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Carbon Capture and Renewables: Strategic Conflicts or Tactical Complementarities

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1 Introduction

Carbon capture and storage (CCS), the main focus of this chapter, is sometimes seen as a key technical fix allowing for the continued combustion of fossil fuels in power stations. This, however, is set in a context where coal use is being challenged around the world, while renewable energy use is accelerating ahead. Those who back the latter may often feel that any talk of finding ways to reduce the impact of continuing to use fossil fuel risks deflecting or slowing the growth of renewables and the more efficient use of energy.

It is certainly the case that fossil fuel interests want to stay in the game as long as possible and they will see ameliorative clean-up options as a way to extract as much value as possible from the major investments that they have made in the past. Some may also see emission clean-up technology as more viable than renewable energy technology, with the latter sometimes being depicted as being far-off and even utopian. We hear less of that view nowadays, with renewables supplying around 25% of global (and UK) electricity, but it is still the case that fossil fuels remain the dominant power suppliers globally, and they will be so for some while. In which case, if carbon emission reduction is seen as urgent, then clean-up options are also urgent, if only perhaps as an interim measure.

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This chapter looks at some of the key options for abating emissions from the combustion of fossil fuels, focussing on the various types of carbon capture, their potentials and problems and also looking at possible conflicts or complementarities with renewables, in the context of diminishing reliance on fossil fuel. Improving the efficiency with which the energy from fossil fuels is produced and used is also important, since that can reduce carbon emissions per kWh produced and/or used, but the main focus in what follows is carbon capture, which has been seen as a way to deal with the emissions *once produced*, with potentially wide-scale applications and implications (GCCSI, 2017).

Quite apart from the technical and economic issues explored below, the carbon capture approach has its limitations. Although 'air capture' (i.e. direct from the atmosphere) might play a role, carbon capture at the exhaust level is not practical for the carbon dioxide (CO_2) emissions from burning fossil fuels in cars, trucks, buses and aircraft. Moreover, carbon capture, wherever applied, does not deal with impacts from the use of fossil fuels other than CO_2 production, such as the social and ecological impacts and risks of coal mining, oil and gas extraction and the transport of these fuels. In addition, and crucially, there are the other environmental and health impacts of burning fossil fuels, with air quality being a key issue. Although some of the acid gas and particulate emissions from the use of fossil fuels in power plants and industry may be removed as part of, or in conjunction with, some carbon capture processes, that is incidental to carbon capture. Its main focus is CO_2, so as to allow for continued fossil fuel combustion with fewer climate impacts.

2 Carbon Capture Options for Power Plants and Industry

While some see the various clean-up/ameliorative options as potential rivals to renewables, deflecting support from them, some of these options may complement rather than undermine renewables, so that conflicts might be reduced somewhat. For example, while Carbon Capture and Storage might be seen as just a way to allow for the continued use of fossil fuel, its initial development for that purpose might also be seen as an interim step toward the adoption of 'negative carbon' Biomass with Carbon Capture and Storage (BECCS). It is also argued that fossil plants with CCS can play a role in balancing the variable output from renewables. So, it is claimed, renewables *need* fossil CCS for backup. As we shall see, it may also be the case that CCS and other carbon capture techniques may need renewables to provide carbon free energy to power them. So, there are possible synergies.

Leaving those arguments aside for now, there is the more general issue of whether CCS, or indeed BECCS, is needed, or viable on a large scale, with some seeing CCS as likely to be too expensive and risky. The technological basics are relatively straight forward. Carbon Capture and Storage involves the capture of the CO_2 gas produced from the combustion of fossil fuels in power plants or industrial plants, via chemical absorption and then release, with the CO_2 gas being pumped in compressed form along pipes for storage under pressure in empty undersea oil and natural gas wells or other geological strata. It is sometimes claimed that CCS can reduce emissions from the use of fossil fuel in power plants by up to 90%, although in practice its overall efficiency may be more like 60–70%, partly since the various CCS processes use energy and supplying this using fossil fuels adds more CO_2 emissions.

In the power plant context, the overall efficiency and cost of CCS will depend on whether it is a coal or gas fired plant (oil-fired power plants are now rare) and on whether a pre- or post-combustion capture approach is used. The latter approach is easier, and the necessary equipment can in theory be retrofitted to any suitable existing plants, but for coal plants, pre-combustion capture (involving an initial gasification stage) may be more efficient and can provide a source of hydrogen, although it is less developed and currently costlier. Enhanced Oxyfuel combustion (in an oxygen rich environment) offers another also less developed route, with the concentration of the CO_2 that is produced being higher and more easily captured (CCSA, 2018). Unabated coal plants produce more CO_2/kWh than gas plants, so inevitably they have been the initial focus for CCS, but as coal use diminishes, gas CCS may become more important.

Whichever route is followed, clearly CCS will push up the cost of energy supply since extensive extra systems have to be built, perhaps adding up to 50% to the overall capital cost of the plant. In the retrofit context, it involves building a new clean-up plant alongside the existing power plant. Overall plant energy conversion efficiency can fall by around 10%, and water use/kWh may increase by up to 4 times, compared to a plant without CCS (Tzimas, 2011). Transmission of the captured CO_2 also adds to the overall cost: pipework has to be built and energy has to be used for pumping and compression. Storage adds further costs and is at present the most uncertain of all the costs, since it depends on the location [CUT]—given that there are few full-scale CCS projects as yet, most of the costs are uncertain. Nevertheless, the International Energy Association (IEA) GHG project has claimed, perhaps rather optimistically, that "*the cost of avoiding CO_2 emissions is 40–60 US\$/tonne of CO_2 (depending on the type of plant and where the CO_2 is stored), which is comparable to other means of achieving large reductions in emissions*" (IEA, 2018).

Permanent storage of the captured CO_2 is obviously the aim, but some doubt whether it can be achieved reliably over very long periods, depending on the location and its geology. Oil and natural gas were trapped underground in strata safely for eons, until the artesian well cap was breached for extraction, so it is argued that refilling them with compressed CO_2 should not involve extra risks. However, the space available in such wells is relatively limited. While, in something of a symmetrical exchange, they might in theory be sufficient to take most of the CO_2 from oil and gas burning, we also have large amounts of CO_2 from coal burning to deal with, and the coal did not come from these sites. There are other geological options, with, in theory, more space available, such as open aquifers, but they may be less secure. Accidental rupture and rapid release of large volumes of gas could be very dangerous, particularly if the storage sites were on land rather than offshore. When cool, CO_2 is heavier than air, so it could produce a suffocating blanket of gas. That actually happened at a Lake in Cameroon in 1986, when a large cloud of trapped, naturally produced, CO_2 was released, killing over 1,700 people (Atlas Obscura, 2013).

However, all being well, in the CCS context, it is thought that some of the stored gas may, in time, bond with rocks and perhaps form new solid calcium carbonate deposits. Some experience with geological injection and storage has been gained from Enhanced Oil Recovery using injected gas, although very long-term storage would involve new challenges (DECC, 2015).

Despite the technical complexity and reliability issues, CCS has been seen as vital, with the IEA arguing that, globally, "*CCS could deliver 13% of the cumulative emissions reductions needed by 2050 to limit the global increase in temperature to 2°C (IEA 2DS)*" (ETI, 2017). There was also some urgency, with Oxford Prof. Myles Allen arguing that "*early investment in carbon dioxide disposal is crucial because most of the cheapest options, like underground storage, will take decades to develop and gain public acceptance*" (Allen, 2016: 684).

BECCS too has attracted interest (Gough and Vaughan, 2015). Burning biomass can be (roughly) carbon *neutral*, since the carbon had previously been absorbed from the air by plant growth, but if the CO_2 produced is then captured, the process can be overall carbon *negative*. The ETI has estimated that BECCS could supply around 10% of UK power along with substantial net carbon reduction, servicing around 10 GW of power generation and other industrial sources fitted with CCS (Gammer and Newton-Cross, 2016). However, views differ on the need for and viability of BECCS (Carbon Brief, 2016; Lowe, 2016). Clearly its progress depends on the development of bioenergy technology and the necessary sustainable biomass sources. Its wide scale use implies a very significant increase in biomass production and land use (Newton-Cross and Evans, 2015), although with major uncertainties about the scale needed and the ultimate global potential (Wiltshire and Davies-Barnard, 2015). Crucially, it also depends on the success of CCS. That has not so far been spectacular—See Box 2.1.

Box 2.1: Progress on carbon capture

Some coal CCS prototypes were tested in Germany and elsewhere, and two large coal CCS projects are running in North America, but further progress on CCS has been slow, with concerns about the cost leading the UK to halt its £1 billion CCS competition in 2015. It had taken a while for suitable schemes to come forward, with the White Rose project at the Drax site near Selby, Yorkshire, and a Shell project at Peterhead in Scotland eventually being selected as candidates. But with the funding gone, in 2015, both projects were abandoned. This outcome was seen by some as very unfortunate (ETI 2015; Oxburgh 2016). Explaining the decision, then Prime Minister David Cameron said, "*You spend £1 bn on carbon capture and storage, you get some carbon capture and storage capacity and it would cost you, at the current estimate, something like £170 per megawatt-hour. That compares with unabated gas costing £65, onshore wind perhaps as costing £70 and nuclear costing, say, £90* […] *Governing is about making decisions, and it seemed to me that the right decision was to say that we would not go ahead with the £1 bn, because that is £1 bn that we can spend on other capital investment projects, including energy projects such as making progress on energy storage or modular reactors*" (Cameron, 2016).

The UK cut back has been replicated elsewhere, with, subsequently, work on the flagship US Kemper coal CCS project being halted after massive cost overruns (to US$7.5 billion); it has been converted to a gas plant (Fehrenbacher, 2017). Norway, already a CCS pioneer with its enhanced oil recovery technology, has also cut its CCS funding (Cuff, 2017a). Some project work continues around the world, and the Global CCS Institute lists 17 CCS-type projects running worldwide (GCCSI, 2018). However, most are gas processing and chemical plants, not power plants. Although more CCS projects of various types are planned, at present, there are just two working coal CCS power projects, the US$1 billion Petra Nova project in the USA (EIA, 2017) and the US $1.5 billion Boundary Dam project in Canada (IEA, 2015). They both use the captured CO_2 for Enhanced Oil Recovery (so CO_2 will be produced again when the oil is burnt). Despite some interests in Australia and China, large coal CCS projects seem unlikely to prosper, with there being criticisms of the existing projects in terms of the high cost, high energy use (up to 25% of the plants output) and low final carbon capture rates (Homes à Court, 2017). In time, new CCS technology may of course reduce costs, for example for the capture phase (Papageorgiou, 2014; Ondrey, 2015; Novek et al., 2016), but, for the moment, the overall message seems to be that, with costs seen as high, it is 'game over' for fossil CCS as a major option for power plants (Simon, 2017).

The prospects for BECCS are therefore also unclear. It also has opponents. As with CCS, not all the carbon can be captured. Moreover, those concerned about the environmental impact of the increased use of biomass are inevitably unhappy with BECCS. They see it as having major land-use impacts and as undermining important carbon sinks (Biofuelwatch, 2015). In a report on biomass for Chatham House, Duncan Brack says: "*The reliance on BECCS of so many of the climate mitigation scenarios reviewed by the IPCC* [International Panel on Climate Change] *is of major concern, potentially distracting attention from other mitigation options and encouraging decision makers to lock themselves into high-carbon options in the short term on the assumption that the emissions thus generated can be compensated for in the long term*" (Brack, 2017: 12). A similar view was adopted by a recent critical study from the Netherlands Environmental Assessment Agency and the Copernicus Institute (van Vuuren et al., 2018), claiming that BECCS was not vital, and arguing for more of a focus on other mitigation options, with its lead author saying that that it was 'unfortunate' that work to date on meeting the Paris '1.5C' target has been so dominated by BECCS (Evans, 2018).

Nevertheless, there is still support for BECCS and for CCS. Indeed, the UK government's advisory Committee on Climate Change (CCC) insist that BECCS is vital to meet climate targets (CCC, 2018). A small BECCS pilot project is underway at the Drax plant in Yorkshire (Drax, 2018), although that has no storage as yet. Moreover, there are also plans for a larger prototype CCS fossil gas project in Scotland 'in the mid-2020s', with offshore storage (Keane, 2018).

Clearly, as indicated in Box 2.1, the cost of CCS has proved to be a key factor in its slow progress. So, for the moment the prospects for CCS, and therefore also BECCS, look limited, with other decarbonisation options being seen as possibly more attractive. Auke Lont, the CEO of Norwegian power grid operator Statnett, has said that, given the emergence of renewables at a cost "*below seven euro cent per kilowatt hour… there is no room for carbon capture and storage in the power sector. In the power sector, the game is over because other technologies have surpassed CCS*" (Simon, 2017).

While there is still some pressure for adding CCS to new gas plants, it seems unlikely that anyone would now build a new coal plant with CCS. These setbacks will not be welcomed by those who see CCS as the best way to secure a future for fossil fuel, or by those who believe CCS and/or BECCS are vital to cope with or reduce carbon emissions. For example, the UK Energy and Climate Change Select Committee has claimed that, without CCS, the UK "*will not remain on the least-cost path to our statutory decarbonisation*" (ECCSC, 2016: 3).

Most recent energy scenarios have included CCS as a key element, and some have included BECCS, although the emphasis has varied. For example, the IPCC have backed both CCS and BECCS strongly (IPCC, 2017), and while the IEA, in a joint report with the International Renewable Energy Association (IRENA) sees CCS as important for the power and industrial sectors, IRENA see CCS as being deployed exclusively in the industry sector, with renewables dominating the mix: they do not look at BECCS (IRENA, 2017).

Certainly, CCS can be used for carbon emissions from industrial processes, as well as from power plants. It may be that this will be the main focus, since, some argue, CCS may offer an easier way to decarbonise industrial activities than replacing their use of fossil fuel with renewables. That is debatable: it depends on the industrial process. In some (e.g. fertiliser and chemical production), CO_2 generation is inherent to the manufacturing process, and CCS might be attractive, although, if, rather than CCS, carbon capture and *utilisation* is adopted (i.e. CCU), then some industries may find it possible to develop valuable new products, including synthetic fuels. For example, the captured CO_2 could be processed chemically with hydrogen to make methane gas or liquid methanol. In general, CCU does look more economically attractive than CCS, given that it offers the potential for new valuable products, and it may be that, unlike CCS, it will prosper in some sectors. However, as is explored later, synfuel production using captured CO_2 requires a source of hydrogen (e.g. from electrolysis of water, or steam reformation of fossil gas), and overall CCU does still rely on complex capture and conversion technology. So, there may be efficiency and cost limitations to synfuel production (Dimitriou et al., 2015). Moreover, the combustion of synfuels will produce CO_2, so, unlike with CCS, there are no carbon gains with this CCU option, and the adoption of this approach for biomass plants, i.e. 'BECCU' (Biomass Carbon Capture and Utilisation), would lose the negative carbon benefits of BECCS.

3 Air Capture

While the debate continues over which is the best way to deal with emissions directly from power plants and industry, there are also other more general carbon capture options under development, based [of CUT] on capturing CO_2 from the air. Unlike conventional CCS, they have the advantage of also being able to deal indirectly with the CO_2 added to the atmosphere from other sources, such as cars and aircraft, where CCS is not possible.

In so-called Direct Air Capture, air is sucked through large filters in towers containing an absorbent such as liquid sodium hydroxide, which reacts with the CO_2 to give sodium carbonate. Solid *adsorbent* options also exist. The captured CO_2 is then released and stored or used as a source of carbon for chemical or synfuel production, with, in either case, the sorbent being recycled for reuse (Lackner, 2015). The CO_2 storage route offers a *carbon negative* option, in the sense that it pulls CO_2 directly out the atmosphere. However, unlike BECCS, it would not generate energy, indeed it would use energy. The synfuel approach (sometimes labelled 'Air to Fuel', or A2F), does offer an energy output, but since burning synfuels would generate CO_2, the overall process would no longer be carbon negative. Moreover, as with fossil CCU and BECCU, hydrogen, as well as more energy, would be required to make the synfuel.

There are other significant issues, whichever route is taken. At around 0.04%, the proportion of CO_2 in air is very much lower than in the exhausts of power plants or industrial flue pipes, so the air capture approach has a fundamental problem compared with conventional CCS or CCU. It needs to handle large volumes of air in large scale units and more energy is needed to achieve similar capture rates. Whereas fossil plant CCU can make use of amine absorbents for CO_2 capture, they are expensive, and to deal with the much larger volumes of gas that have to be processed to get at the small CO_2 component, for Air capture, lower cost but less efficient chemical extraction options have to be used, requiring more energy. Nevertheless, some see Air capture as viable. Indeed, Bill Gates has supported the development of one such system (Crew, 2015). It seems a long shot, although it may yet prosper, especially in its CCU/synfuel variant, as may some other developments in the atmospheric CCU/A2F field (ACS, 2015).

The main advantage air capture has over conventional power plant/industrial CCS/CCU, apart from being potentially carbon negative (if the CO_2 is stored), is that it can be done anywhere. It does not have to be at or near a power plant. It does take space, but it is argued that, since it is much more efficient at carbon capture than plant photosynthesis, it will take much less room/tonne of carbon than BECCS and would require perhaps 1,000 times less area/tonne carbon [, CUT] than growing trees to capture CO_2. Costs remain high, at around \$600/tonne C, but there are hopes of getting down to \$100 or less. However, that has to be compared to the \$60–90/tonne C claimed by some fossil plant CCS projects and the \$30/tonne evidently achieved by one Indian CCU project (Cuff, 2018).

Moreover, given that it does requires energy, it seems unlikely to be cheaper to extract CO_2 from air than to avoid its production by using renewable energy powered devices, such as wind turbines, directly for power. Although renewable energy sources can be used to power the air capture process, it is not clear if that is the best use for their output in carbon saving terms. Hopefully that will become clearer after current trials in Switzerland and Canada, with talk of using PV solar or other renewables for the energy input

(Peters, 2017; Vidal, 2018). There is also a unit in Iceland, working on a geothermal energy site (Cuff, 2017b).

Apart from the more obvious and low costs carbon negative route of planting trees, there are other sometimes exotic global geoengineering-based air capture ideas, though they may have large scale, unpredictable, possibly even irreversible environmental impacts, e.g. seeding the seas with ferric compounds to increase greenhouse gas retention (Keller et al., 2014). By contrast, although it takes space, planting more trees seems so much easier and less risky, although trees do die and rot and can catch fire, so releasing the CO_2 they have absorbed and stored back into the air. Nevertheless, reforestation is an attractive carbon sink option, and also offers other environmental benefits. More subtly, changes in farming practices including 'no till' soil management, can have major GHG absorption implications. So, may biochar production: it can improve soil quality and CO_2 retention. Perhaps we do not need artificial 'Air Capture' trees.

However, if significant amounts of carbon are to be captured biologically, the scale of operation required, as with BECCS, would have to be vast. A recent review of all the negative emission technologies (NETs) by the European Academies' Science Advisory Council (EASAC) concluded that they had 'limited realistic potential' to halt increases in the concentration of greenhouse gases in the air at the scale envisioned in the Intergovernmental Panel on Climate Change scenarios (EASAC, 2018).

It looked at reforestation, afforestation, improved soil management techniques, ocean fertilisation and BECCS, as well as enhanced geo-chemical absorption and direct air capture and carbon storage. Given the technical and land use limitations, it suggested that these NETs, even taken together, did not have the potential to deliver carbon removals at the 12 Gigaton Carbon p.a. scale and at the rate of deployment envisaged as needed by the IPCC to help reach the carbon reduction targets agreed in the Paris climate accord. The maximum potential of the biological options as identified in the literature by EASAC was around 10 GT p.a., with reforestation/afforestation possibly offering 3.3 GT p.a., BECCS 3.3 GT p.a., and better land use management 2–3 GT p.a., while ocean fertilisation offered under 1 GT p.a. However, all of these estimates were seen as very optimistic. For example, on trees, it noted that, sadly, it was hard enough just fighting deforestation.

Direct Air Capture came out at possibly slightly ahead at 3.3 + GT p.a. but overall, in its press release for the EASAC report mentioned above, EASAC (2018: 1) warned that "*scenarios and projections that suggest that NETs future contribution to CDR* [CO_2 removal] *that allow Paris targets to be* *met thus appear optimistic on the basis of current knowledge and should not form the basis of developing, analysing, and comparing scenarios of longer-term energy pathways for the EU… Relying on NETs to compensate for failures to adequately mitigate emissions may have serious implications for future generation*".

So, there are major limits. Certainly, unless carried out on a vast scale, air capture on its own, by whatever means, is unlikely to be sufficient to deal with the scale of our historic, current and projected carbon emissions, some of which have gone into, or will go into, the seas (Cao and Caldeira, 2010). Extracting CO_2 from the oceans might be an option, and some have suggested that fuel could be made from it (Morgan, 2013). The concentration of CO_2 in the oceans is higher than in the air, so it might be worth it. The extracted CO_2 would of course be replenished in the seawater by CO_2 absorbed from the air, but it has been suggested that schemes that consume/remove and sequester excess ocean CO_2 can effectively address both excess ocean and air CO_2, sidestepping the need for direct air CO_2 capture. That may be true, but the cycle will have to be continually repeated, whatever technology and CO_2 location is used, if CO_2 is still being added to the air from combustion.

That is fundamental problem with carbon capture. If more CO_2 is being added, there will be an endless need for energy-using technical fixes for carbon reduction, with potentially diminishing returns. Air capture or CO_2 extraction from the oceans also seem to offer few collateral benefits for renewables. There might possibly be a supporting role for renewables in providing the necessary energy, but it is not clear if that is the best use for them, and, more generally, there is a risk that support for carbon capture may detract from support for renewables and energy efficiency. In terms of the NETs the EASAC review looked at, including air capture, one of its authors commented "*negative emissions technologies are very interesting, but they are not an alternative to deep and rapid emissions reductions. These remain the safest and most reliable option that we have*" (Shepherd, 2018). The implication being that we should focus on the latter, and not be sidelined or deflected.

4 The Hydrogen Option

While air capture has limits, and direct power plant and industrial carbon capture may have problems, there is a hybrid CCS/CCU approach to enabling the continued use of fossil fuel that may hold some promise. That is the idea of converting fossil gas into hydrogen by steam reformation, with CCS added to reduce emissions. Earlier above, mention was made of the use of hydrogen to convert CO_2 captured from power plants or industry into synfuels such as methane. That was also an option for air and ocean captured CO_2. However, in this new CCU/CCS variant, fossil methane is the *starting* point. It is converted to hydrogen which is then used as a fuel, the extracted CO_2 being stored, making the overall process (apart from the energy needed to run it) near carbon neutral, since the hydrogen when burnt does not generate CO_2. This approach might have potential for complementarity with renewables, as the technology develops, by opening the way up the use of fully 'green' renewable hydrogen as a fuel, with no fossil gas or CCS then being needed.

Certainly, once produced, hydrogen offers a clean and flexible new energy vector. When burnt in air it just produces water (and some trace NOx) and it can be used as a replacement for fossil gas in many contexts, including home heating. Mixtures of hydrogen and fossil gas are already in use in the USA and Germany and elsewhere, but it is also possible to go for 100% hydrogen if modern plastic pipe work is available. In theory, depending on how it is sourced, with hydrogen as a fuel, there should be significant reductions in emission compared with the continued direct use of fossil gas e.g. for domestic heating and cooking. By contrast with the current UK plan for decarbonisation of home heating by installing electric heat pumps, it would avoid the need to replace domestic gas-using appliances. The existing cookers and gas fired boilers would only need small adjustments to run on hydrogen. Moreover, rather than stressing the power grid further, the existing gas mains can continue to be used, with only minor upgrades. In the UK, the gas main carries around 4 times more energy than the power grid, so a full switch over to electric heating would be very difficult to achieve. There are already plans for the injection of hydrogen, or syngases derived from it, into to the UK gas grid (Ambrose, 2018) and also a 100% hydrogen gas main switch-over proposal, the H21 scheme in the city of Leeds, as well as the Cadent project in the Liverpool/Manchester area—see Box 2.2. The estimated capital cost are relatively high e.g. around £2bn for H21, with £139 million p.a. operating costs, and £600m for Cadent, with operating costs near £60m p.a. But projects like this may offer a new way forward, given the attractions of hydrogen as a fuel for heating.

Box 2.2: Hydrogen options

The Leeds H21 project involves a switch over to 100% hydrogen, made by steam reformation of fossil gas, injected in the Leeds gas mains, with CCS taking care of the CO_2 produced in the conversion process. It is seen as pioneering showcase effort that, if successful, could be replicated in other cities (H21, 2016). In parallel, a somewhat smaller Cadent Liverpool-Manchester Hydrogen Cluster project, still at concept stage, aims initially to supply a high hydrogen mix just to selected industrial gas customers, although possibly also, in a blended mix with fossil gas, to domestic consumers. The CO_2 produced from steam reformation process would be captured and then stored in depleted gas wells in Liverpool Bay (Cadent, 2017).

As noted above, in term of gas use, the change-over to 100% hydrogen would require some system adjustment. Hydrogen at high concentrations can cause embrittlement of metal pipework, with the potential for leaks or ruptures. Fortunately, most of the UKs old iron gas mains pipework has been upgrade with plastic pipes, but not all. That programme would have be extended to every house. The replacement of burners in appliances is also not a trivial operation. In the UK, before the advent of North Sea Gas, appliances used to run on Town Gas made from coal, which included a high proportion of hydrogen along with methane and carbon monoxide. For the change-over to North Sea gas (which is mostly methane), starting the late 1960s, the burner jets of all appliances had to be replaced, in a national refit programme. It took about 10 years to complete the full change over, which cost around £100m. In effect, that process would have to be reversed to allow appliances to run on 100% hydrogen.

There are also some more fundamental efficiency issues. There will be losses associated with the multi-stage gas conversion and CCS process, including some energy use for the reformation process so that, for the H21 system, is was estimated that 47% more gas will be needed to get the same heat output as would be obtained if the gas was used directly for heating. So, the net emissions saved, even with CCS, would only be 59% compared with the conventional gas route (Lowes, 2016).

There are also non-fossil options for the systems like this. Some biogas, produced by Anaerobic Digestion (AD) of farm and other wastes, might also be used as a feedstock for hydrogen production via steam reformation, rather than just fossil gas (Sattar et al., 2014). If 100% green biogas was used, the process would be carbon negative with CCS, or carbon neutral without it. But if we have green biogas, then why go for conversion to hydrogen? Why not just inject AD-derived bio-methane into the gas mains? Or perhaps go for a blended mixture. That is what is being done elsewhere. Blending may be necessary since there is unlikely to be sufficient biogas available, even if also using food waste, to meet heat demand, although low-carbon syn-gases from industrial sources might be used (Abbess, 2015).

Alternatively, there is electrolysis route. Hydrogen gas can be produced directly by the electrolysis of water, using electricity from wind and PV solar plants. In addition to use for heating, as in the H21 concept, it can be used for balancing variable renewables. Hydrogen, made using surplus renewable electricity, generated when availability is high and/or power demand is low, would be stored, ready to be used to make electricity again, in a gas turbine or fuel cell, when wind and/or solar availability is low, and/or demand for it is high (Sky, 2014). This idea is under rapid development in Germany and elsewhere (Ogleby, 2018), with CCU variants also being developed. For example, in some cases, the hydrogen gas is converted to methane, using CO_2 captured from power plants, and then injected into the gas main for heating (Windgas, 2017). Hydrogen or methane can also be used a vehicle fuel. Clearly this overall 'Power to Gas' (P2G) concept can yield a range of useful fuel options (Hydrogenics, 2018).

However, the Power-to-Gas conversion process is at present relative inefficient (50–60% typically) making the resultant green hydrogen or methane expensive. According to French company Engie, which is looking to shift to green hydrogen production and distribution, steam reforming of hydrocarbons, which accounts for 95% of hydrogen produced today, costs about €2/kilo, compared to €6/kilo for electrolysis (De Clercq, 2017). But, as electrolysis technology improves, with the advent of high efficiency PEM (Proton-Exchange Membrane) cells like the one developed by UK company ITM Power, costs are falling. ITM Power claim that their PEM cell has an overall efficiency, with heat recovery, of 86% and it has been wining orders for its technology in Germany as well as the UK (ITM Power, 2018). They clearly see this as the way ahead (Cooley, 2017). The Power to Gas hydrogen option will be looked at as part of the H21 programme, although given its still relatively high cost, it is not seen as likely to be a major option for now, even though it would avoid having to use CCS. However, that may change as the costs of renewables and P2G fall and the cost of fossil gas rises (Richard, 2018). Certainly, recent studies have suggested that this approach merits attention (Institution of Mechanical Engineers (IMechE), IMechE, 2018; Butera et al., 2018).

Both of these projects are focused on hydrogen production via steam reformation, so that CCS is vital if this approach is to expand. However, whether, as one commentator suggested "*the prospect of a hydrogen-based energy system could prove a clinching argument for the development of CCS*", remains to be seen (Keay, 2018: 20).

As noted in Box 2.2, for the moment, most hydrogen is produced using steam reformation of fossil fuel, but, since it can also be produced using renewables, some see the focus on fossil-derived hydrogen, sometimes called 'brown hydrogen', as a diversion from a switch to genuinely 'green hydrogen' produced using renewables sources (with no need for CCS), including synthetic green gases from Power to Gas (P2G) conversion. Others however see it, and the development of industrial sources of hydrogen, as a possible step on the way to the adoption of renewable hydrogen, by establishing greener gas in the heating market, ready for later replacement by fully green biogas and P2G syngas, when and if that becomes available on a wide scale (Abbess, 2015). The point being that, at present, as noted in Box 2.2, hydrogen from steam reformation is much more economically viable than (renewable) power-to-gas conversion. While that may be true for now, it ignores the emission issues associated with using fossil gas and adding CCS would push up the cost. P2G avoids that. But, as noted in Box 2.2, for the moment that route is not being looked at seriously for the Leeds H21 project.

That highlights a key strategic problem that emerges in this and other ostensibly interim fossil fuel-use cases. If we continue to focus on the cheaper short-term ameliorative options, the longer-term renewable options will always remain longer-term: they have to be promoted before they can (hopefully) become competitive. That is what has been done to some extent with renewables so far, often in the face of objections from those seeking support for ameliorative measures for fossil fuel use, which usually look cheaper and easier in the short term. Renewables have nevertheless succeeded in moving out of niches into the mainstream, aided by subsidies which have helped them to become increasingly competitive. Carbon capture, in its various forms, has so far not been able the achieve that, and, given its problems, it may never do so. However, to the extent that some of the carbon capture technologies may have a useful interim role to play in emission reduction and possibly also synfuel production, a more coherent approach than just leaving them to sink or swim may be needed.

5 Optimal Carbon Reduction

In his ‘Systems Thinking for Geoengineering Policy’, Robert Chris, looking very broadly at geoengineering possibilities, argues that we should promote approaches to dealing with climate change that are “*robust against the widest range of plausible futures, rather than optimal only for the most likely*” (Chris, 2015). Certainly, options should not be foreclosed, and a strategic framework is arguably needed which identifies an acceptable role for carbon capture in its various forms, with full attention being given the likely impacts (Williamson, 2016), but attention also being given to the strategic carbon reduction issues and options. It is clear, even to those looking to near 100% renewable scenarios, backed by the wide adoption of energy efficiency measures, that fossil fuel use will continue for some while, particularly in the heating, industrial and transport sectors. While ideas are emerging for dealing with these sectors using renewable sources, they will take time to develop fully, so some fossil fuels may have to continue to take the strain for a while. In which case they need to be cleaned up.

In a context of diminishing reliance on fossil fuel, that should not be a problem in principle, even for the most devoted renewable energy enthusiasts, but the key issue will be the timeframe—how fast can renewables be expanded, how much can energy efficiency help slow and ideally reduce demand? What do we need to do to get emission down rapidly, so as keep temperature rises below danger levels? And, not incidentally, what role might nuclear power play in all this?

There are a range of scenarios addressing issues like this. For example, the IRENA scenario mentioned earlier (part of a joint report with the IEA), has renewables supplying 82% of global electricity by 2050, and 65% of global primary energy by then, with CCS only in limited industrial use (IRENA, 2017). More radically, there is no fossil, nuclear or CCS use in the scenario by Jacobson et al. at Stanford University, which looks to wind, water and solar power supplying 100% of *all energy* by 2050 globally (Jacobson et al., 2017). That may sound ambitious, but with several countries already obtaining over 50% of their electricity from renewables, hydro included, projections like this no longer look impossible, although their realisation in practice will depend on a range political and economic factors.

However, it remains to be seen if that will be enough political support to meet the ambitious carbon reduction goals agreed in 2016 in Paris (Victor et al., 2017). Certainly, a recent study led by the Potsdam Institute claimed that conventional mitigation measures would not be sufficient and what it labelled as Carbon Dioxide Removal technologies (CDR) were vital to meet the 1.5°C Paris climate target without overshoot (Kriegler et al., 2018). For the foreseeable future, fossil fuels are thus likely to play a key role, with, in some countries, that probably being unavoidable for some while. For example, 90% of South Africa's electricity comes from coal plants. It will take time to change that (Cook and Elliott, 2018). In which case, although change must be a high priority, we need to decide which interim ameliorative technologies to adopt in parallel.

As we have seen there are many options, depending on the context. Gas plant CCS may prove viable in some locations, but there will be diminishing returns from building major new long-lived coal CCS plants, and CCS is perhaps anyway more suited to the chemical and industrial sector, which we will need into the future. CCU, creating value from captured carbon by making synfuels from it, also has its attractions, even if burning them will produce CO_2.

Not all the options for carbon reduction from fossil fuel use involve CCS or CCU. In all sectors, fossil fuel use can be improved to reduce energy waste and in the industrial sector there are many opportunities to improve process efficiency and make better use of byproducts. In the power sector, Combined Heat and Power (CHP)/cogen, linked to district heating networks and heat stores, can be a relatively low carbon option. By using some of the otherwise wasted heat, CHP gets much better value from the fossil fuel input than non-CHP plant, with overall energy conversion efficiencies of up to 80%, and with biomass feedstock net carbon emissions could be almost zero. Moreover, while it may be hard (and uneconomic) to operate CCS and CCU systems flexibly, CHP plants, linked to heat stores, can be used flexibly to balance the variable output from renewables, by varying the ratio of heat to power output. If there is too much green power on the grid, the CHP plant can produce mostly heat. If demand for that is low, it can be stored. If green power availability is low, the proportion of CHP plant power output can be raised, and if there is still demand for heat it can be drawn from the heat store. Although CHP does need a nearby heat load to serve, in the power sector, it can be a flexible and valuable transitional option for heat as well as power, complimenting renewables, and capable of reducing emissions/kWh significantly, without the need for CCS. CHP can also be used in the industrial context, meeting power and heat demand directly and reducing emissions.

The UK governments new Industrial Strategy (HMG, 2017) seeks to decarbonise all sectors, including manufacturing, and, although CHP gets some backing, along with district heating, CCS and CCU have been promoted as options within its Clean Growth Strategy. £20m has been provided for a 'Carbon Capture Usage and Storage' (CCUS) demonstration programme. The aim is to "*demonstrate international leadership in carbon capture usage and storage (CCUS), by collaborating with global partners and investing up to £100m in leading edge CCUS and industrial innovation to drive down costs*" (BEIS, 2017).

The appeal of CCS and CCU in the industrial context is clear. As noted earlier, one of the arguments for CCS/CCU is that it will be hard to provide non-fossil energy for some energy intensive industries. However, in addition to its role in the wider power sector, CHP could play a role here too, and it is also possible to use renewables to power some of these processes. So, we may not need much fossil CCS for industrial heat and power. See Box 2.3 for some examples.

Box 2.3: Renewables for industrial emission reduction—avoiding CCS

Renewable sources can be used to power product manufacture, but there are also some options in the primary material sector, e.g. steel and aluminium production. Given that these activities can be very energy intensive, there is a major incentive to cut energy use so as to reduce emissions and also cut costs. Improved process efficiency is the obvious first step.

However, in some cases, renewables are also now an attractive way to cut industrial costs and emissions. As the percentage of renewable input to the grid system grows, grid power can supply the power needed with increasingly low carbon content. But it is also possible to do this directly, using power generated on site or nearby. This has already been done with some so-called 'merchant power' projects, for example at Ford's engine plant in Dagenham in East London, which has installed a series of large wind turbines. Ideas are now also emerging for primary industry. For example, the Lochaber Aluminium smelter near Fort William in Scotland is to get power from a wind farm with up to 54 wind turbines at nearby Glenshero, which may also supply Liberty's Dalzell steel mill in Motherwell. That could make some of the steel for the turbines (Musaddique, 2017).

Steel production is also being revamped by the GFG Alliance, which has a 'Greensteel strategy' which aims to cut the amount of raw steel imported to the UK, by dramatically increasing the amount of scrap steel which is recycled, and also to use renewables for its processing. It plans to use electric arc furnaces part-powered by renewable energy to melt scrap steel so that it can be reused, a process which is more environmentally friendly than primary steel-making in a blast furnace powered by coal. It is claimed that "*Greensteel, made using renewable energy, has only one tenth of the carbon footprint of blast furnace production*" (Tovey, 2017).

There are some other similar plans. For example, a forge in Sheffield aims to use biogas, supplied from an anaerobic digester fed with food and other waste from a nearby waste recycling centre (REM, 2017). Further afield, an Australian steel works is to have 1 GW of renewable power supply, including 680 MW of PV, with 100 MW of batteries, 100 MW of demand response and 120 MW of pumped hydro storage (Climate Action, 2017).

Large scale, zero carbon, primary material production and manufacturing using renewable energy may still be some way off, but, in principle, it seems credible, with, in some locations, direct use being made of Concentrated Solar Power plants, which, with overnight on-site heat storage, can deliver power 24/7 (Jacobson et al., 2017).

It has yet to be proven, but, as the grid-linked renewable energy system develops, with storage and other backup, the industrial use of renewables may make more sense environmentally and economically than fossil or biomass CCS, although it remains unclear whether CCU might still have an advantage, depending on the industry. In some cases (e.g. chemicals and fertilisers), CO_2 production may be unavoidable. In the main however, renewables can provide carbon free energy for most of industry. Some see a role for new types of nuclear plant in the industrial context, possibly run in CHP mode, supplying heat, power and perhaps also generating hydrogen, although, quite apart from nuclear safety and security issues, the economics of nuclear power remain uncertain (Elliott, 2017). If hydrogen is to be produced, and/or heat supplied, renewables may offer a better route.

There are other views on the role of fossil fuel and its CO_2 implications, some of them quite radical. For example, Oxford Prof. Peter Edwards and Cambridge Prof. Sir John Meurig Thomas have argued that:

> *fossil fuels should not be burnt (with the attendant CO_2 emissions)* [but should be] *catalytically decomposed to generate high-purity hydrogen as a renewable-energy carrier. The other product of this non-combustion route is solid carbon—not the climate-damaging gaseous CO_2—a useful starting material for other products. The bottom line is that fossil fuels have great potential in producing "green hydrogen" without CO_2 emissions. CO_2 mitigation technologies can therefore be applied to the continued use of fossil fuels.* (Edwards and Thomas, 2017)

That is certainly an interesting perspective, a new role for carbon, avoiding the need for CO_2 capture, and opening up the possibility of a whole new patterns of fuel production and industrial interaction, though still based on fossil resource use. As we have seen, fossil gas is already used to make hydrogen economically, and CCU could widen that, but it is not clear what the economics of this more comprehensive non-combustion approach would be. Some energy would be needed to drive the conversion process. As in the case of Air Capture, renewables might play a support role in providing that. To that extent, it might be seen as offering some synergistic support for renewables, although, arguably, it would be better to use renewables directly. Moreover, if synfuels like hydrogen are seen as valuable, then the Power-to-Gas renewables approach may deliver them with fewer problems. For example, although combustion-related emissions are avoided in the proposed fossil resource conversion process, it will presumably generate waste products, some of which may be hazardous. In addition, the environmental problems of fossil resource extraction and transport would remain. Moreover, and crucially, the fossil resource is limited: so, unlike renewables, it is not a long-term option.

For the moment we are faced with the urgent need to deal with the emissions that are being produced from combustion, while seeking to reduce or avoid them longer term. The non-combustion carbon-use model outlined above offers no direct help with the first of these requirement (it does not capture CO_2), although, if it proved to be technically and economically viable, it could offer a medium-term carbon emission-free synfuel option. However, given the extraction and waste issues and the energy costs, it might be seen as an unwelcome and risky rival to full commitment to renewables, with limited collateral or synergistic benefits, and also no long-term future.

Although, as we have seen, some of the other options also have limits, some of them are more developed. Even so, they may be also face limits. As noted earlier, EASAC drew together some estimates of the maximum possible potential, based on its literature review, on the Negative Emission Technologies. It suggested that a 10 GT (Gigatons) p.a. total estimate for negative carbon technologies (which excludes fossil CCS) might still be high, and was anyway well short of 12 GT p.a. envisaged as needed by the IPCC, although EASAC did note an estimate of up to 4 or more GT p.a. for fossil CCS (EASAC, 2018). Table 2.1 draws the main EASAC maximum estimates together. Some of the main issues, as identified above, are also noted.

There is broadly comparable data for some of the above in a recent PNAS study and in a linked review by Climate Brief, although wider ranges are offered, the latter argued that the natural carbon sink options could possibly store as much carbon as BECCS (Hausfather, 2018).

EASAC did not look at possible *utilisation* options, just at Negative Emission Technologies, although it did include fossil CCS, which, as shown in Table 2.1, had the highest score. Looking more widely, Table 2.2 presents a summary of all the options looked at above, including CCU, indicating, in rough terms, their potential for carbon reduction.

As can be seen, while trees and other bio-sequestration measures may do well, in line with Table 2.1, it is suggested that net carbon emissions from fossil fuel energy production with CCS might be attractive in tonnage terms. CCU may not be fully carbon neutral, but it is low carbon (depending on the efficiency of the overall CCS process), but net emissions are raised with CCU, assuming synfuels are produced and burnt, although the net CO_2 produced would be offset if green hydrogen is used to make them. Similarly, with synfuels from BECCU. Although the biomass feed stock for this is near net carbon neutral, using fossil hydrogen to make synfuel for combustion would mean the overall process would not even be carbon neutral. But it could be if

Table 2.1 Maximum estimates for carbon saving

	Gigatons of carbon captured per annum	Key issues
Fossil carbon and capture	4+	Not carbon negative
Air capture and storage	3.3+	Low CO_2 concentrations in air so more energy needed
Bio-sequestration—Forest planting	3.3	Low photosynthesis efficiency so need space and time
Biomass with CCS	3.3	Low photosynthesis efficiency so need space and time
Improved land/soil management	2.5	Slow organic processes
Ocean fertilisation	1	Potential eco-impacts

Source: Adapted from EASAC (2018)

green hydrogen was used. By contrast, BECCS is carbon negative, taking CO_2 out of the carbon cycle. That is also true in the case of Air Capture with storage, although no energy is produced, while some energy is required, whereas with Air capture and synfuel production, some net energy is produced, although hydrogen is needed and the overall A2F process is then not carbon negative, since the synfuels are burnt. The use of green hydrogen, and also renewables for the operating energy, would however improve the A2F situation- it might then be near carbon neutral.

In the case of renewable Power to Gas (P2G) hydrogen production (not covered by EASAC), direct carbon production is zero, and it is not raised if synfuels are produced (using CO_2) and then burnt, since this carbon has been captured. The fossil gas to hydrogen (H21) route looked at above would have higher conversion losses than simple fossil CCS, but the carbon saved might still be similar. Certainly, burning the hydrogen produced would not generate CO_2. That is also the case with the non-combustion route, and that process itself has no carbon emissions, although it needs energy.

For the sake of completeness, Table 2.2 also includes energy efficiency, which can cut energy use dramatically and so avoid carbon emissions. CHP is

Table 2.2 Summary of carbon reduction measure impacts and requirements

Technology	Net carbon emissions	Requirements
Trees and bio-capture	Negative/Cyclic	Land area/land management, time!
Fossil CCS	Low	Large-scale indefinite CO_2 storage
Fossil CCU to synfuel	High/Medium[a]	Hydrogen to make synfuel
BECCS	Negative	Large biomass area and storage volumes
BECCU to synfuels	Low/Zero[a]	Hydrogen to make synfuel
Air capture + storage	Low/Negative[a]	Energy for the process and large storage
Air capture to synfuel (A2F)	Low/Zero[a]	Energy and Hydrogen to make synfuel
Fossil gas to H2 with CCS	Low	Large-scale indefinite CO_2 storage, energy
Renewable P2G—H2	Zero	Renewable energy input
Renewable P2G—CH4	Zero	Renewable energy input, plus CO_2
Non-combustion route to H2	Zero/Low	Energy to drive the process
Fossil CHP (but low C heat)	High/Medium	Nearby heat demand
Biomass CHP (+ low C heat)	Low/Zero	Nearby heat demand
Renewables (wind/solar)	Zero	Some land use implications
Nuclear	Low	Fuel production, waste storage, security
Efficient use of energy	Negative	Willingness to invest to save!

[a] If green hydrogen/renewables for power is used

also included. That can have low carbon emissions, depending on the fuel used. Direct use of renewables like wind or solar would of course have zero direct carbon emissions. Finally, there is the nuclear option. It too has zero direct CO_2 emissions, but unlike renewables such as wind and solar, it requires energy to make its fuel and the carbon debt associated with that is likely to increase as the uranium resource is depleted and lower grade ores have to be used. It also has many other problematic issues and uncertain prospects (Elliott, 2017).

Note that all these emission estimates are in absolute terms, indicating very roughly how much CO_2 output might result from each option, including from any subsequent synfuel use and from the energy used for the capture process. 'High' is this context means the same as, or similar to, conventional unabated fossil generation. Strictly, Air Capture with storage falls outside of this ranking (it does not produce any energy), but its carbon impacts can still be usefully compared. A more substantial assessment would cover the relative costs (hard to do at this early stage) and also include the carbon implications of the energy embedded in the technologies, and of any grid balancing required or provided. The latter is important since, in the short term, fossil fueled plants will play a role in balancing variable renewables, but longer term there are better ways to balance renewables, without having to extract, transport and burn fossil fuels, and then store CO_2 forever (Elliott, 2016).

6 Conclusion

It can be argued that the best way to store carbon is to leave it in the ground, and to look elsewhere for energy. Certainly, the various carbon capture ideas discussed above, trees and soil capture apart, do seem a little inelegant in engineering terms. Fossil CCS is a classic 'end of pipe' technical fix, capturing a waste gas and pumping it underground in the hope that will stay there, all so that we can continue to use fossil fuels for a while longer, while avoiding some of their emission impacts. Fossil CCU may be more commercially attractive, in that it offers new syn-fuel options, and avoids the problems of storage, although it is in its infancy, and it is not a negative carbon option or even carbon neutral, since the fossil synfuel is burnt. Direct Air Capture is also in its infancy, and it too is an energy hungry process, but, with carbon storage and using renewables for power, it could still be negative carbon, or, without storage, a source of synfuel, though their combustion would generate CO_2. BECCS and BECCU would avoid direct fossil fuel use, and BECCS could deliver negative carbon, although at the cost of extensive land use for biomass production and the need for CO_2 storage space. Finally, the non-combustion approach to fossil resource use avoids CO_2 production, but relies on a limited fossil resource, with their still being potential environmental impacts from their extraction, transport and use.

By contrast, in general, renewables, and in some contexts CHP, along with energy efficiency, arguably look much better bets, both now and in the long-term, in energy, environmental and cost terms. The renewable resource is very large and will last indefinitely, the impacts from using it are generally low and costs are falling rapidly. Energy efficiency improvements are also usually very cost effective and are vital to cut emissions. They also complement renewables: lowering energy demand makes it easier to meet it with renewables.

In this context, and given the problems discussed above, the potential for carbon capture of whatever sort looks a little limited at present. Even adopting what some might see as an optimistic assessment of CCS, the UK government recently projected that there might only be 1 GW of fossil CCS in place in the UK by 2035, as opposed to 45 GW of renewables (BEIS, 2018). Deployment of CCS elsewhere might be more extensive, and perhaps should be, for example given the continued use of coal in some Asian countries. However, China is now trying to cut back rapidly on coal use (CER, 2018) and, interestingly, a critical report on CCS for the Global Warming Policy Foundation, which is not usually a fan of renewables, claimed that "*for China, investment in the transmission grid to permit wind generation in the west to be managed jointly with hydro plants in the rest of the country is a far cheaper way of reducing CO_2 emissions in the next 10–15 years than retrofitting existing coal plants with CCS or building new coal plants with CCS*" (Hughes, 2017: x).

However, new CCU/low carbon technologies are emerging which might offer new, less costly, opportunities in some locations (Gorder, 2018; Sulleyman, 2018) and certainly enthusiasm for carbon capture still remains. For example, the Global CCS Institute says that "*CCS is needed because the amount of fossil fuels we burn continues to rise*" and looks to massive expansion of fossil CCS. Nevertheless, it insists that "*CCS is not a 'front' for the coal or wider fossil fuel industry*", suggesting that CCS can be run in parallel with renewables, and indeed that it will help to balance variable renewables, although it also quotes some very low estimates for potential renewable contributions (GCCSI, 2017: 12).

While energy futures can be debated, as we have seen, in strategic terms, it may be wise to be cautious about the potentials quoted by enthusiasts for the various carbon reduction options. As the EASAC President warned in relation to NETs:

> *whether consciously or subconsciously, thinking that technology will come to the rescue if we fail to sufficiently mitigate may be an attractive vision. If such technologies are seen as a potential fail-safe or backup measure, they could influence priorities on shorter-term mitigation strategies, since the promise of future cost-effective removal technologies is politically more appealing than engaging in rapid and deep mitigation policies now. Placing an unrealistic expectation on such technologies could thus have irreversibly damaging consequences on future generations in the event of them failing to deliver. This would be a moral hazard which would be the antithesis of sustainable development.* (EASAC, 2018: iv)

Nevertheless, the EASAC did accept that some of the technologies "*can make some contributions to remove* CO_2 *from the atmosphere even now, while research, development and demonstration may allow others to make a limited future contribution*" (EASAC, 2018: iv).

Given this more limited role for NETs and carbon capture, some of the potential conflicts with renewables might be avoided. However, that clearly depends on the strategic context. If fundamental conflicts over energy strategy persist, fuelled by climate denial and/or doubts about renewables, then it will be hard to pursue a rational interim mix of renewables and abated fossil plants, or other carbon reduction options. Support for all the latter may be resisted by green zealots as 'backsliding', and opportunities for synergies, productive co-operation and complementarity may be lost. That has been the case at times with gas plants used for balancing variable renewables. Although there are other grid balancing options (Elliott, 2016), some fossil gas plants will be needed for some while, even though, longer term, they may be able to use biogas or P2G syngas. Similarly, for CHP, it can offer significant benefits including grid balancing, even if, initially, it uses fossil fuel.

In the interim, in the context of a limited short to medium term role for carbon capture and exit from carbon, strategic issues will emerge. For example, would the limited role for carbon capture provide a sufficient base to develop CCS for BECCS? Moreover, *should* BECCS be developed, given its land use and other limitations? In the context of a decreasing role for fossil fuel, BECCS would no longer be in danger of providing a 'fig leaf' for continued fossil fuel use, so the debate might be less fraught. However, its outcome is still unclear. The same might be said for Direct Air Capture: it would no longer be seen as compensating for continued *long-term* fossil fuel use. So, some might see Air Capture as playing a limited role in the short to medium term. However, whether it would be seen as viable on a significant scale as a longer-term post-carbon clean-up option is unclear. That issue, and the interim role of carbon capture and utilisation, would be open for debate, which would be eased if there was no risk of supporting the continued use of fossil fuels. But by contrast, the non-combustion approach to fossil resource use would seem to retain the potential for at least some continued conflict: although it would not produce CO_2, essentially it would underpin the arguably unsustainable use of relatively scarce resources, while possibly inhibiting the full and rapid development of renewables.

There are some interesting parallels in all this with the situation in relation to the long-term disposal of nuclear waste. All agree that what we have produced so far has to go somewhere, but many environmentalists are unwilling to support proposals for repositories while more waste is planned to be produced in new nuclear plants. Nuclear waste and CO_2 are very different, but the strategic conflict is the same: the solutions are hard to discuss while more is being produced, with no end in sight. However, as far as fossil fuels are concerned, the end is in sight, and some say that is also the case for nuclear. But until these endpoints are ascertained and confirmed, we can accept negotiations over what to do next will be difficult.

Hopefully that situation can be resolved. In the case of CO_2, that will be important, since some fossil fuel use will continue for a while. For some 'greens', perhaps understandably, having anything to do with fossil fuel will remain an anathema, but if we are to move successfully to a sustainable future, some way to deal with residual, interim CO_2 production from them will have to be found. That is also the case for some non-energy industrial CO_2 production, which may be hard to avoid. Moreover, although they may be overstated, there may be at least some potential strategic synergies between carbon capture and renewables. As we have seen CCS might open up some non-fossil options, like BECCS or green hydrogen use. Meanwhile, renewables may be needed to provide zero carbon energy to run CCS/CCU systems, while renewables may need CCS to enable fossil fuelled plants to pay an interim role in balancing variable renewables. So 'greens' may have to learn to 'deal with the devil with a long spoon', at least for a while. In a context where renewables are dominant and expanding, and a diminishing reliance on fossil fuel has been agreed, that may be less threatening to them.

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