CHAPTER 1

Introduction – Carbon Capture and Storage

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1.1 Introduction

Humanity is profoundly good at exploiting the Earth's abundant supply of fossil fuels, and we have built our global economy on this basis. This in and of itself is not a bad thing. The challenge is that our exploitation of these natural resources has been carried out in an unsustainable way for well over a century. We are now firmly ensconced in the Anthropocene, and the effects are becoming increasingly apparent.[†]

In 1965, global population, gross domestic product (GDP), and CO_2 emissions were 3.34 billion, \$1.97 trillion, and 11.29 Gt_{CO_2}, respectively. For the UK, those figures were approximately 54.24 million, \$100 billion, and 687.8 Mt_{CO_2}. By 2017, the global figures had increased to 7.55 billion, \$80.93 trillion, and 33.44 Gt_{CO_2}. For the UK in the same year, those figures were approximately 66.73 million, \$2.63 trillion, and 398.2 Mt_{CO2}.[1–3]

In 1965, fossil fuels provided 94% of the world's energy, with modern renewable energy, *i.e.* wind and solar power, providing approximately 0%. By

[†]At the time of writing, the temperature in London is above 30 °C, with temperatures in France last week having exceeded 45 °C (on June 28, 2019).

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2017, the share of fossil energy had decreased to 85%, but modern renewables had only increased to 3% of the total energy consumption. The balance was supplied by nuclear power (4%) and hydro power (7%). These data, illustrated in Figure 1.1, are offered not as condemnation nor endorsement, rather simply as facts.

At the time of writing,[‡] and as illustrated in Figure 1.2, estimates are that anthropogenic CO_2 emissions in 2018 significantly exceed those in previous years. This is despite the conclusion of the 2015 Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCC), wherein it was agreed to keep ''global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius''.[4]

Thus, the evident inertia of the global energy system, combined with recent legally binding legislation requiring the transition to a net zero emissions economy by 2050[§] require that we find a pragmatic solution. This solution must necessarily be socially equitable, technically feasible, and financially viable,[¶] if it is ever to become more than an academic thought experiment.

It is this pragmatism that brings us to the concepts of carbon capture and storage (CCS) and greenhouse gas removal (GGR). The term ''CCS'' refers to a

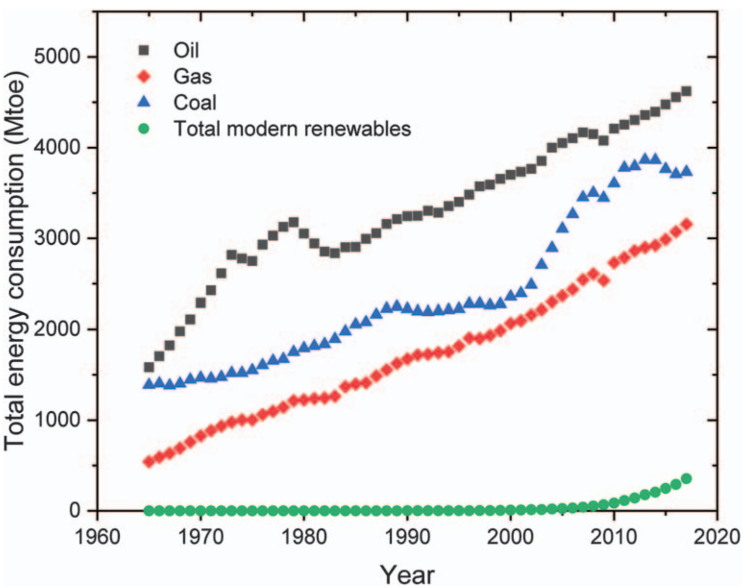

Figure 1.1 Global primary energy consumption since 1965.
Data from the BP Statistical Review of World Energy, June 2018.[1]

[‡]June 29, 2019.
[§]Thus far, the UK, France, Norway, Sweden and Finland have made this commitment.
[¶]In this context, it is worth noting that the CO_2 and energy intensity of GDP in 2017 was less than 10% of what it was in 1965. Similarly, GDP per capita in 2017 was 1820% of what it was in 1965.

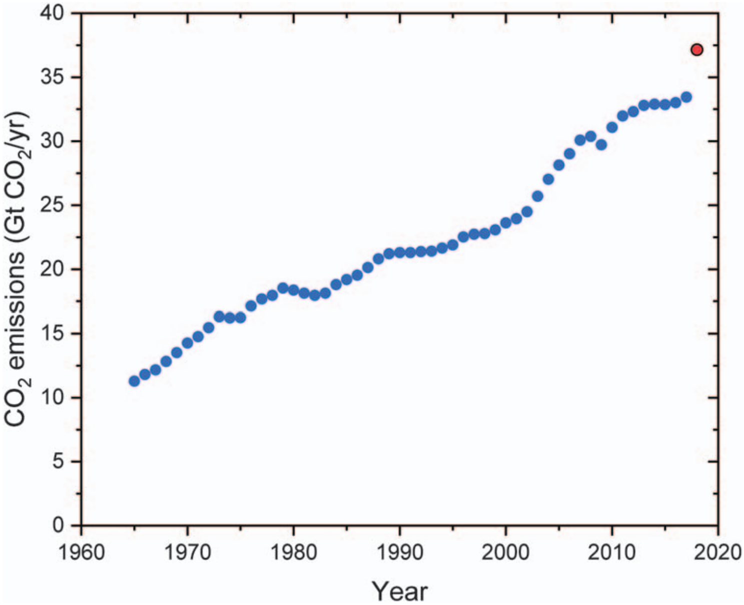

Figure 1.2 Total anthropogenic CO_2 emissions.
Data from the BP Statistical Review of World Energy, June 2018.[1] The red data point shows the provisional data point for 2018.

suite of technologies that can enable the continued exploitation of fossil energy resources, but with the additionality of capturing the carbon released upon their combustion, and its subsequent resequestration in the lithosphere. Put another way, CCS is an example of the circular economy concept – the carbon has been stored in the lithosphere for millions of years. CCS involves simply putting it back, as opposed to dumping it into the atmosphere as has been common practice since the industrial revolution. GGR also refers to a suite of options,‖ such as bioenergy with CCS (BECCS), direct air capture (DAC) and afforestation, for the removal of greenhouse gases, primarily CO_2, from the atmosphere.

An important point about both CCS and GGR (*e.g.*, BECCS or DAC) is that they primarily rely upon technical elements that are individually mature and well-understood. The concept of removing CO_2 from a gas stream was developed in the 1930s.[8] There are currently more than 7000 km of CO_2 pipelines in the US alone,[9] and whilst CO_2 injection for enhanced oil recovery has been commercial practice in the United States since 1972,** CO_2 injection into saline aquifer formations in the North Sea has been ongoing at the Mt scale since 1996 in the Sleipner field. Importantly, geologically sequestered CO_2 can be considered to be secure (*e.g.* Miocic *et al.*[10] and Postma *et al.*[11]). Obviously, further research and innovation will

‖Discussed extensively in Minx *et al.*,[5] Fuss *et al.*[6] and Nemet *et al.*[7]
**Specifically in the Saroc Field, West Texas.

improve existing options, and develop new options, but there are no insurmountable technical problems that prohibit the immediate deployment of these technologies in the energy and industrial sectors.

Moreover, it is understood, *via* the Intergovernmental Panel on Climate Change (IPCC) that both CCS and GGR are indispensable to meeting the terms of the Paris Agreement. CCS was found to be uniquely important in meeting the original 2 °C target – the majority of scenarios could not be solved without it, and those that could found solutions that were, on average, 138% more costly.[††] Put another way, ensuring the availability of CCS is more important to meeting our climate targets than any of nuclear, renewable, or bio energy. GGR has become prominent for two primary reasons – offsetting hard to reach emissions, such as those from aviation or agriculture, in terms of conventional mitigation, and addressing what now appears to be the inevitable overshoot of the remaining budget[13,14] commensurate with the 1.5 °C target. In this context, it is vital to recognise that GGR is not, in any way, an alternative to mitigation. It is an addition. There are no credible scenarios that meet the Paris target that do not require the large scale removal of CO_2 from the atmosphere. In some scenarios, the amount of CO_2 being removed from the atmosphere in 2100 is in the order of 20 Gt_{CO_2} per year – approximately the amount being emitted in 1990. This is a very large number.

Given the broad agreement on their importance, and their technological maturity, it might be surprising that there are so few large scale projects currently operating. The UK, for example, clearly recognises the importance of CCS, with Her Majesty's Government (HMG) having made three attempts to deploy the technology in the power sector since the G8 Summit in 2005. They all – obviously – failed.

Whilst the reasons for failure are manifold and nuanced, one important aspect is market failure. Whereas with wind or solar power, the product is obvious – renewable energy. Many regions have specific targets for explicitly *renewable* energy,[‡‡] thus creating a market. Revenue stabilisation is thereafter provided *via* Contracts for Difference (CfDs), or equivalent instruments. The combination of market creation and revenue stabilisation clears the way for investment. The same is not true for "low carbon" – or even "zero carbon" – energy.

There is also the issue of cost; inaugurated in 2013, the London Array comprised 175 individual turbines and a capacity of 630 MW, and came at a cost of £1.8 billion. In other words, it is possible to have commercially operating wind power for some tens of millions of pounds – relative chicken feed. Note that the first commercial wind farm was an onshore 0.6 MW array of twenty 30 kW wind turbines deployed in New Hampshire in 1980.

[††]This was the average. Some solutions were as much as 250% more expensive when CCS was excluded.[12]

[‡‡]For example, the European Union's Renewable Energy Directive, which aimed at having 20% of the EU's energy supply come from renewable sources by 2020. The UK's target was 15%.

As CCS is intended to integrate with conventional power generation, it necessarily comes on a large scale. For example, the White Rose CCS project was going to generate 426 MW of electricity and store 2 Mt_{CO_2} per year in a saline aquifer. The economies of scale of power generation and CO_2 transport and storage infrastructure simply do not lend themselves to small scale operation. CCS necessarily comes with a large price tag – failure is costly.

The point around infrastructure is also important – deploying CCS means deploying the full chain; the capture, transport, and storage. Conventional wisdom says that the majority of the cost is associated with the initial capture step, which is true. However, the majority of the risk comes from the integration of the chain, and the liability associated with the long term storage of the CO_2, which affects project price. Thus, at the time of writing, understanding exactly how to price this risk and manage this liability in the context of different sectors is still emerging. A key part of managing this will be close engagement between the public and private sectors: both sectors co-created the problem of climate change,[§§] both sectors will necessarily have to work together to co-create the solution, recognising the value of CCS[15] to the least cost, and a resilient energy system that delivers upon our climate goals.

Similar problems will, no doubt, be faced with the deployment of GGR technology. In the case of BECCS, it is necessary to go further and recognise the value of both biorenewable energy, and also that of removing the CO_2 from the atmosphere. Arguably, given that CO_2 in the atmosphere is a common global problem, its removal is therefore a public good and is consequently deserving of public remuneration. Whilst BECCS will permanently remove CO_2 from the atmosphere, the same is not true of so-called ‘‘nature-based’’ solutions, such as afforestation. Certainly, whilst the forests are growing, there is necessary drawdown and storage of CO_2. However, the permanence of this storage is a function of forest management, and remains vulnerable to fire risks. Thus, whereas with geologically sequestered CO_2, the risk of leakage is small and reduces with time, that risk is perpetual in the case of forest carbon. How, then, will this risk be managed, and on what basis will afforestation, and equivalent approaches, be remunerated? Throughout the remainder of this book, these questions, and more, are discussed, and detailed descriptions of the individual technological elements provided.

1.2 Conclusion

Of the 7.55 billion people on the planet, over a billion do not have access to electricity.[16] Many more than this billion do not have reliable access. Further, more than 2.8 billion people – more than one in three people alive today – lack access to clean cooking fuels; a cause of chronic ill-health. The vast majority of these people live in sub-Saharan Africa and developing Asia. The 7th Sustainable Development Goal of the United Nations Development

[§§]The private sector provided fossil fuels, but only in response to public sector demand.

Programme is to "ensure access to affordable, reliable, sustainable and modern energy for all". By 2100, it is anticipated that the global population will exceed 11 billion.[17] Given the pre-eminence of fossil fuels in supplying the world's energy, it stretches credulity to believe that fossil fuels will not continue to play an important role, even if that role is diminished from today. Simultaneously, it is recognised that the continued emission of CO_2 into the atmosphere will lead to dangerous climate change. Deploying both CCS and GGR technologies, as part of a portfolio of measures, is integral to meeting both climate change and sustainable development goals.

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