Methanol has some advantages over ammonia in that it is more stable (easier to store or “bunker”), less toxic, and can be used in existing engines. It seems to have stolen an early lead with Maersk placing orders for 19 dual fuel ships that can run on methanol and supporting the development of new e-methanol production facilities. The advantage of ammonia over methanol from a decarb perspective is that, well, it has no carbs. So for methanol to be truly decarbonised it would need to have point-source capture + storage (Carbon Ridge is working on that) or be e-methanol.

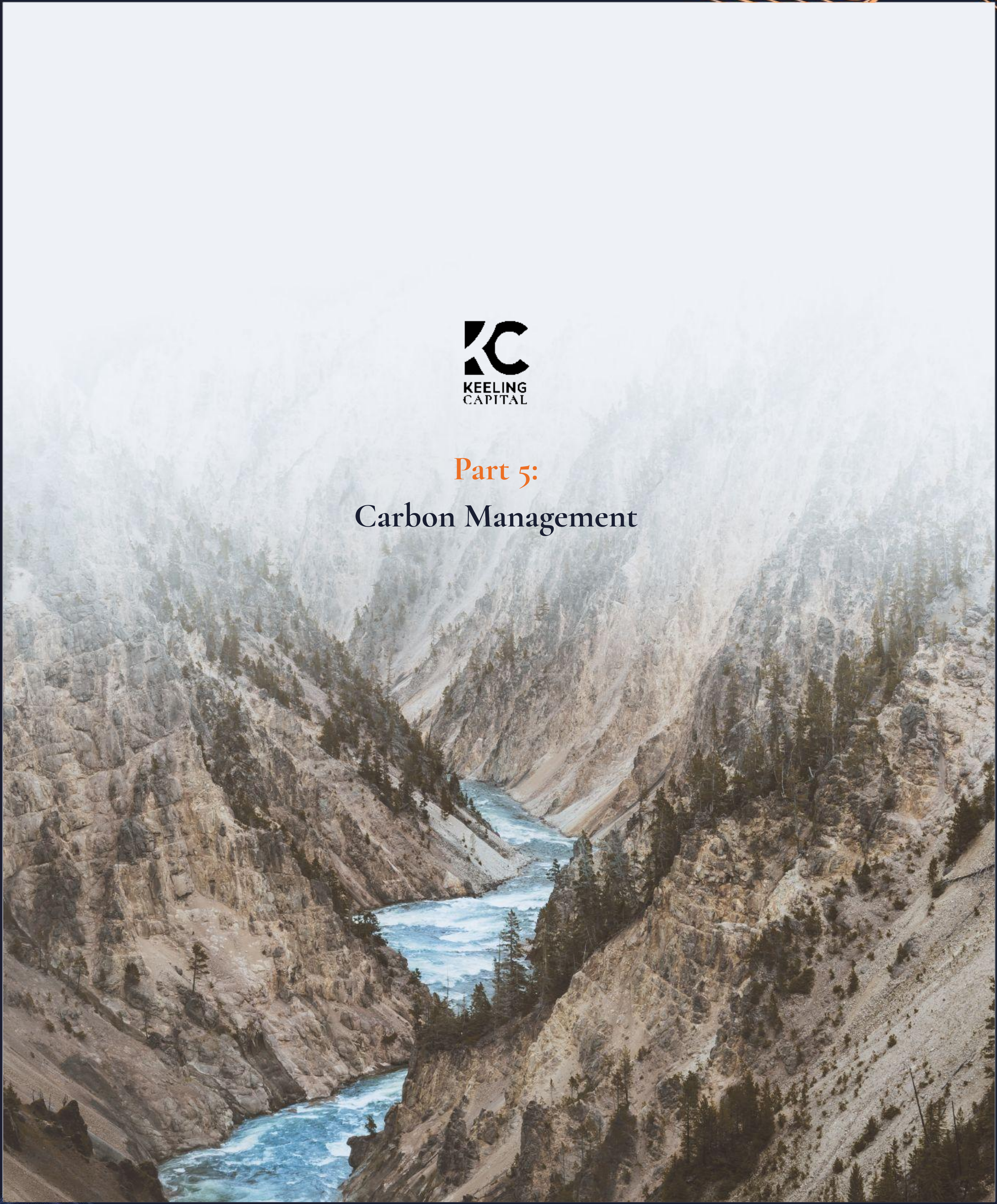
Long duration storage

There doesn’t seem to be a consensus on this one, but transforming excess electricity into molecules is a highly scalable way to store energy over long periods. That could involve storing hydrogen in salt caverns, or converting into methane which fits within existing energy infrastructure (e.g. Electrochaea) or another derivative like ammonia.

Other - miscellaneous

There are other niche applications for green molecules as energy carriers either already in use (e.g. forklifts) or under development (back-up generators, mining equipment), but they don’t represent large chunks of energy demand or emissions. One example I came across recently, which blew my mind - Japan is planning on using ammonia as a fuel to burn in modified thermal power plants, allowing them to extend the life of their existing coal fleet. This is a great example illustrating that the particularities of politics / geography / infrastructure will mean that there will be a far more heterogeneous landscape than energy economics or engineering by itself would suggest.

At the end of the day, scaling up the production of green molecules to the point of climate relevant is going to be incredibly challenging. It will require the vast build out of new infrastructure, both so we can achieve the energy abundance where it makes sense to push molecules up the energy ladder (see Part 3) and then distribute / store / use them. It also will require the orchestration of large and embedded systems. The truth is that we are going to be using fossil fuels as chemical inputs and energy-carriers for a long time to come. This requires that we scale carbon management infrastructure across the energy system to reduce the flow of greenhouse gases (decarbonising hydrocarbon supply and point source carbon capture) and then the stock (carbon dioxide removal).



Part 5:

Carbon Management

Any serious framework for climate transition needs to make contact with the reality that fossil fuels are going to be with us for many decades to come and to plan accordingly. Enter carbon management. Generally speaking, carbon management encompasses carbon capture (trapping CO2 from concentrated streams either from combustion or chemical processes) or carbon dioxide removal ("CDR" - taking CO2 out of the ambient air), plus whatever happens once the CO2 is caught, either sequestering it underground ("go back to where you came from!") or utilising it as a feedstock to reduce aggregate fossil fuel demand. The utilisation piece overlaps with the discussion of green molecules, so we'll just touch on it lightly here. There is also another massive element of carbon management, which isn't talked about nearly enough. That is oil and gas scope 1 and 2 emissions. Whilst not traditionally thought of as part of the decarbonisation puzzle, they are too important to omit if we want to be at all comprehensive so we've included them here.

Carbon Management - not a "moral hazard"

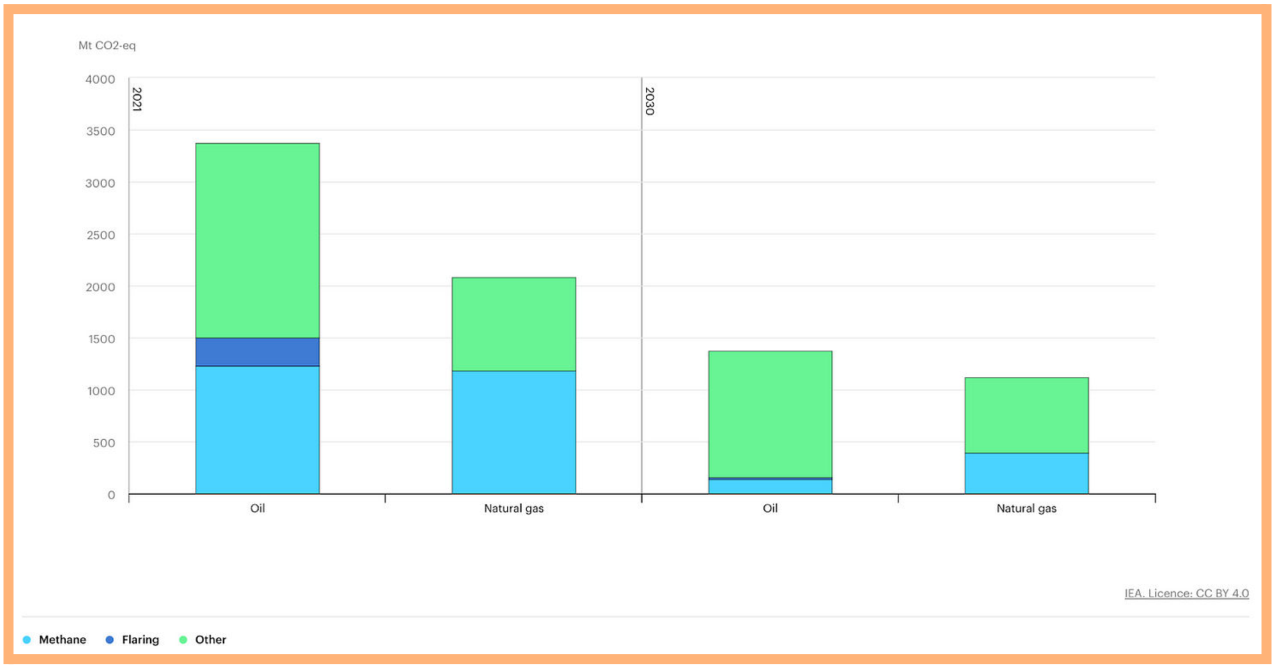
There is something that we should put to bed at the outset here. That is the notion that, by developing carbon capture or carbon removal technologies, we are somehow creating a moral hazard that will result in an unduly-extended role for fossil fuels. Whilst we should certainly be vigilant for specific instances where this might occur, on a macro level this is a non-issue, propagated by people who either don't know what they're talking about or are more concerned with signalling ideological purity than getting real about what the energy transition is going to take. Fossil fuels aren't going to be with us for decades because oil companies manage to convince us there is a CDR magic wand that will fix the climate. They will be with us for decades because we are not able or willing to build the infrastructure to replace them any faster than that. And that is not because stakeholders have rationalised the climate impact, but rather because it takes a long time to mobilise, permitting is hard, companies don't want to (realistically *can't* as shareholders would change management) mothball long-lived assets and take huge write downs, and, critically, all of these fossil-heavy assets produce the things we depend on as a society (steel, cement, plastic, transport, etc) and the only viable path is "construction before destruction" (to borrow from China's climate plan). So, no - the threat of moral hazard from CDR is totally immaterial to fossil fuel's longevity and that "debate" should be permanently sequestered.

Decarbonising hydrocarbon supply

Oil and gas Scope 1 and 2 emissions

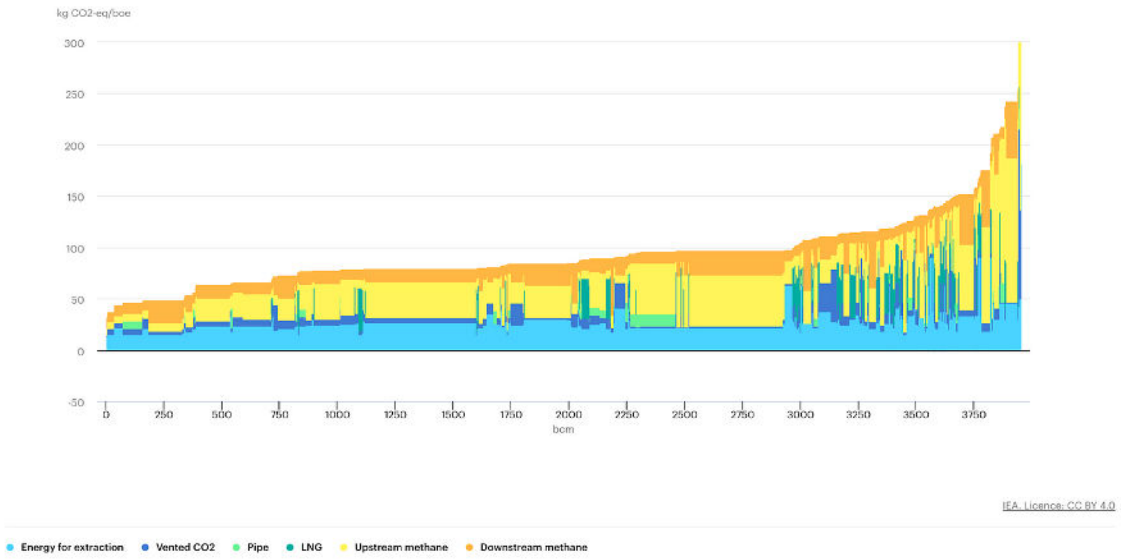
As a quick reminder, scope 1 refers to emissions through on-site activities in own operations, scope 2 refers to emissions related to energy used in own operations and supplied from outside (e.g. electricity from the grid). Scope 3, on the other hand, refers to emissions that occur either in the supply chain or through use of a company's product or service. The climate community tends to be outraged by suggestions that oil and gas companies might have Net Zero commitments that focus on their scope 1 and 2 emissions but exclude the emissions related to end combustion of their product (which dwarf emissions from own operations).

We have an alternative perspective. Two reasons: Firstly, oil and gas companies' scope 3 emissions turn up in everyone else's scope 1 and 2 emissions, either used directly or indirectly in their own operations. If all other sectors decarbonise their operations through efficiency, electrification and (for utilities, or commercial industrial customers producing their own power) decarbonisation of electricity, then emissions from the use of oil and gas (i.e. O&G companies' scope 3 emissions) also falls. Our view is that it is not the responsibility of the oil and gas industry to refuse to supply the hydrocarbons that our society, for the time being, requires. Quite the opposite in fact, as we're finding out in this global energy crunch. Secondly, scope 1 and 2 emissions from the oil and gas industry, whilst much smaller than scope 3, are very significant indeed, accounting **for about 5.5 GT of CO2 equivalent**, or a bit more than 10% of total GHG emissions globally. The IEA sees this needing to drop by more than 50% by 2030, largely through reduction in methane leaks. Note that that drop of 2-3GT of emissions by the end of the decade would totally dwarf any possible gains by CCS and CDR over the same period.



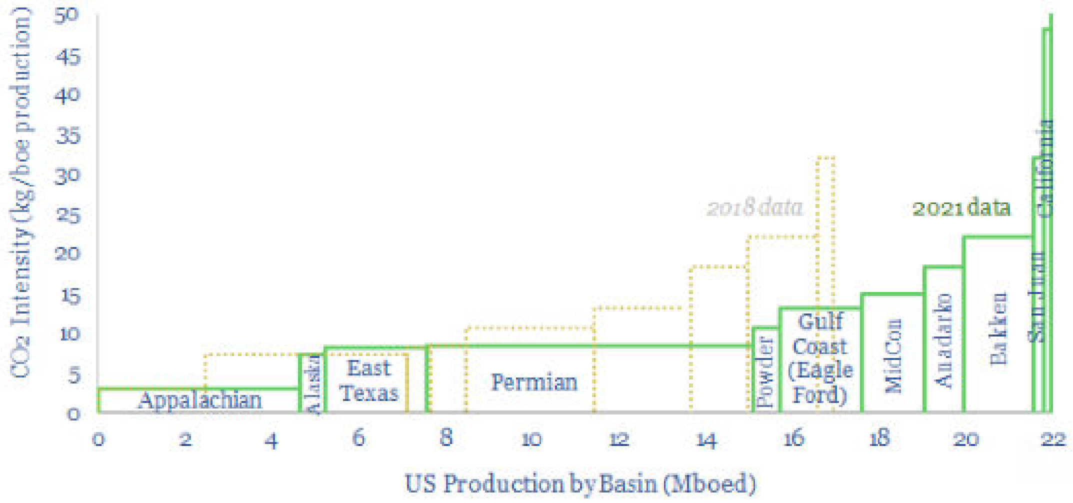
IEA

In the case of both oil and gas, the carbon intensity varies drastically between the highest- and lowest-intensity producers (4-5x difference between in both cases). So making climate-conscious choices about procurement is an important first step. Gas chart below, with the scale going from 50 to 300 kg CO2e / barrel of oil equivalent:



IEA

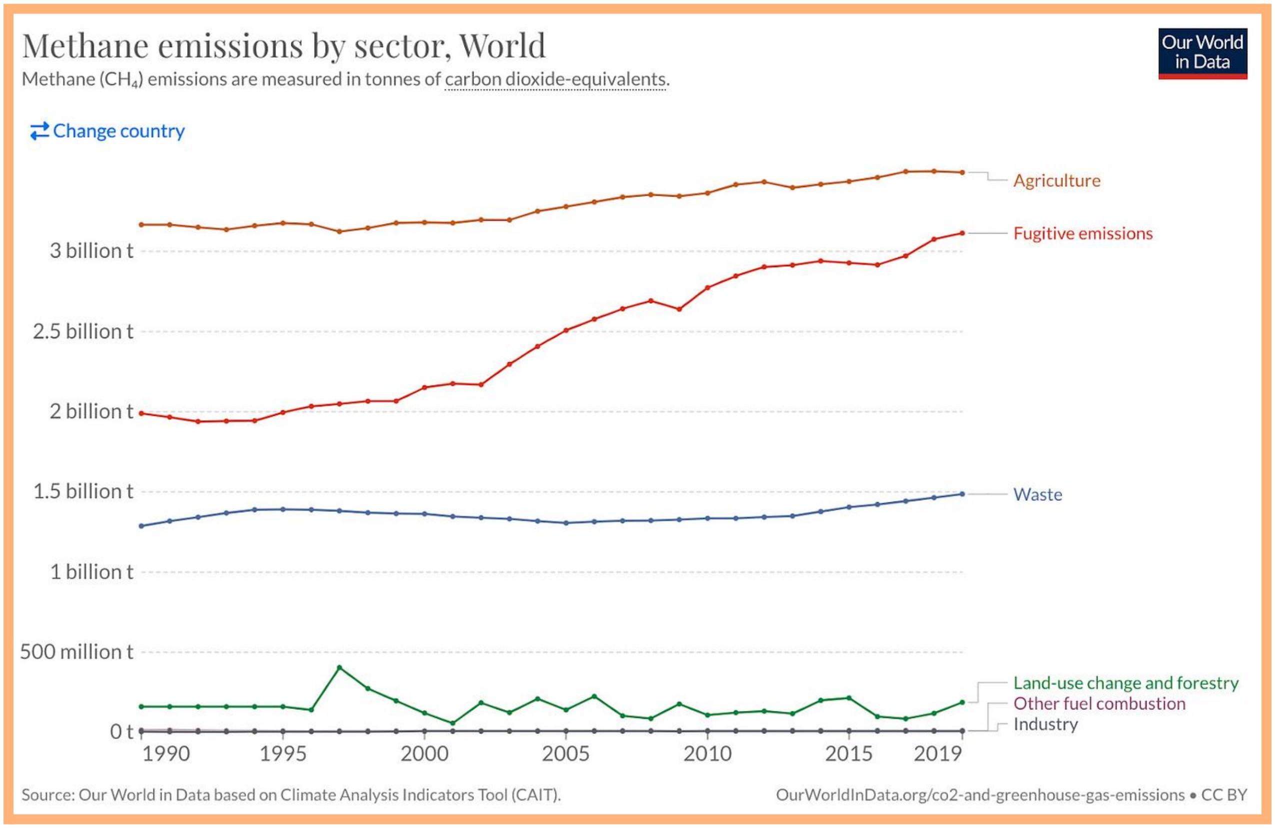
Here is another chart just on US oil production using EPA data (although self-disclosed, so taken with a grain of salt). Californian oil ~15x more carbon intensive than Appalachian:



EPA / Thunder Said Energy

Methane reduction in energy production

As seen in the above two charts, methane leaks represent a huge portion of emissions from hydrocarbon production and it has been growing in recent years, so that now it is almost equivalent to those from agriculture (see below). But there is hope! There have been big leaps in the technology and interest in this area recently, with BNEF estimating the oil and gas methane detection market to reach about $1bn / year by 2025 (e.g. check out Project Canary). The Inflation Reduction Act provides for fines starting at $900 / ton in 2024 and increasing to $1500 per ton from 2026 onwards. It also provided for $1.5bn of assistance for oil and gas companies to upgrade equipment. The key to this will be accountability, so we eagerly await the launch of MethaneSAT, a highly sensitive satellite to detect leaks, which will happen later this year.



Our World in Data

Carbon Capture, Utilisation & Storage (CCUS)

Carbon Capture, what is it good for

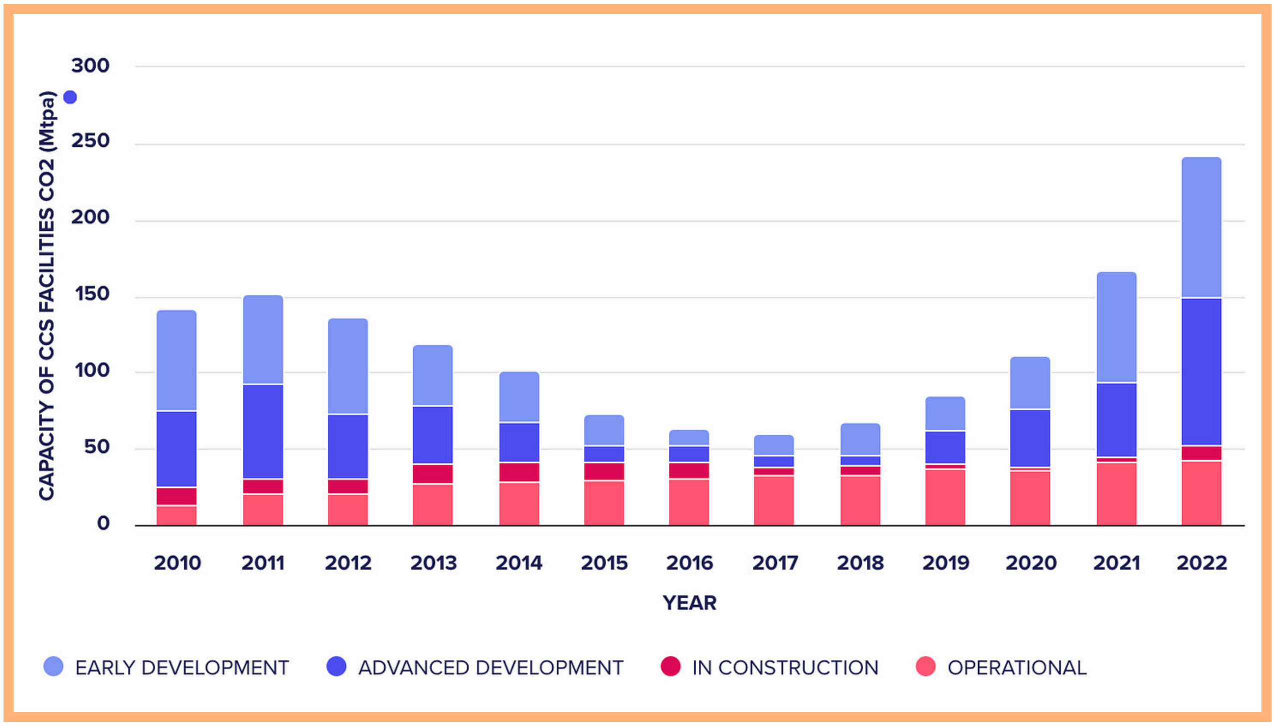
To reiterate, carbon capture, as opposed to "removal" is capturing CO2 from concentrated sources before it enters the atmosphere. It will be critical for decarbonising industries that are not easily electrified and particularly where there are higher concentrations of CO2, which are relatively easier and cheaper to capture than more dilute streams that require more energy to separate the CO2 from the other gases. That points to things like cement production, chemicals and fertiliser production, ethanol, and oil and gas refining.

How does it work?

Up till today carbon capture has been done using chemical absorption, where the flu gas is run through a chemical solvent (an amine) which selectively absorbs the CO2. It is then heated to drive off the CO2 and recover the original solvent. The energy requirement of this necessarily represents a cost and a drag on output (parasitic load) in the power sector. Other approaches that are being developed focus on producing a purer stream of CO2 that can be captured directly. This includes indirect heating for lime / cement production so that the pure CO2 emissions from the chemical process can be captured separately from any heating emissions (LEILAC) or through oxy-combustion where fuel is burned in pure oxygen rather than air, again producing a clean CO2 stream (NET Power, Clean Energy Systems - also touched on in Part 3), or indeed, by combining the two technologies like Origen Carbon Solutions, where they are using oxy-combustion as the heat source for lime production (which can, in turn be used for carbon removal through calcium looping, but that's getting ahead of ourselves). There are also alternatives to amine-based solvents in solid sorbents like metal organic frameworks developed by Mosaic Materials (acquired by Baker Hughes last year) and Svante.

What is the current status of CCS?

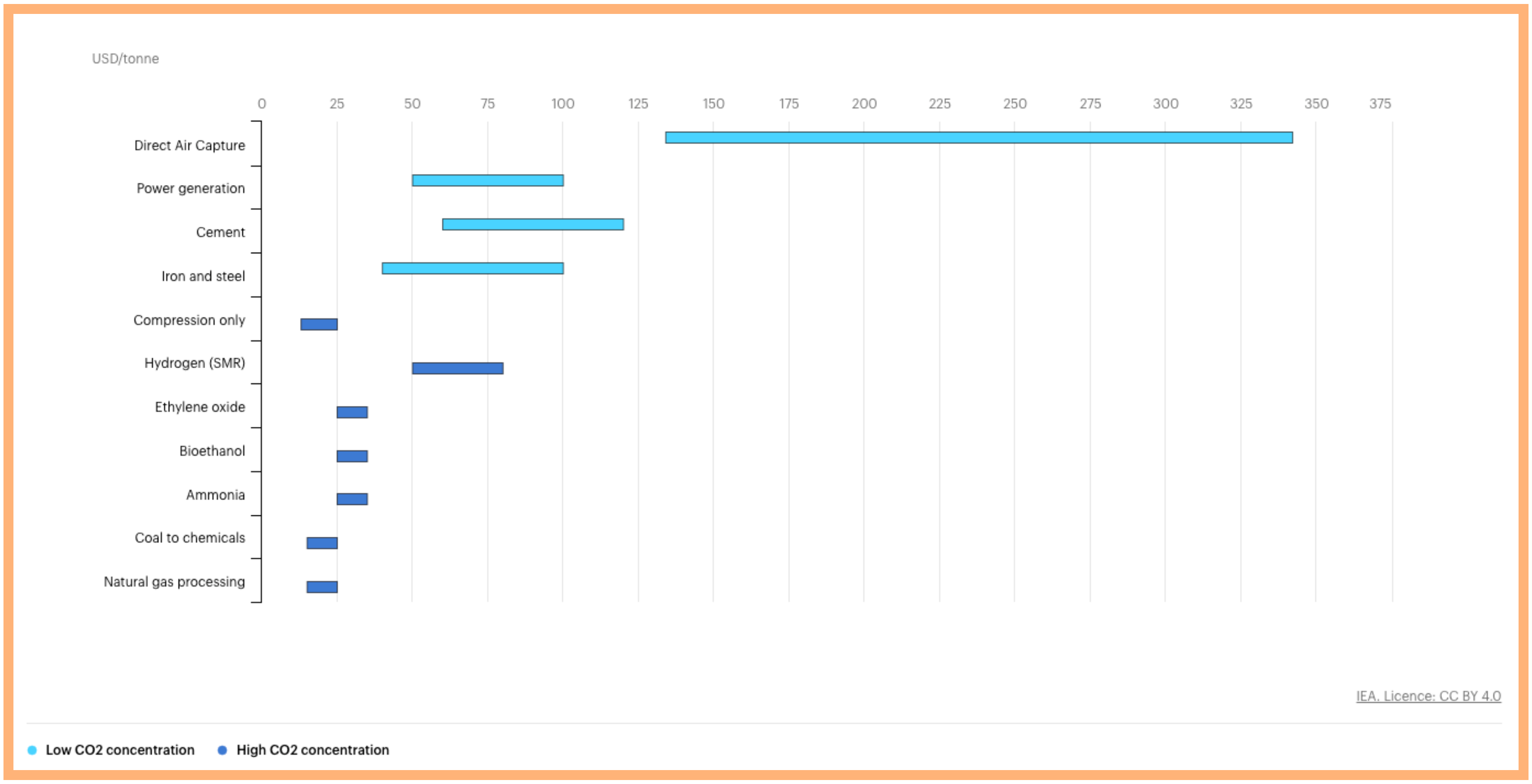
Today there are 30 operational facilities capturing 42 Mtpa (million tonnes per annum) of CO2. Of that, three quarters (30 Mtpa) is used for enhanced oil recovery ("EOR"), with almost all of the rest going to dedicated geological storage. Most of the emissions captured today are from natural gas processing. There are a further 196 projects either in construction or development, with identified capture capacity of about 200 Mtpa (a quarter of the pipeline projects haven't stated a capacity yet). The number of projects in the pipeline jumped by a staggering 44% between 2021 and 2022. The proportions for EOR vs dedicated geological storage flip dramatically in the pipeline projects - only 14 Mtpa are identified for EOR vs 145 Mtpa for dedicated geological sequestration (the balance is yet to be determined). The biggest sources of capture in the pipeline are natural gas processing (67Mtpa) and power generation (65 Mtpa) with the biggest single project being the East Coast Cluster at Teeside (27 Mtpa) capturing various industrial emissions. The full list of projects can be found here.



Global CCS Institute

How much does capture cost?

The cost of capture varies between sources, with high concentrations being cheaper to capture (as mentioned above). Estimates vary substantially between different sources, but most fall within $25-100 / tonne depending on the source, with natural gas processing potentially as low as $15 / tonne (which seems extremely low). Below are estimated ranges from the IEA (note Direct Air Capture at the top $125-350 / tonne is CDR, discussed more below).

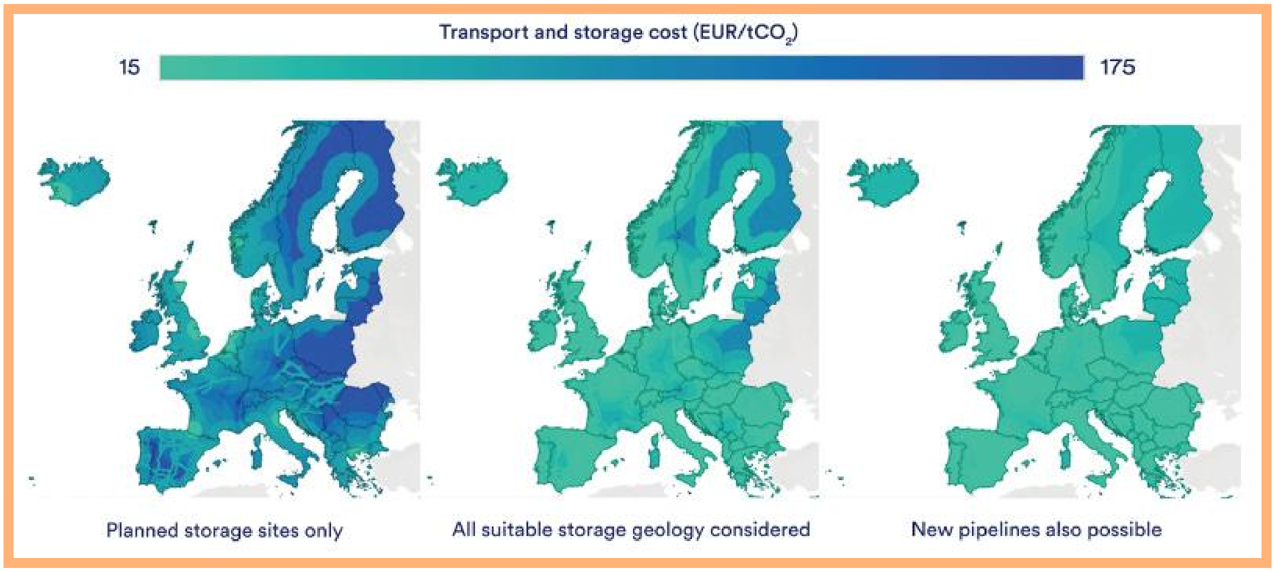


IEA. Licence: CC BY 4.0

IEA

Transport and storage

The total cost of CCS includes not only the capture portion, but also the costs of transport to a suitable storage site and then the sequestration. These costs can be the same again or more as the capture costs and can really be driven down by the buildout of shared infrastructure, particularly CO2 pipelines. This is vividly highlighted in work done by Clean Air Task Force on CCS in Europe. It shows that the costs of transport and sequestration is currently well north of EUR 100 / tonne in many places in Europe, but that the entire continent could fall to below EUR 60 / tonne with the development of more storage sites and pipelines. Work is already underway on a number of shared infrastructure projects including the East Coast Cluster in the UK mentioned above, the Porthos project in Rotterdam and two different pipeline projects for ethanol producers in the US Mid-West, Heartland Greenway and Summit Carbon. Note also that, according to modelling by Zero Labs at Princeton, CCS could be scaled to 200 Mtpa in the US by 2030, but transport and storage infrastructure is the rate-limiting factor. There is ample geological storage globally, but a limited amount of expertise to establish and operate the class VI wells for injection and storage of gases. Note that one of the major advantages of carbon removal (as opposed to capture) is that, since the source of CO2 is the atmosphere, projects can generally be co-located with storage facilities, or in some cases, the storage and capture happen in the same step.



Clean Air Task Force

Carbon Utilisation

One of the ways to make carbon capture (or removal) more economic is to find someone who will pay you for the CO2. Today the main use for CO2 as an input is the production of urea for fertiliser (where CO2 is mixed with ammonia), but that CO2 is largely sourced on-site as part of the ammonia production. The only scale use of CO2 as a commodity from CCS facilities today is EOR (more below). As covered in Green Molecules, there are opportunities to use CO2 as a feedstock to produce fuel or chemicals, but that tends to be highly energy intensive and expensive. In the most authoritative report on CO2 utilisation, researchers at Columbia identified a few use cases where CO2 utilisation is competitive today and those that are most likely to be in the near future. They conclude that currently profitable pathways represent at 1.6 Gtpa abatement opportunity, with the total CO2 utilisation opportunity at almost 7 Gtpa, but with a current cost penalty of 2.5-7.5x depending on the material.

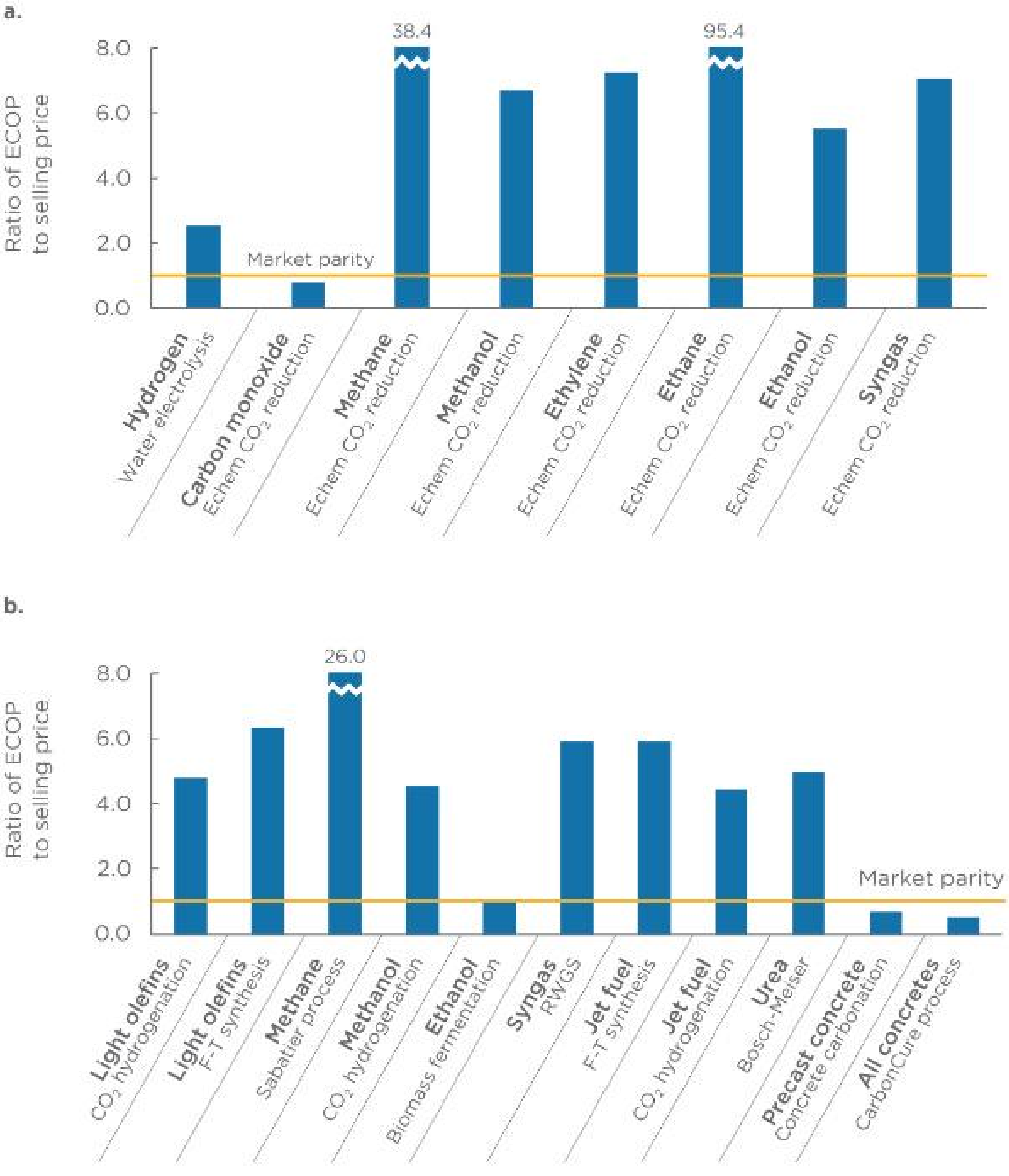


Figure 2: Ratio of ECOP to selling price for a) electrochemical and b) thermochemical CO_2 recycling pathways

Columbia University

Enhanced Oil Recovery

EOR generally refers to the process of squeezing extra oil out of partially depleted reservoirs, or tertiary production. One of the ways that can be done is by injecting CO2 down wells to force up remaining oil. On the surface of it, this might seem counter productive as it is producing yet more oil, but almost all of the CO2 that is injected down the well is kept there permanently. Where the CO2 is sourced from facilities that otherwise would have put it directly into the atmosphere, that creates a net emissions saving vs the base case. As it happens, most of the CO2 used for EOR today is sourced from underground reservoirs, so it comes from, and is put back into, the ground. There have been a number of lifecycle analyses done on EOR, the punchline seems to be that it reduces the carbon intensity of oil by about a third, even factoring in something for potentially higher overall oil use (see below). There is even the promise that, if the the CO2 is taken from CDR (i.e. out of the atmosphere) it could result in carbon-neutral oil. Vox have a good primer on CO2 EOR here.

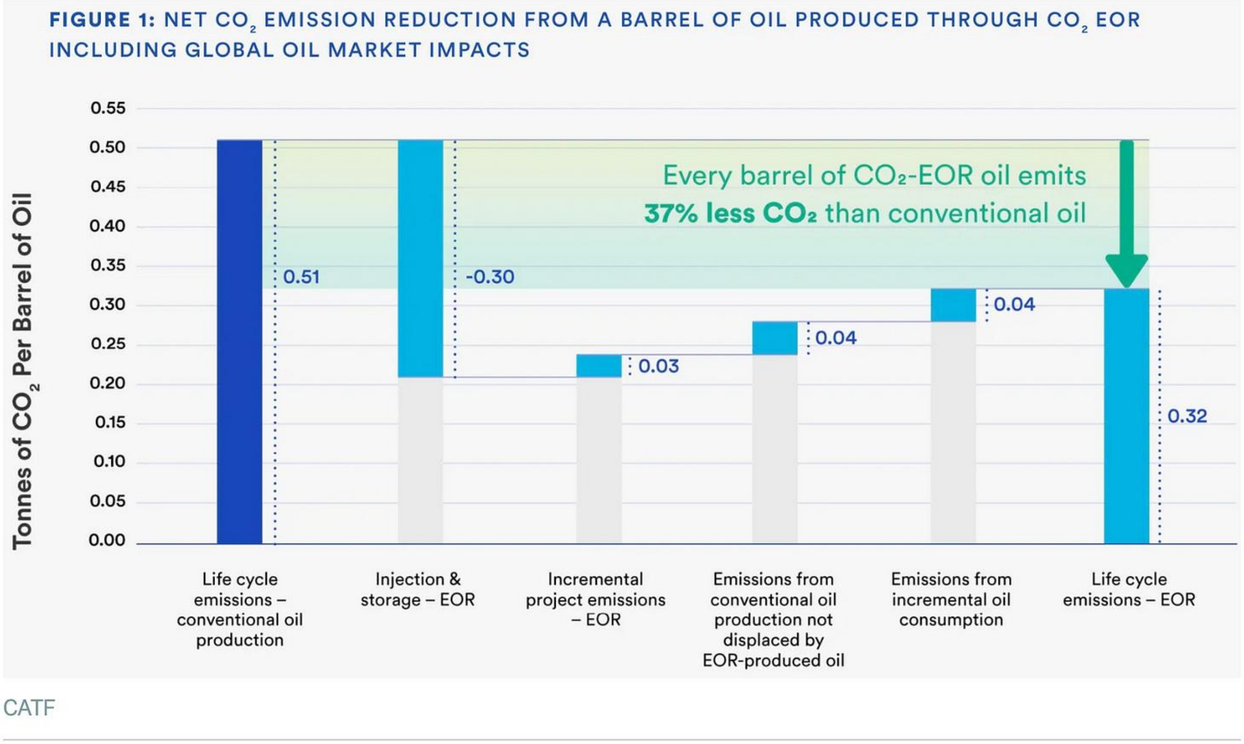


FIGURE 1: NET CO_2 EMISSION REDUCTION FROM A BARREL OF OIL PRODUCED THROUGH CO_2 EOR INCLUDING GLOBAL OIL MARKET IMPACTS

CATF

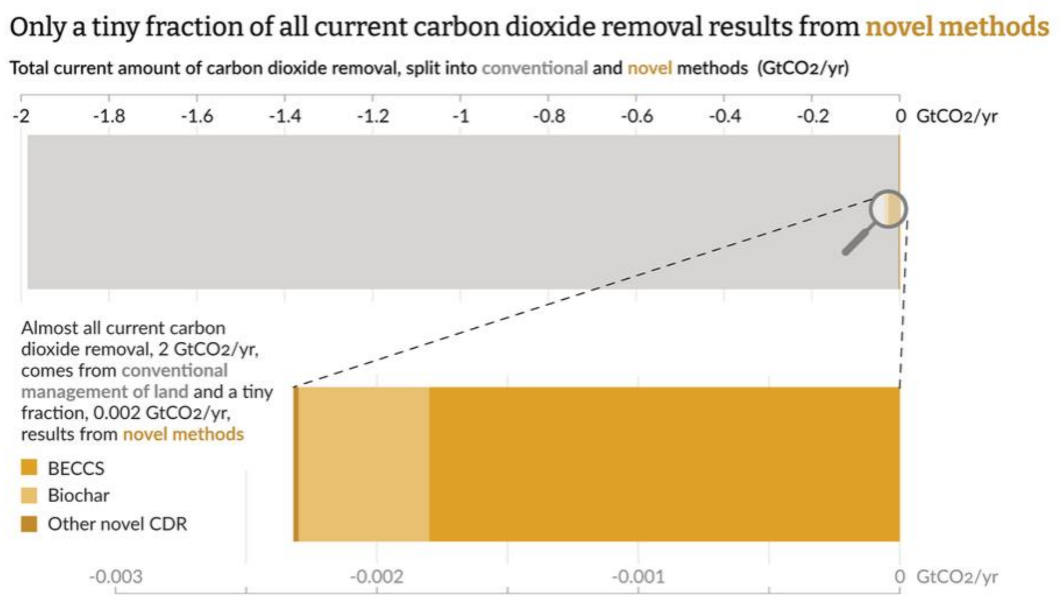
Clean Air Task Force

Carbon Dioxide Removal

There is no getting around it - we are going to need to remove carbon dioxide from the atmosphere, and lots of it. The IPCC has said - stating the obvious - that CDR is unavoidable. Estimates for exactly how much we need inevitably vary but we're certainly talking about gigatonnes / year by the second half of this century from a standing start. Everyone is pursuing *Net* Zero because *Absolute* Zero is a fantasy (although one that is nevertheless sometimes promoted by ill-informed zealots). Even with a monumental effort to decarbonise, there will be certain residual emissions from things like aviation, agriculture and industry that we aren't able to abate, or to do so would be significantly more expensive than drawing the carbon out of the atmosphere. Once that is done, we have something like a trillion tonnes of legacy carbon that is already destabilising the climate that we'll want to address over time. So, whatever the exact number is for CDR, we are going to require it on an absolutely massive scale and we need to get there from a standing start.

State of CDR today

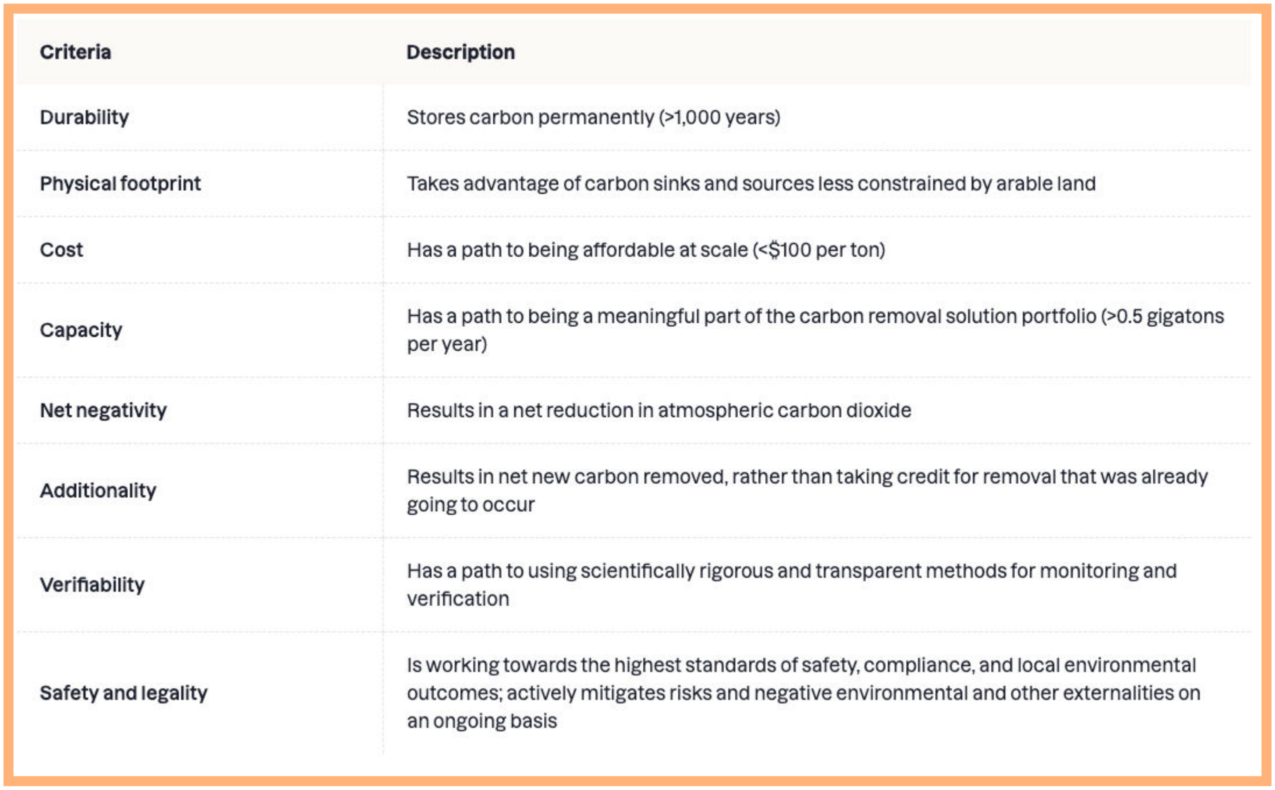
Earlier this year a number of researchers launched State of CDR. In their inaugural report they find that there is actually quite a bit of CDR that occurs through conventional land management (forest management, reforestation, etc). They estimate that about 2 Gtpa occurs through these pathways, which represents 99.9% of the total. Of the rest, most is BECCS (Bio-Energy with Carbon Capture and Sequestration) at 1.8 Mtp and biochar at 0.5 Mtpa with the balance of novel pathways discussed below coming in at just 20,000 tpa. Note that it is pretty unusual to count CDR from conventional land management, as most discussions focus on novel pathways.



www.stateofcdr.org

Key attributes for high-quality CDR

There are several criteria that need to be met for CDR solutions to qualify as high-quality. These are set out clearly by [Frontier Climate](), a collaborative for to serve as large-scale offtakers for emerging CDR projects started by Stripe with a number of other high-profile partners:



Criteria	Description
Durability	Stores carbon permanently (>1,000 years)
Physical footprint	Takes advantage of carbon sinks and sources less constrained by arable land
Cost	Has a path to being affordable at scale (<$100 per ton)
Capacity	Has a path to being a meaningful part of the carbon removal solution portfolio (>0.5 gigatons per year)
Net negativity	Results in a net reduction in atmospheric carbon dioxide
Additionality	Results in net new carbon removed, rather than taking credit for removal that was already going to occur
Verifiability	Has a path to using scientifically rigorous and transparent methods for monitoring and verification
Safety and legality	Is working towards the highest standards of safety, compliance, and local environmental outcomes; actively mitigates risks and negative environmental and other externalities on an ongoing basis

Frontier Climate

CDR Pathways

There are many pathways to achieve CDR. Many of them use or somehow lean on natural fast (between plants and the atmosphere) and slow (rocks / atmosphere / oceans) carbon cycles, whereas others, like DAC, are fully engineered. Every single one of these is a deep subject in itself, so this is just the briefest of introductions. You can get an intuitive sense of the relative costs and benefits of each with the Road to 10GT tool. The below list is non-exhaustive, but hits the main categories. A terrific resource in this space is the CDR Primer and there is a lot of content on the Open Air Collective website.

- **Nature-Based**: As mentioned above, effectively all CDR today comes from using natural systems and photosynthesis to lock up carbon. There is huge potential for this to be scaled with co-benefits such as increasing biodiversity. Most of Nature-based Solutions

(NbS) refer to forests, but they also could include peatlands (important in our homeland of Ireland), wetland restoration and Blue Carbon (mangroves, seagrasses).

- **BECCS**: An example of cutting nature's fast carbon cycle, BECCS gets plants to draw down carbon out of the atmosphere, burns them as a fuel, but then traps the CO2, putting it underground rather than back into the atmosphere. BECCS has traditionally been given the most emphasis, but there are serious challenges related to sustainability of feedstock and land-use requirements.

- **Biochar**: Biochar locks in the carbon from wood and agricultural waste streams by heating it in an oxygen-deprived environment. This can be added to soil, which has benefits for soil health and water retention. This is a low-cost, technologically-ready pathway with co-benefits, so should get more attention than it does. An adjacent approach is that being taken by Charm Industrial, who are working towards turning agricultural waste into bio-oil and putting it back underground.

- **Mineralisation / enhanced weathering**: This pathway taps into the natural process of silicate rocks absorbing CO2 and turning it into stone. These can be substances like olivine, which Project Vesta is spreading on the coast, or basalt, which can be crushed and spread on farmland, which is the approach being taken by Lithos Carbon and Undo. This approach can also be used with mining tailings and fly ash from coal plants, which gives the dual opportunity for CDR plus environmental remediation, like is being done by Travertine. We wrote more on mineralisation here.

- **Ocean-based**: Focussing on another part of the slow carbon cycle are approaches that seek to increase the ocean's capacity to take up atmospheric carbon. We wrote a separate post on this here. A couple of interesting recent developments were the announcement of Ebb Carbon's series A, led by Evok Innovations and Prelude and the launch of Captura, with the former head of Carbon Engineering at the helm. Both of those are using enhanced ocean alkalinity. Others are looking at sinking biomass into the deep ocean, so the carbon doesn't get recycled back to the atmosphere (Running Tide, Gigaton in Israel).

- **Soil carbon**: Encouraging higher carbon content in soil through either regenerative agriculture practices (no/low-till, cover-crops, rotation), managed grazing, or with biologics that help to fix soil carbon (e.g. Loam Bio), this is a promising area that we would love to see scaled up, again due to regular co-benefits with biodiversity that come with soil health. This pathway currently is facing difficulties around the measurement part (Enrich Ag and others are working on that) and the difficulty of converting farmers to new practices (others are chipping away at barriers here like Mad Capital).

- **Direct Air Capture (DAC)**: DAC refers to the chemical / mineral capture of CO2 from the atmosphere and is perhaps the gold standard of CDR in that it is clearly additional and measurable, has low land requirements and can be sited anywhere (i.e. next to dedicated storage facilities). The major drawback of DAC (and it is a big one) is that it is incredibly energy intensive. Arguably the two most advanced companies in the CDR space are DAC companies, Climeworks in Europe and Carbon Engineering in the US, who just broke ground on their 0.5Mtpa facility in Texas in partnership with Occidental Petroleum. Occidental is betting big on DAC, with their CEO, Vicky Hollub, suggesting that their carbon removal businesses could soon be as big as their petrochem business. Their development platform, 1PointFive, is way out ahead in terms of their deployment plans over the next decade. A couple of others to watch are Avnos, which produces water as part of their process, and Heirloom, which uses the calcium looping process, similar to Origen.

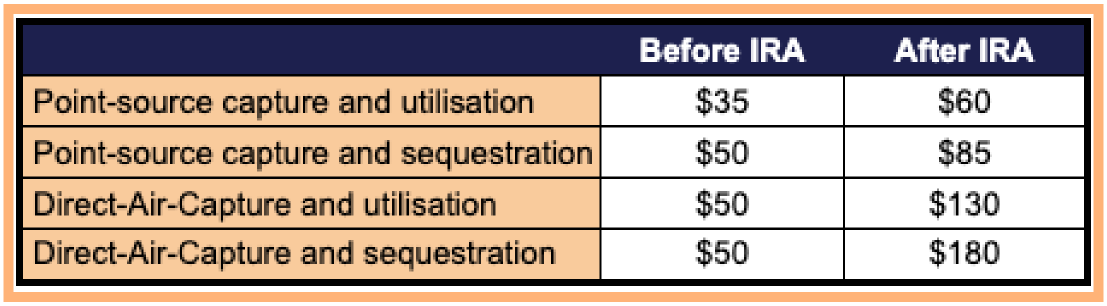
Carbon offsets

This is a thorny topic that is too big to get into properly here, but ultimately is an important part of the solution set. Carbon offsets come in many different varieties, but generally involve paying for some carbon-beneficial deviation from a baseline scenario, to provide some additionality. Traditionally there has been a lot of renewable energy projects, more efficient cookstoves that burn less wood, as well as paying to keep forests standing that might otherwise have been cut down (REDD+). Offsets got a very public kicking last year with the release of a report from the Guardian saying that 90% of rainforest offsets certified by the main standard aren't worth the paper they aren't written on, largely because the baseline risk of deforestation was overstated. This integrity gap is one of the biggest challenges for this sector, where there is abundant demand, if only buyers could have confidence in the projects. The bit of the value chain that deals with this is known as monitoring, reporting and verification, or "MRV". MRV is also critical to carbon removal, but it is less of an issue as it is generally being integrated as those solutions are developed and is often easier in any case. A couple of examples of companies doing carbon credit ratings are Sylvera and BeZero, but there has been an explosion of activity in the space (arguably disproportional to the current size of the market, so we'd expect to see a lot of attrition).

Major policy supports for carbon capture / removal

US - Section45Q

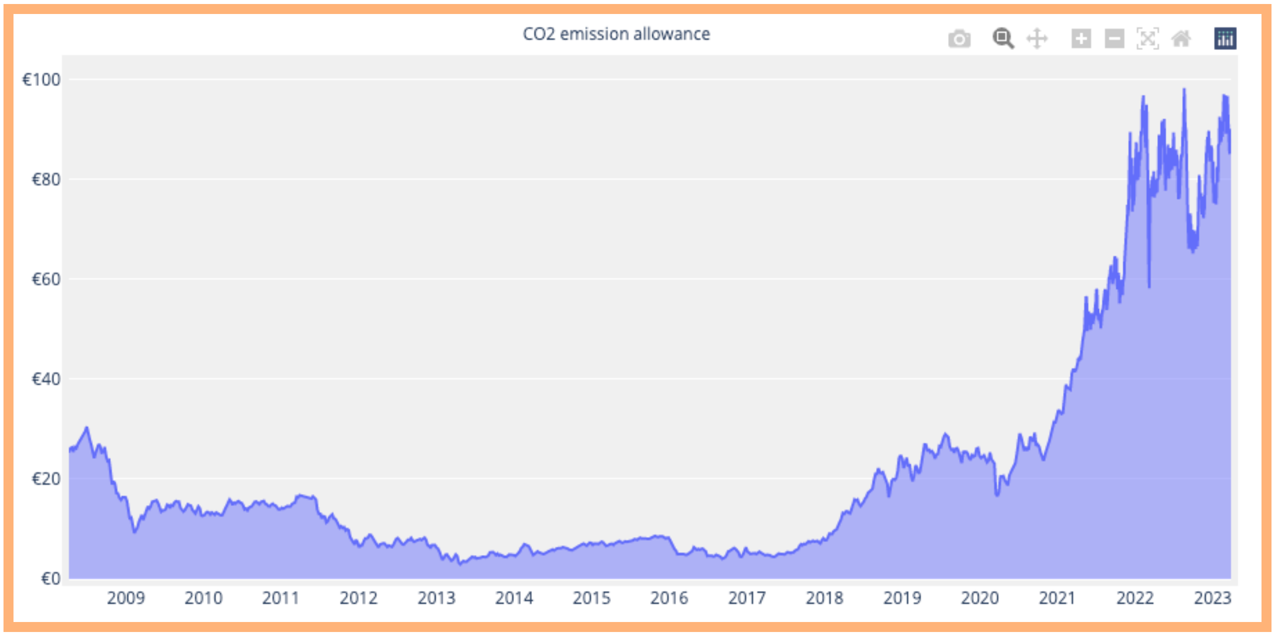
The Section 45Q tax credits for carbon management provide a different level of credit for different scenarios and were given a huge upgrade under the Inflation Reduction Act. The IRA also changed the threshold for projects to make much smaller projects eligible and pushed out the required start of construction date to the start of 2033.



	Before IRA	After IRA
Point-source capture and utilisation	$35	$60
Point-source capture and sequestration	$50	$85
Direct-Air-Capture and utilisation	$50	$130
Direct-Air-Capture and sequestration	$50	$180

EU - Emissions Trading System (ETS)

The ETS is Europe's cap and trade system, whereby the allowable amount of credits (EU Allowances or "EUAs") reduces over time and those polluters who exceed their threshold need to buy credits from those who managed to reduce emissions below their allowance. The scheme currently covers the energy sector (power and heat production) plus most heavy industry and intra-European aviation. The cost of EUAs has surged over the last couple of years as reforms have been implemented, putting a lot more CCS projects in- or near-in-the-money.



And with that, we conclude our speed skate over the surface of the Energy Transition. As you can see, there is a lot to do, which also means there is no shortage of opportunities. This transition is going to be multi-decadal. We have no time to waste, so we need to feel the urgency, but also need to settle in for a long journey. Our hope is that this document can serve as a jumping off point for readers and has helped to add some clarity and framework to an often bamboozling space. If readers have any questions or comments, we'd love to hear from you. We're always trying to get to better answers and to better outcomes. Onwards!