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Published in:
Historical Materialism

DOI:
[10.1163/1569206X-29012021](https://doi.org/10.1163/1569206X-29012021)

2021

[Link to publication](#)

Citation for published version (APA):

Malm, A., & Carton, W. (2021). Seize the Means of Carbon Removal: The Political Economy of Direct Air Capture. *Historical Materialism*, 29(1), 3–48. <https://doi.org/10.1163/1569206X-29012021>

Total number of authors:
2

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HISTORICAL MATERIALISM 29.1 (2021) 3–48

historical materialism
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Editorial Perspective



Seize the Means of Carbon Removal: The Political Economy of Direct Air Capture

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Abstract

The left must confront the politics of removing carbon from the atmosphere – a topic rapidly making its way to the top of the climate agenda. We here examine the technology of direct air capture, tracing its intellectual origins and laying bare the political economy of its current manifestations. We find a space crowded with ideology-laden metaphors, ample fossil-capital entanglements and bold visions for a new, ethereal frontier of capital accumulation. These diversions must be cut short if a technology with the capacity to help repair at least some climate damage is to be of any use. Only socialising the means of removal will allow this to happen.

Keywords

carbon removal – negative emissions – direct air capture – climate-change mitigation – political economy – carbon capture and usage

Soldiers of ancient Mediterranean empires are thought to have carried weights straining against the limits of human endurance. Willingly drafted or not, they were trained in loaded marches, also known as forced foot marches, during which the maximum tolerable burden could be ascertained; this has remained a common military exercise. One could imagine an officer of slightly sadistic bent adding weight to see at what point the first bodies would collapse. He might place extra stones in the rucksacks, likely to break bones when the recruits topple over. Some aspects of such a scenario correspond to what the earth's climate system is currently undergoing: staggering under the load, it receives yet more carbon dioxide into the atmosphere, every additional ton stacked on top of the former; the cumulative process works its way towards breakdown, with only the briefest decelerations so far. The Covid-19 pandemic cut global emissions by some 7 per cent for 2020. That means last year's stone was about one twelfth smaller than the previous; or, given the perpetual growth, CO₂ emissions had the same size as in 2011.¹ Far too much is in the air for the climate to stay reasonably stable – and yet more is being inserted year after year, which means that it is no longer enough to aim for zero emissions, a turnaround that would inevitably take some time to complete. The excess has to be unloaded. This is the rationale for carbon dioxide removal, a topic rapidly making its way to the top of the climate agenda.

In a much-quoted paper from 2008, James Hansen and his colleagues noted that the prevailing atmospheric CO₂ concentration had already put the climate in danger of being destabilised: it then stood at 385 parts per million (ppm). As of 2020, it has reached 417 ppm, a peak not seen in several million years, rising by between 2 and 3 ppm per annum. Hansen and his team famously suggested that humanity should aim to return to 350 ppm, a plateau where a climate congenial to civilisation could be maintained; the proposal was picked up by 350.org, the activist network instrumental in forming the contemporary climate movement. Implicit in it was carbon dioxide removal – or 'drawdown' – on a gigantic scale. Hansen and colleagues hinted at industrial technologies for capturing the gas and called for a massive research and development effort.²

1 Friedlingstein, O'Sullivan, Jones *et al.* 2020.

2 Hansen, Sato, Kharecha *et al.* 2008.

Around the same time, energy-system modellers started pointing in a similar direction, though for a subtly different reason.³ They talked up the prospect of drawdown not to reduce atmospheric concentrations to historic levels, but to help compensate for locked-in or supposedly unavoidable *future* emissions – taking back what the world cannot help but continue to let out.⁴

By the time the Paris agreement codified the targets of ‘well below’ 2°C of warming and preferably no more than 1.5°C, scientific calls for removal had grown into a background chorus. When the IPCC in 2014 assessed various pathways that would keep the world from exceeding the 2°C limit, the bulk rested on the work of ‘negative emissions technologies’, yet another term for getting the carbon back into the ground. Its 2018 compendium of routes to 1.5°C relied on the same assumption: if too much is emitted to stay at that threshold, the ‘overshoot’ can be taken back at a later date.⁵ The Paris agreement rallied states around this wager. Buried deep in the text that governments signed onto was an acknowledgement that targets would be met not just by reducing emissions, but by striking a balance between their continuation and future removals. This was not completely new, of course; natural carbon sinks had long been imagined as a counterforce to anthropogenic climate wracking.⁶ But scientists now feared that nature cannot be trusted to do all this work on its own. It would take thousands of years for forests and oceans and rocks to absorb the glut of CO₂. Planting new forests has a one-off effect; once they have matured, their uptake levels off. There simply is not enough land to plant the number of trees needed.⁷ Instead there would have to be technologies for retrieving the gas, operating as swiftly and continuously as those for emitting it, but in reverse. The message of the IPCC models had an existential charge: on such technologies, the future of the habitable earth now depend.

1 The Means of Carbon Removal

The quest for negative emissions initially focused on one particular technology. By covering vast expanses of land with eucalyptus, sugarcane or some other fast-growing plant, humans can withdraw tons of CO₂ from the air via plain photosynthesis. The harvest can be transported to power plants and

3 Azar, Lindgren, Larson and Möllersten 2006; Van Vuuren, Den Elzen, Lucas *et al.* 2007.

4 On the two uses of carbon removal, see for example Meadowcroft 2013.

5 Anderson and Peters 2016; IPCC 2018.

6 Lövbrand 2004; Fogel 2005.

7 For an excellent discussion, see Buck 2019, pp. 95–116.

burnt as any fuel. Filters can grab the CO₂ from the column of smoke, the gas collected as a pure stream later to be injected in cavities underground, and if this cycle is repeated non-stop, a good deal of carbon will indeed be pulled out of the atmosphere. The technology is known as 'bioenergy with carbon capture and storage', or BECCS, one of the innumerable ugly acronyms that litter the language of climate politics like so much detritus on the beach, testimony to three decades of failure to rein in business-as-usual. The scientific models designed to show a path to 2 or 1.5°C relied on a massive roll-out of BECCS to counteract the expected emissions of the twenty-first century. However, barely had the modellers betted on BECCS than a very considerable drawback came into sight: this technology would devour land. Estimates of the area required for a deployment of BECCS sufficient to hold warming below 2°C ended up in the neighbourhood of total current cropland. Somewhere on earth, in other words, space equivalent to all that currently devoted to cultivation would have to be carved out, just to make room for those biomass plantations (not to mention their irrigation, estimated to demand twice the amount of water currently used in agriculture).⁸ This could happen by razing what remains of tropical rainforests, or by cutting deep into fields – that is, by devastating either biodiversity or food supplies, or some mixture of both. BECCS quickly lost its lustre. That does not mean it has been ditched across the board; as with many other false and debunked solutions, BECCS plods on, governments in the global North refusing to let go of it. But in the past couple of years, the quest for negative emissions has turned to other technologies without the same conspicuous drawback. Prominent among these is 'direct air capture' or DAC.

Here no photosynthesis is involved. Instead that process is mimicked by chemical engineering. Air – any air outdoors, or 'ambient air' in the technical jargon – is drawn into a device that works somewhat like a leaf or a lung. Inside, there is a filter equipped with a 'sorbent', a substance that snatches the molecules of CO₂ and binds them, while letting other elements waft away. When the filter is saturated with CO₂, it is taken out and heated up to the point where the gas can be purified, while the sorbent is regenerated for a new round; switched on again, the fans will make fresh air breeze through the system, and so on. The trick of scrubbing CO₂ from the air is not a novelty: it has long been used in submarines and space stations. Now it would be applied to the biosphere as a whole.

8 See for example Field and Mach 2017, p. 707; Obersteiner, Bednar, Wagner *et al.* 2018, p. 8; Heck, Gerten, Lucht and Popp 2018; Jones and Albanito 2020. For critical perspectives on BECCS – as well as on solar-radiation management a.k.a. solar geoengineering, left out in the present article – see Sapinski, Buck and Malm (eds.) 2020.

The captured CO₂ would be ripe for permanent storage. And indeed, in 2017, harnessing the peculiar geology of Iceland, Swiss company Climeworks opened the first plant that directly captures CO₂ and turns it into a mineral – a negative stone, as it were – buried between 400 and 800 meters under the ground. Climeworks is one of the three start-ups that currently form the cutting edge of DAC technology, the other two being Global Thermostat in the US and Carbon Engineering in Canada. All three are tiny outfits. All are undergoing explosive growth, and all have demonstrated in their own fashion that direct air capture is in fact possible. It is photosynthesis on steroids: Climeworks claims to do the job of 36,000 trees with the footprint of one.⁹ While Iceland is out of the way, the company's pilot plant in an industrial zone in Hinwil outside Zürich is easily accessible; here visitors can inspect the rows of machines that look like oversized clothes dryers and, behind them, the thick balloons that hold pure, concentrated CO₂. Everyone from the *Financial Times* to Greta Thunberg has made the pilgrimage.

DAC holds out a promise of almost irresistible allure: to undo the damage fossil-fuel combustion has inflicted on this planet. It is preferable to BECCS in that it makes no claims on arable land. It would compete neither with wildlife nor cereals, since the 'artificial trees' can be erected practically anywhere – including, as in Hinwil, on top of a waste-incineration plant. Hence DAC is now making its way into the models the IPCC passes on to 'policymakers'.¹⁰ The first stirrings of support from governments in advanced capitalist countries have registered. In 2018 a bipartisan US law gave companies a tax credit of up to \$50 for every ton of CO₂ sequestered; in another exercise in acronym production, it was christened the Furthering carbon capture, Utilization, Technology, Underground storage, and Reduced Emissions Act – or FUTURE Act, in a word. Businesspeople, however, tend to refer to it as 45Q, after the section of the Internal Revenue Code that can be invoked for a CO₂ burial rebate. Neither Donald Trump nor his cabinet of climate denialists put any spokes in this wheel. In the summer of 2020, erstwhile denialist Boris Johnson copied it as part of his plan to 'rebuild Britain and fuel economic recovery': £100m was earmarked for developing 'a brand new clean technology', namely DAC, which might 'be deployed across the country to remove carbon from the air'. The PM had reportedly been convinced of the virtues of DAC by his advisor Dominic Cummings, not widely known for his environmentalist passions.¹¹

9 Repsol Foundation 2020.

10 See for example Fuhrman, McJeon, Patel *et al.* 2020. As for the spatial mobility of DAC, it is restricted by suitable sites for geological sequestration and access to renewable energy (in the absence of which there would have to be pipelines for transporting the pure CO₂ and transmission of electricity); on these two factors, see further below.

11 Gov.uk 2020; Wright 2020.

In an ideal world, states like these would now be busy phasing out all fossil fuels as aggressively and rapidly as physically possible, plus mustering the counterforces of carbon dioxide removal so as to set the earth free from a burden that has been excessive for some time. But what marks out this overheating world is, of course, that it is rather far from ideal.

2 Metaphors for Delay

To understand the role direct air capture plays in the present moment, we need to trace its intellectual origins. The father of the technology is Klaus Lackner. A man of big ideas, relocating from the Bonn Republic to the US in the early 1980s, Lackner first gained notoriety as a physicist at Los Alamos National Laboratory, renowned cradle of the atomic bomb. Bemoaning the timidity of his fellow scientists, no longer prone to thinking on the scale of the Manhattan or Apollo projects, he came up with a proposition for something exceedingly ground-breaking: machines capable of replicating themselves and solving the world's most pressing problems in the process. He imagined them as robots no larger than suitcases. He would position them on a yard of desert land. Observing a strict division of labour, some would scrape dirt from the desert floor, others extract useful metals from the dirt, yet others shape them into machine parts and assemble new replicas of all these lines of automata. From a Greek word for 'to grow', Lackner gave his robots the name *auxons*. Doubling in number every six months, fanning out across the American continent, the population of auxons would be programmed to execute three more tasks: building solar panels, thereby supplying unlimited energy to themselves and all humanity; constructing water-desalination units; and, last but not least, converting airborne CO₂ into 'a layer of "marble" approximately 50 cm thick'.¹² And all this with no inputs other than sunlight and air and raw common dirt. In 1995, *Discovery Magazine* dubbed it 'one of seven ideas that can change the world'.¹³ No auxon has since been sighted. Representing a recurring dream of bourgeois civilisation – fully-automated labouring armies, capable of moving and begetting themselves, with no will or deviation – the scheme might have run up against the laws of thermodynamics.¹⁴ Lackner seems to have quietly dropped it. He did stay, though, with the idea of direct air capture, elaborated

¹² Lackner and Wendt 1995, p. 79. The scheme is laid out in full in this article.

¹³ Bass 1995.

¹⁴ On the history of this dream, see Kang 2011.

in a series of articles from the mid-1990s onwards as an exciting solution to the problem of global warming.¹⁵

Lackner has managed to unveil his own workable contraption for capturing CO₂; it looks somewhat like an accordion, raised and expanded so the surfaces can touch the air. It was recently sold to an Irish start-up called Silicon Kingdom, while Lackner stayed behind in his laboratories at Arizona State University, but his main achievement may not be to conjure actual machines.¹⁶ He should rather be regarded as the progenitor and ideologist of DAC, at his most visionary in a manifesto called 'Climate Change is a Waste Management Problem'. Here he makes the case for reclassifying CO₂ as the atmospheric equivalent of sewage. The act of emitting it is like that for which you go to the loo. DAC devices, it follows, are toilets for flushing out excreta from humanity; the only wonder is why they have not yet been built *en masse*. Lackner clearly intends the metaphor to be taken seriously. It has a series of implications: rich Americans must have bladders two thousand times larger than poor Mozambicans.¹⁷ Or, asking people to cease burning fossil fuels would be like telling them to stop peeing – which is just what Lackner argues: 'Rewarding people for going to the bathroom less would be nonsensical.'¹⁸

Here is a way out of the embarrassing predicament of hitherto existing climate politics. Supplanting the futile calls for emissions reductions, DAC would treat carbon dioxide as one more natural effluent. 'A waste management perspective makes it unnecessary to demonize or outlaw activities that create waste streams. It's OK for people to use toilets' – the whole problem redefined at one stroke. Now it would be superfluous to dismantle or even tinker with existing energy infrastructure. 'Only the construction of a parallel infrastructure' is imperative, with little need for 'large-scale' or 'top-down' coordination; it can be left to private companies to install the lavatories. Perhaps best of all, unlike attempts to cut back on combustion, this programme 'does not threaten the political, social, and economic interests associated with the fossil energy

15 *Inter alia* Lackner, Wendt, Butt *et al.* 1995; Lackner, Ziock and Grimes 1999; Elliott, Lackner, Ziock *et al.* 2001; Lackner, Wilson and Ziock 2001; Lackner 2003; Lackner, Brennan, Matter *et al.* 2012. In Elliott, Lackner, Ziock *et al.* 2001, Lackner and his colleagues imagined strips of land covered with material absorbing CO₂; the strips would be walled or fenced in and run 'from pole to pole'.

16 Temple 2019a; Silicon Kingdom Holdings, <mechanicaltrees.com>.

17 For figures on such emission disparities produced for the occasion of the Paris summit, see Chancel and Piketty 2015; Oxfam 2015; and the even more dizzying update, Oxfam 2020.

18 Lackner and Jospe 2017, p. 84. For this discourse in a broader context, see Buck 2020.

system – and does not automatically trigger opposition from those interests.¹⁹ There is, in short, no need for mutiny.

Already in the days of the auxons, Lackner used the bathroom metaphor and trumpeted that his robots would take the heat off climate politics; the themes run through his oeuvre.²⁰ He has pointed out that there is enough coal in the ground to raise the CO₂ concentration to 3,500 ppm. Bring it on: DAC would ‘allow utilization of the known coal reserves without accumulation of carbon dioxide in the atmosphere.’²¹ Cars and planes and ships can continue to exude CO₂ when there are tens or hundreds of millions of DAC machines to take care of it.²² This, Lackner has explained to the readers of *Science*, is how we ‘render fossil fuels environmentally acceptable’. He keeps an eye on the capital fixed in mines and pipelines and terminals and airports, which, if emissions were to be pushed to zero in a few decades or years, would risk obliteration. DAC would let such primary infrastructure ‘live out its useful life.’²³ This is a technology ‘friendly to established industries’, having no quarrel with the guardians of the status quo; one member of Lackner’s team at Arizona State has found an apposite analogue in the plan to plant one trillion trees.²⁴ At the World Economic Forum in February 2020, Donald Trump again confounded the world by pledging his support for this measure ‘to protect the environment’ (he did not use the word ‘climate’). As the *New York Times* noticed, he could take the bait because ‘it was practically sacrifice-free, no war on coal, no transition from fossil fuels, no energy conservation or investment in renewable sources of power’ – nothing of what this president found so repulsive.²⁵ Not entirely without sacrifice, though: some would have to give up space for those one trillion trees, and presumably it would not be owners of golf courses. But that is beside the point. From the perspective of the Arizona labs, the trillion-trees fancy shows how DAC could be sold: as a well-nigh miraculous technology for gliding over antagonism.

19 Lackner and Jospe 2017, pp. 84, 88. While Lackner is usually credited with being the first to propose DAC, *Nature* published a brief letter by Swiss-German nuclear physicist Walter Seifritz in 1990, five years before Lackner’s articles began to appear. The letter opens with the following sentence: ‘If fossil fuels are to be used on a massive scale and the greenhouse effect avoided, carbon dioxide in the atmosphere must be reduced’ by means of chemical reactions and re-injection underground: air capture conceived from the start as a life extension for the fossil economy. Seifritz 1990.

20 Bass 1995; Lackner and Wendt 1995, p. 79.

21 Lackner, Wendt, Butt *et al.* 1995, p. 1168; cf. Lackner, Wilson and Ziock 2001, pp. 32–4.

22 Lackner 2010, p. 71.

23 Lackner 2003, pp. 1677–8. Cf. Lackner, Ziock and Grimes 1999, pp. 1–4.

24 Elliott, Lackner, Ziock *et al.* 2001, p. 1235; Morton 2020, pp. 83–4.

25 Friedman 2020.

In this vision, then, DAC is not a complement to leaving fossil fuels in the ground. It stands in for it through an endlessly extended loop. Lackner occasionally professes awareness that emissions should also be slashed, but it is hard to shake off the impression that an attraction of DAC is its eminent compatibility with the prevailing order.²⁶ It is reinforced by the currency his arguments have gained among proponents and practitioners alike.²⁷ One of the most lionised scientists of the climate system and the carbon cycle, Wallace Broecker, befriended Lackner in the early years of the millennium and converted to his gospel; together, the two men spread it to Iceland. Broecker gave the metaphor a more strictly alimentary and faecal content: burning fossil fuels is in ‘direct analogy to eating food’. The cesspool that hovers above us needs to be matched by a subsurface sewage system. ‘Thanks to Lackner, it now seems possible that, as far as fossil fuels are concerned, we really might have our cake and eat it too’, Broecker consigned his insight to paper, hastening to add that this ‘is not a “technical fix” that allows us to burn more fossil fuels, any more than sewage systems allow us to eat more.’²⁸ But a more literal naturalisation of fossil-fuel consumption is hard to think of. Buying into the discourse of waste management, Broecker saw DAC as the saviour of ‘our wonderful gadgets’, notably automobiles.²⁹ A turn to the air ‘recognizes that fossil fuels aren’t going away’ and therefore ‘should appeal to oil and coal companies, which aren’t going away either’.³⁰

All three leading start-ups have vented similar notions. The founders and CEOs of Global Thermostat, Graciela Chichilnisky and Peter Eisenberger, worked with Lackner at the venerable Earth Institute of Columbia University; they have contended that DAC ‘provides a solution of the global warming problem in the short run’, as we wait until fossil fuels ‘have depreciated their investments’.³¹ A fossil fuel phase-out is not thinkable this side of 2050. While Chichilnisky and Eisenberger assure us that a ‘long-run renewable energy solution’ is necessary in the end, it is ‘*not* realistic in the short run’ because ‘most of the energy used in the planet today is obtained from fossil sources such as oil, gas and coal’.³² Only DAC can save us from this trap. Despite the very rapid

26 See, for example, Lackner, Wilson and Ziock 2001, p. 36; Lackner, Brennan, Matter *et al.* 2012, p. 13160.

27 The bathroom metaphor continues to attract fans. Even the (rightly) acclaimed socialist sci-fi writer Kim Stanley Robinson recently joined their number, promoting DAC as ‘sewage treatment for the skies’. Robinson 2020.

28 Kunzig and Broecker 2009, pp. 15, 229, 268. On the ideas developed out of the collaboration between Broecker and Lackner, see pp. 230–59; on their deeds in Iceland, pp. 254–6.

29 Broecker 2013, p. 3.

30 Kunzig and Broecker 2009, p. 268.

31 Chichilnisky and Eisenberger 2009, pp. 426–8.

32 Chichilnisky and Eisenberger 2009, p. 418.

advances in renewables, this remains a leading theme of their work. In a presentation the couple gave together with Lackner at a 'direct air capture climate mobilization summit' in July 2020, ecumenically including all the main players in the business, DAC was advertised as an escape route from the disruptions of a rapid shift away from fossil fuels.³³

David Keith is the founder of Carbon Engineering and a ubiquitous presence in the conversations: his work concludes that DAC has 'lower adjustment costs than conventional mitigation options'. Or, forthrightly, 'it is optimal to pollute more when it is possible to clean up afterward'.³⁴ The company's current CEO, Steve Oldham, argues that 'it is wishful thinking to believe we can instantly eliminate fossil fuels, across the planet'; hence we need to 'be pragmatic', which involves acknowledging that 'removal of CO₂ from the atmosphere is just as good, if not better, than stopping an emission' (depending on the cost of the latter).³⁵ This reasoning clearly appeals to investors, one of whom was interviewed by *Forbes* and dryly observed that 'right-leaning investors and politicians like the fact that Carbon Engineering uses technology to enable the continued use of oil'.³⁶ Even Climeworks, the most politically sophisticated of the three, has castigated the standard climate narrative for its ascetic moralism. As one of the company's representatives explained when we interviewed him in Zürich: 'We have tried climate policy for, what is it, 40 years now, based on abstinence. It hasn't worked. If the only solution you offer is to stop flying, to stop eating meat, to stop driving a car, you won't get people on board' – these being essential components of 'lifestyles that especially those in industrialized countries have become accustomed to'.³⁷ Life with DAC comes without the duty to abstain.

Somewhat more subtly, plenty of papers on DAC rest on a syllogism: the fossil economy is nowhere near coming to an end; this has catastrophic consequences; hence we must do something completely different to save the planet. 'Given the reliance on fossil fuels, widespread adoption' of direct air capture is indispensable, runs a typical phrase, the keyword here being *given*.³⁸ In their most optimistic moments, the luminaries of DAC think they can obviate the effects of this given reliance and go far beyond it. Lackner has circulated a

33 Elk Coast Institute 2020, p. 30.

34 Keith, Minh and Stolaroff 2006, pp. 33–4.

35 Interview with Steve Oldham, 27 August 2020.

36 Kobayashi-Solomon 2019b.

37 Interview with Climeworks representative, who requested anonymity, 20 February 2020; second part of quotation from Beuttler, Charles and Wurzbacher 2019, p. 5.

38 Lackner, Brennan, Matter *et al.* 2012, p. 13156. For just one more case, cf. Eisenberger, Cohen, Chichilnisky *et al.* 2009, pp. 973–6. It might be noted that the second listed author of this article, Roger W. Cohen, was an inveterate climate-change denialist.

back-of-the-envelope calculation saying that one hundred million machines would nullify current annual emissions, but there is no reason to stop there: we could build more and soak up past emissions too. With four hundred million machines, 10 ppm can be drawn down every year, bringing us back to 350 ppm and further still.³⁹ Looking ahead, Lackner and Global Thermostat envision the technology as precisely that: an instrument for setting the preferred temperature on the planet and even buffer against Milankovitch cycles. There will be no more ice ages. Thousands of years into the future, the New York metropolitan area can be saved from advancing glaciers.⁴⁰

A more relevant question, however, is what role DAC plays on the threshold to the third decade of this century. It need not exist beyond a handful of prototypes to have an impact. Merely the mental picture of millions of machines may insidiously, consciously or subconsciously, influence policymakers and the public: down the road, there will be a technology to bail us out. The urgency of cutting back on fossil fuels is then blunted. This effect is sometimes referred to as ‘mitigation deterrence’ – the appearance of some other option that makes the mitigation of climate change look less critical, not because that option is proven and present in the material world, but because it has settled in the ‘social imaginary’.⁴¹

It is in the nature of this effect that it cannot be measured precisely. Yet its fingerprints are all over the discussion on negative emissions. Even the models that underpin IPCC reports are guilty of it; indeed, they came to rely on these technologies precisely because they offered an escape clause from emissions cuts of the most radical, immediate kind.⁴² The recent flood of corporate commitments to ‘net zero’ – from Amazon, Apple, Rolls Royce, H&M, even Shell and BP – bear witness to the same effect, by serving up still speculative megaremovals as ready substitutes for actual reforms now. In the UN climate negotiations, the nations least interested in mitigation have been the most ardent promoters of systems that bind CO₂ – forests in Poland, to take but one prominent example. There is a strong suspicion that BECCS had the same function in the wake of Paris, when even the most enlightened governments returned home from the summit to oversee further circuits of business-as-usual.⁴³ Now DAC looks like the likely next candidate. Given what we know about the history of dominant classes denying the problem and delaying action, it would be naïve to think that the same dynamics are not at play here. Should the

39 Broecker 2013, p. 2.

40 Eisenberger 2014, p. 974; Elk Coast Institute 2020, pp. 12, 17.

41 Markusson, McLaren and Tyfield 2018, pp. 1–9.

42 Carton 2020; Azar, Lindgren, Larson and Möllersten 2006; Van Vuuren, Den Elzen, Lucas *et al.* 2007.

43 McLaren and Markusson 2020, pp. 392–7.

technology fail to scale up, its principal work would then be performed in the realm of ideology, with a result on the accumulation of CO₂ exactly opposite to that (putatively) intended.⁴⁴

3 In the Service of Fossil Capital

It then comes as little surprise that DAC is being embraced by fossil capital.⁴⁵ In June 2019, ExxonMobil signed a contract with Global Thermostat to ramp up its version of the technology. Until then, this start-up had built half a dozen pilot facilities from simple transport containers, with a capacity to capture up to 4,000 metric tons of CO₂ per year. When ExxonMobil agreed to share its money and engineers, Chichilnisky and Eisenberger envisioned a leap to the gigaton scale.⁴⁶ The partnership went back a long way: focusing on alternative fuels, Eisenberger worked for Exxon Corporate Research in the 1980s. 'He doesn't have an unkind word to say about his former employer Exxon, and he's quick to point out that fossil fuels were key in advancing human society to where it is today. "Now we have to switch – it's part of the natural evolution of our species", he explained to one journalist.⁴⁷ ExxonMobil sent its vice president of research and development to the 'mobilization summit' in 2020.

Carbon Engineering was there too; it appears to have received most of its initial capital from Bill Gates and N. Murray Edwards, one of the main investors in the Canadian tar sands. Not to be left behind, Anglo-Australian mining and petroleum conglomerate BHP and Chevron announced investments in the same firm in 2019, but they were outdone by Occidental, which aimed highest: to become the first corporation selling carbon-negative oil.⁴⁸ One market analyst at *Forbes*, writing 'both from the perspective of a member of the human race and from the perspective of a cold-hearted investor', hailed the batch of oil investments into Carbon Engineering as 'a historic inflection point in capitalism's battle against climate change'. Finally, construction had begun on 'the infrastructure necessary to "treat" the atmosphere in the same way that modern sewage systems treat waste water'.⁴⁹

44 Cf. Realmonde, Drouet, Gambhir *et al.* 2019, pp. 3, 8. David Keith is aware of the risk that 'air capture may reduce the amount of mitigation in the short run' and appears to accept it. Keith, Minh and Stolaroff 2006, p. 36.

45 The trend was duly noted in Elliot 2020.

46 ExxonMobil 2019; Soltoff 2019.

47 Siegel 2018.

48 Krauss 2019; Rathi 2019.

49 Kobayashi-Solomon 2019a.

Alone in the triumvirate, Climeworks has made it a *point d'honneur* to refuse money from this corner. Perhaps reflecting Atlantic divides, the Swiss chafe at their North American competitors' avidity for oil and gas funding – 'you obviously have a very big interest from fossil sources to make their waste green', and this 'kind of colours our industry.'⁵⁰ When Climeworks acquired Antecy, a minor DAC venture in the Netherlands collaborating with Shell, the fraternisation was officially terminated. But Climeworks has had no compunction about partnering with Audi and Lufthansa.⁵¹ As for Shell, it has put some eggs in Lackner's basket: in 2018, the corporation commenced funding of his Arizona labs.⁵² Total picked a lesser known start-up headquartered in Cambridge.⁵³ Over in Qatar, the state sought to move into 'the spotlight as a country that takes climate change seriously' by transforming air-conditioning systems into DAC apparatuses, with the assistance of its largest foreign investor, Qatar Shell.⁵⁴ Saudi Aramco has caught wind of the prospects too.⁵⁵ When he laid out plans for making DAC a pillar of the Kingdom in July 2020, energy minister Prince Abdul Aziz bin Salman Al-Saud offered a succinct declaration: 'Carbon is not the enemy.'⁵⁶

It should be kept in mind that, so far, the money spent on DAC by these investors is a nugatory fraction of the sums poured into ever-expanded extraction of oil and gas. Fossil capital seizes this productive force *in utero* for its ideological services.⁵⁷ They can be bought on the cheap, since what matters is the appearance of a progression towards harmlessness – quite possibly in response to the progress of the climate movement. The latter's crest of mobilisation in the years 2018–19 coincides neatly with the rush to DAC. But there is also another possibility: if the climate emergency reaches a political tipping-point of a different magnitude and states gather the resolve to start sealing wells and mines, a parallel infrastructure under development might help to keep them open.⁵⁸ Then it would be a matter of colossal upscaling. For such an eventuality, know-how would have to be acquired. Fossil capital would here be

50 Interview with Climeworks representative.

51 Audi USA 2014; Delamaide 2020a.

52 Center for Negative Carbon Emissions 2018.

53 Total 2020. Name of start-up: Cambridge Quantum Computing.

54 Al-Taie 2020.

55 See Saudi Aramco 2020a.

56 Kane 2020.

57 For another example and elaboration of this dynamic, see Carton 2019.

58 In the convoluted words of Fiona Wild, vice president for sustainability and climate change at BHP: 'This [investing in DAC in general and Carbon Engineering in particular] is about recognizing that climate change poses significant risks to all economic sectors. Climate change is no longer seen as a fringe issue. It's a business risk that requires a business response.' Krauss 2019. Or as Lackner himself puts it: 'Oil companies' entire business

hedging against ‘stranded assets’: shielding itself against a coming mass liquidation of property. But DAC not only protects old branches of accumulation. It sprouts brand new ones too.

4 Brave New Carbon Economy

When CO₂ is purified upon capture, the owner faces the choice of what to do with it. All of it can be entombed underground, locked out of the carbon cycle for something like eternity, never to be touched again. Or it can be utilised in the production of commodities. In Hinwil, the CO₂ is ferried off to a Coca-Cola plant, where it gives the fizz to soft drinks; a domestic producer of mineral water, extracted from alpine sources and sold in suitably green PET bottles, likewise purchases the sparkle from the air. Some is piped into a nearby greenhouse for enhanced fertilisation. None is stored, and this holds for every DAC plant currently in operation, except the one in Iceland; but beverages and vegetables can only swallow a limited amount of CO₂. ‘The next big thing’ for Climeworks and others in the business is synthetic fuels, or synfuels: making the pure CO₂ react with hydrogen and other commonly occurring substances and refining it into copies of diesel and gasoline. Indeed, any fuel hitherto derived from subterranean reservoirs could potentially be supplanted by a fuel whose carbon is plucked out of thin air.

This alchemy has a century-long tradition. It began in Germany, where manufacturers sought to substitute for imports by transmuting ‘virtually their only abundant domestic raw materials – coal, water, wood, earth, and air – into one synthetic compound after another’, such as nitrogen, rubber, fibres, explosives, poison gases and, last but not least, hydrocarbon fuels.⁵⁹ Churning out such fuels in the absence of oil riches became an overriding concern of the Third Reich, which in 1934 inaugurated the first plant employing the Fischer-Tropsch process for converting elements of coal into liquids. Starved of the black gold, the Nazis had to figure out how to synthesise its own surrogates by pressing the famed inventiveness of the nation’s chemical industry to new heights. After the war, this torch was carried forward by the South African apartheid regime, likewise cut off from oil; Sasol, the company that provided its energy base, continued to perfect techniques for liquefaction. On the shoulders of these two

model will fall apart if carbon dioxide cannot be recovered from the atmosphere and environmental carbon constraints become more severe.’ Lackner and Jospe 2017, p. 87.

59 Hayes 2001, p. 1.

giants, synfuel industries now stand.⁶⁰ 'As shown by Germany during World War II and by South Africa during apartheid, manufacturing artificial gasoline is readily doable', Broecker waxed hopeful.⁶¹ DAC companies and their partners in oil, gas, auto and aviation experiment with the Fischer-Tropsch process and other reactions to optimise the transmogrification of air into fuel, dispatching a steady stream of progress reports. Climeworks' biggest coup so far is a deal with a Norwegian consortium to build the first plant for producing fossil-free jet fuel. A combination of the Swiss filters, Norwegian water and wind and the Fischer-Tropsch formula will, from 2026, if things go according to plan, allow planes to fly on ether.⁶²

Synfuels hold a key for unlocking one of the largest markets in world capitalism to DAC. Planes, cars, trucks and ships could all switch to synfuels, chemically identical to what came before them, with no need for retrofitting – let alone retirement – of vehicles. In the vision of Climeworks, this is the supreme deliverance from 'abstinence': wherever we wanted to go with fossil fuels, we can soon go with air.⁶³ Serving the incumbent technomass with climate-neutral energy is an ambition of some vintage. Lackner envisaged his auxons producing hydrocarbon compounds 'to accommodate existing consumption patterns'; Eisenberger wished to 'enable us to drive our cars while cooling and fertilizing the planet'.⁶⁴ The approaching deadlines of climate breakdown and the seemingly absolute inertia of the reigning infrastructure have now made this a hot pursuit. Onto the stage storms Rob McGinnis, dressed in the Silicon Valley uniform of jeans and black t-shirt: he promises to sell gasoline made solely of air, water and electricity in American gas stations already in 2021. He says it will be as cheap as the fossil variety. It could crowd out the lot of it. McGinnis has some experience of mammoth projects and removal exercises; during the first Iraq war, he cleaned mines from battlefields and harbours in the Gulf.⁶⁵ The start-up he owns, aptly named Prometheus, received a financial shot in the arm from BMW in the summer of 2020.⁶⁶ Whether that will suffice to overturn the gasoline market remains to be seen, but it is now clear that McGinnis is one DAC capitalist among many readying to save the world by means of wondrously aerial merchandise.

60 On Sasol, see the chapter 'Sanctioning Apartheid' in Jones 2015, pp. 52–92; for an overview of this German–South African chemical history, see Leckel 2009.

61 Broecker 2013, p. 3.

62 Grasso Macola 2020; Delamaide 2020b.

63 Beuttler, Charles and Wurzbacher 2019, p. 5.

64 Lackner and Wendt 1995, p. 77; Eisenberger 2014, p. 985.

65 Service 2019; for the technical details of his ambition, see McGinnis 2020; for the futurism of Prometheus, visit <prometheusfuels.com>.

66 Malewar 2020.

They call themselves ‘air miners’.⁶⁷ Forming a distinctive ‘space’ – the generic business term for a community of start-ups, researchers and investors, reeking of air-conditioned conference rooms and slick pitches – they throw out one commodity after another. One New York-based outfit has tied CO₂ into polymers and manufactured sneakers, spotlessly white, designed for the finest boutiques: the first ‘shoe without a footprint’ (courtesy of some financial assistance from NRG Energy, which runs nearly 100 fossil-fuelled power-plants in the US). A German enterprise fabricates foam for mattresses (‘Sleep on carbon dioxide? Absolutely!’). Air Protein™ cooks ‘the world’s first air-based meat’; Air Co. goes for vodka, Novo Nutrients for fish feed. Two companies claim to be compressing air into diamonds. One, Go Negative, tells customers to pre-order a sooty, black bracelet of mineralised CO₂, possibly a rather narrow niche market; more money awaits in the construction sector. Made of Air, Carbon Cure, Carbon Infinity are some of the ventures developing concrete, steel, plastics, graphite and other building materials downstream of DAC.⁶⁸

Because of the versatility of purified CO₂ – all manner of carbon-based compounds can be coaxed out of it – the prophets of this ‘space’ see new life being breathed into industrial capitalism *in toto*. There will be no end to the gains in revenues and jobs.⁶⁹ Goldman Sachs shares in the excitement; albeit still a ‘wild card’, DAC is nothing short of the ‘key technology’ to decarbonisation, since it is ‘almost infinitely scalable and standardizable’.⁷⁰ Modules can be placed wherever there is air. No more outlays on locating oilfields or elongating pipelines: the all-purpose raw material can be downloaded from above.⁷¹ Since the CO₂-rich atmosphere is distributed with gracious evenness around the globe, this would inaugurate an era where natural-resource endowments cease to matter – in Marxian terms, the eradication of ground-rent – placing plenitude at anyone’s fingertips. When we spoke to Nicholas Eisenberger, next to his father in the hierarchy of Global Thermostat, he laid out the company’s trajectory from fizz to steel and ‘tons of other things’ and predicted that word would eventually reach ‘somebody in the Kalahari Desert. A bush

67 See for example the website ‘AirMiners: The Index of Companies Mining Carbon from the Air’, <airminers.org>.

68 See, in order of mention, <10xbeta.com>, <covestra.com>, <airprotein.com>, <aircompany.com>, <novonutrients.com>, <adadiamonds.com>, <aetherdiamonds.com>, <gonegative.co>, <madeofair.com>, <carboncure.com>, <carboninfinity.com>. In anticipation of the technology’s imminent take-off, some of these companies currently depend, it should be noted, on carbon captured at smokestacks.

69 See, for example, Larsen, Herndon and Hiltbrand 2020a; Larsen, Herndon and Hiltbrand 2020b; Circular Carbon Network 2019.

70 Goldman Sachs 2019, pp. 16, 5.

71 See, for example, Gertner 2019; Lackner, Brennan, Matter *et al.* 2012, p. 13160; Keith 2009, p. 1655.

tribesman' could create his own air-based emporium.⁷² Futurist tech guru Peter Diamandis has foreseen the logical next step: 'beyond Earth-bound utility, DAC could hold countless vital applications in extra-planetary ventures. With a 98 per cent CO₂ atmosphere, Mars could be an ideal target for DAC, not to mention an optimal source of needed commodities.'⁷³ Believers in fully-automated luxury communism may have some material to work with here.

This is capitalism at its most dizzyingly creative and disarmingly charming. Like a perpetual Cambrian explosion, it tries out product after fabulous product, some of which will surely turn out dead ends. But who can dismiss the conjuring powers of capital? One of the productive forces that did most to revolutionise human metabolism in the twentieth century was, after all, a method for picking the fruits of the air: the Haber-Bosch process, foundation of the Green Revolution. In the early twenty-first, the air miners are the latest crop of entrepreneurs to seek to turn the climate crisis into – as the cliché goes – an opportunity for a new wave of capitalist development, more expansive and all-encompassing than anything prior. In *Planetary Improvement: Cleantech Entrepreneurship and the Contradictions of Green Capitalism*, a careful ethnography of the 'space' of clean tech, of which DAC is an outgrowth, Jesse Goldstein reminds us that we have been here before: wind, solar, algae, smart grids, nano-materials have been heralded as the dual-purpose engines of environmental redemption and rejuvenated growth. Many of the boosters he portrays read *Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages* by Carlota Perez, leading exponent of the Schumpeterian theory of long waves of capitalist development, in whose mirror they could see themselves.⁷⁴ As for the Marxist version, Ernest Mandel emphasised that only 'fundamental revolutions in power technology' – entirely 'new machine systems, based on different sources of energy' – have the propulsive force to give capitalism another of its nine lives, as they alone can penetrate into every sphere of commodity production.⁷⁵ Who can rule out carbon from the air as one more such impetus?

But this is also, of course, capitalism at its most stunted and superstitious. If a fundamental paradox of bourgeois modernity is the ever-increasing power to manipulate natural systems and the ever-decreasing capacity to influence

72 Interview with Nicholas Eisenberger, 2 June 2020.

73 Diamandis 2019.

74 Goldstein 2018, p. 24. It should be noted that many of these cleantech resources are again boosted in conjunction with DAC, including algae, on which see, for example, Wilcox, Psarras and Liguori 2017, pp. 1–7.

75 Mandel 1978, p. 118; Mandel 1995, p. 112.

social ones, then the air miners are its most fervent priests.⁷⁶ They combine boundless technological voluntarism with bottomless resignation to political fate. A hundred little Elon Musks, they are working for, as Goldstein puts it, ‘a totally transformed future that will look very much like the present’ – or, as one of his informants divulges: ‘we want to deliver a solution without changing the world.’⁷⁷ But they operate under a darkening sky and are cognisant of it, their confidence bound to a creeping despair about the state of the planet (a motive, Goldstein stresses, not to be written off as affectation). That combination brings to mind Walter Benjamin’s notes on capitalism as a ‘purely cultic religion, perhaps the most extreme that ever existed. Within it, nothing has meaning that is not immediately related to the cult’, whose sole dogma, if there is one, he identifies as ‘utilitarianism’. Whatever can be used must be used to make more money, as in the mandatory rituals of a sect. At the same time, capitalism is ‘the expansion of despair, until despair becomes a religious state of the world in the hope that it will lead to salvation.’ On this ‘passage of the planet “Human” through the house of despair’, there arises a new divinity: the ‘superman’. He is there to allay ‘anxieties, torments and disturbances’. He is the man of object control, ‘the man who has arrived where he is without changing his ways; he is historical man who has grown up right through the sky.’⁷⁸ Right through the sky: the religious features of DAC ideology are manifold: the magic, the will to believe, the millenarian wait for miracles (‘energy miracles’, in the parlance of DAC investor Gates), the fetishism, the levitation, the taking-away of sin, even the ecstatic abrogation of law.⁷⁹

5 Sequestering Exchange-Value

Whatever else direct air capture and utilisation is, however – and this is certainly the heart of the matter – it is not sequestration. It does not remove any carbon dioxide. If you drink a Coca-Cola with fizz collected in the balloons of Climeworks, you will burp the CO₂ back into the air before long. Synfuels

76 Insightful reflections on this paradox can be found in several contributions to Biro (ed.) 2011, not least the editor’s introduction.

77 Goldstein 2018, pp. 64, 27. Cf. for example pp. 141, 157. DAC proponents, however, are not entirely boundless in their technological voluntarism: the case for their favoured tech is commonly built on a dismissal of the potentials for rapid, large-scale uptake of solar and wind. It is because you cannot quickly roll out renewables and let them replace fossil fuels that DAC is needed. What holds together this specific combination of techno-pessimism and optimism is, evidently, an overarching care for the current economic order and its freedom from disturbances.

78 Benjamin 1996, pp. 288–9. For an illuminating exegesis, see Löwy 2009.

79 See, for example, Biello 2016.

return the gas to the atmosphere in the moment of combustion. Bracelets may hold it for some years or even decades, but there will be wear and tear and losses, as such finery is not meant to be hidden away in chests. ‘Certainly it represents a beguiling opportunity – convert a waste product into high-value end products’, one research team observes in *Nature Climate Change*, in the tone of muted exasperation characteristic of the finest climate science; but the vast preponderance of the utilised CO₂ ‘is immediately released into the atmosphere’, and so this whole business is ‘highly unlikely to ever be a realistic alternative to long-term, secure, geological sequestration.’⁸⁰ If there is a biological metaphor for what is going on here, it would be autocoprophagy.

Now there is a pragmatic reason for a DAC capitalist to choose utilisation over sequestration of his captured resource: the latter bears no exchange-value. Laying the CO₂ to eternal rest means, by definition, to forfeit it. Inside the tomb, it is not a commodity on the market: it is a negation of the commodity form – or, in the dispassionate terms of two scientists of chemistry and energy: ‘By its very nature, this has no commercial value.’⁸¹ DAC companies are here left in a conundrum. Their supposed *raison d’être* has scant prospects for realisation in the space of property relations in which they are caught. When we spoke to Nicholas Eisenberger about shifting from utilisation to sequestration, he likened the latter – an analogy inevitable after Covid-19 – to a vaccine. The following exchange ensued:

WC & AM: Just to stay with the analogy here. If you have a vaccine, you have a product for which there would be huge demand, obviously.

NE: Yeah, exactly! Fucking climate change, stop the planet from melting. Huge fucking demand.

WC & AM: But in this field, what’s the product that you can turn into a market opportunity?

NE: I don’t mean to be cheeky here. Life. On earth.

80 Mac Dowell, Fennell, Shah and Maitland 2017, pp. 244–6. Cf. Bruhn, Naims and Olfe-Kräutlein 2016. One should note that this capitalist vision and emerging praxis of utilisation depart from how negative emissions figure in IPCC reports. There the model is one of ‘overshoot’ and reversal – a threshold of CO₂ emissions is first exceeded, after which their rapid decline is paired with large-scale sequestration to stay below a certain temperature level. With pure utilisation, one instead gets overshoot and some potential substitution of fossil fuels with synfuels and other fancy commodities; but without sequestration, the peak is followed by a grand stagnation of excess carbon.

81 Majumdar and Deutch 2018, p. 808.

WC & AM: Sure, but is that something you can sell?

NE: Let's just stick with that. What else can it be. What else can you sell? That's a great quote, I love it. So unbelievably absurd, that's the leap we haven't made, right there, you just said it – life on earth, is that something we can sell? That's our problem, that's where we're stuck.

As the two founders of Global Thermostat have noted, a lowered atmospheric concentration of CO₂ is a public good without boundaries.⁸² If a DAC industry in the US were to reduce it to 350 ppm, the same boon would extend to Mozambique and Qatar and every other country on earth; there is no available course for enclosing it on a national, let alone private estate. What is perfectly feasible, however, is to distil the captured CO₂ into commodities for private sale and consumption – or, in the words of Prince Abdul Aziz bin Salman Al-Saud: 'Carbon is a resource. It is not something that we should just throw and just emit it. Actually, capturing it lets us make money out of it' – a corollary of, or perhaps footnote to, the credo spelled out by Rex Tillerson when he was CEO of ExxonMobil: 'My philosophy is to make money. If I can drill and make money, then that's what I want to do.'⁸³ DAC here opens the horizon for turning the effluent from that drilling into kindling for more accumulation, igniting an epiphenomenal loop on top of fossil capital: after two centuries of self-expanding value passing through the metamorphosis of fossil fuels into CO₂, we can now also have the metamorphosis of CO₂ into practically any commodities, melting all that is in the air into solid gold – capital as auxon, feeding on and replicating itself *ad infinitum*.

This, at least, is the future segments of fossil capital have in sight. In the video promoting the 'footprintless' sneaker, we see one representative of NRG Energy standing in her office high above a vista of smoking chimneys, a mix of unease and thrill in her eyes, asking: 'How do you take this byproduct, CO₂, and turn it into something useful?'⁸⁴ Saudi Aramco claims to have a newfound focus on 'converting emissions to value' – which does not, of course, imply a cessation or even a slowdown of the former.⁸⁵ In the 'circular carbon economy' to which this corporation is now committed, the doxa is 'carbon *management* as opposed to *elimination*!'⁸⁶ And why would something so useful be kept in

82 Chichilnisky and Eisenberger 2009, pp. 432–3.

83 Kane 2020; Rose 2013.

84 NRG 2016.

85 Saudi Aramco 2020b.

86 International Energy Forum 2020, p. 5; emphases in original.

check? ‘Valuing the waste’, Holly Jean Buck has remarked, ‘normalizes production of it.’⁸⁷ In this circle, the upper arc of capture refuels the lower arc of ever-deeper extraction.

The most concrete form of this circularity is the practice known as ‘enhanced oil recovery’: injecting pure CO₂ into nearly-exhausted oil fields, so as to increase the pressure from below and extract the remaining barrels. Occidental has excelled in this technique. Taking CO₂ from naturally occurring reservoirs, the corporation has for years been squeezing out an extra 25 per cent from fields nearing depletion: and now there is a further incentive. When purchasing CO₂ from Carbon Engineering and pushing it under the oil, Occidental can claim 45Q tax credits.⁸⁸ Together with investment firm Rusheen Capital Management, the two in August 2020 launched ‘1pointfive’, a joint venture that wants to construct the world’s largest DAC plant. Suitably situated in the middle of Texas oil country and scheduled to start construction soon, it would capture 1 million tons of CO₂ every year. Much of it would be directed into oil wells, the bulk staying under the ground. If more remains than what comes up with the extracted oil, the net result is drawdown – *voilà*, carbon-negative oil! But if this is a profitable practice, it will give oil companies more money with which to expand their operations – explore, drill, extract afresh and farther afield; not a winding-down of the industry, but a new lease on life. In the words of Occidental, investing in DAC ensures that ‘fossil fuels have a role in the energy portfolio of the world long term.’⁸⁹ It means greater quantities of oil reaching the surface. It goes without saying that this increases the total burden of CO₂ to carry. Saudi Aramco brags about having ‘doubled oil production rates from four of our wells’ after commencing injection of captured CO₂ in 2015; with more capture, the feat can be extrapolated.⁹⁰ Here is another giant market for DAC to enter. Upwards of 90 per cent of the world’s oil reservoirs are thought suitable for enhanced recovery.⁹¹ The CEO of Occidental, Vicky Hollub, has her eyes on a denouement of sorts: ‘The last barrel of oil that’s produced in this world should be from CO₂-enhanced oil recovery’ and *après moi, le déluge*.⁹²

87 Buck 2020, p. 3.

88 Temple 2019b.

89 Davis 2020.

90 Saudi Aramco 2020b. This CO₂, however, is captured not from the air but from the Aramco plant in Hawiyah.

91 Mac Dowell, Fennell, Shah and Maitland 2017, p. 245.

92 Rathi 2019.

6 A Bridge to Nowhere

In enhanced oil recovery, the lines between utilisation and sequestration are blurred. They are blurred further in the future outlook prevalent in this 'space'. The thinking entrepreneurs seem to agree that the telos of DAC is actual, permanent removal that will ultimately bring the CO₂ concentration down. But how do you get there from utilisation? You walk hurriedly on it as on a bridge: DAC companies sell CO₂ to manufacturers of fire extinguishers and frozen food and any other little product that needs the substance, demonstrating the viability of the tech in a plethora of niches; next they learn to substitute for other materials, such as gasoline and meat; oil corporations thirsty for enhancement provide fillips to the operations, which increase in scale; costs plummet; skills accumulate; the number of DAC plants increases by leaps and bounds, until they are potent enough to begin mopping the atmosphere for real.⁹³ In Nicholas Eisenberger's blunt terms: 'I almost don't care how you do this, whether it's durable carbon or not – you've just got to get more practice in. You've got to shoot more goals, and just get better and better.' Somewhere down the line, DAC will have amassed the force to flip on planetary-scale sequestration.

While this rests on a not unrealistic assessment of how technological development might proceed under capitalism, it begs one question: what is to say that an economy adjusted to utilising CO₂ will – at that very point – let go of it? If recycled or 'upcycled' CO₂ really were to diffuse throughout the lines of commodity production, there would presumably be an interest in continuing to drink from this well. If the world's aviation industry begins to fly on syn-fuels from Climeworks, it would scarcely be thrilled about having that resource suddenly reallocated to the nether regions – not a way to sustain a wave of capitalist expansion. It is rather as if the manufacturers of steam-engines, prime movers of the first such wave, conspired to start blowing them up in the moment of their widespread adoption. The risk, in other words, is that DAC will never cross over to the other side.⁹⁴

CO₂ from air can maybe, hypothetically, power an upswing of world capitalism, and it can conceivably roll back the atmospheric concentration – but can it ever do both? Two conditions would have to be fulfilled. First, there would have to be zero energetic and material constraints on expanding DAC technology, so that sequestration would not have to deduct from what has been built for commodity production; the switch could then be an add-on. Such

93 For example Ishimoto, Sugiyama, Kato *et al.* 2017, p. 12; McQueen, Psarras, Pilorgé *et al.* 2020, pp. 7543, 7548; Wilcox 2020; Elk Coast Institute 2020, p. 21.

94 Cf. Mac Dowell, Fennell, Shah and Maitland 2017, pp. 247–8; Buck 2020, p. 3.

a thing could happen in a world of total air cornucopia. We shall presently inspect how realistic the assumption is. Second, there would have to emerge some mechanism for taking the crucial step into burial on an astronomic scale. Where could it come from?

For the time being, Climeworks, the sole DAC company with a single sequestration facility, has to rely on a thin method for profiting from it: offering individuals and companies with spare cash to pay for CO₂ to be removed, just for the sake of it. In the web shop, customers can subscribe to get 740kg of stone sunk into the ground over a year, or – for the more magnanimous – specify a higher amount. They can purchase gift cards to get ‘their loved ones started on their journey to climate positivity’: printable from any device, a certificate of 7kg permanently removed per month. This, of course, is virtue shopping. There is no commodity involved other than the knowledge that one has financed the burial of a sliver of mineralised CO₂. How far can it bankroll sequestration? Will the rich of the world pick up the cheque for ‘life on earth’, much as they have acquired a taste for Tesla (a model for Climeworks)? Will companies like Amazon and Rolls Royce voluntarily flock to DAC providers to negate their own emissions, driving the growth of a massive removal market that can begin to turn the tables on the atmospheric concentration?

Some of the air miners certainly seem to think so. A group calling itself ‘Tomorrow’s Air’ recently partnered with Climeworks to help ‘passionate travellers’ clean up after themselves, with the ambition to ‘keep the joys and benefits of travel possible’. They are part of a trend that goes beyond DAC, encompassing all kinds of carbon-removal methods. In Finland, an organisation called Puro has launched what it claims is ‘the world’s first carbon removal marketplace’, making it possible to ‘neutralize your emissions today’ by investing in biochar and negative concrete. In the US, the start-up Nori has attracted considerable attention by selling carbon-removal credits from soil sequestration. Its website promises to ‘remove your carbon footprint’ for a period of your choosing; those with a particularly troubled conscience can buy off their guilt for the past five years.⁹⁵ All of this, evidently, is just one more way for the well-off to offset their emissions, the latest in a long lineage of ever more creative ways to avoid ‘abstinence’.

Climate politics has a curiously short memory. In deepening distress over its failure to dent the emissions curve, it keeps stumbling upon the same solutions, seemingly oblivious to their familiarity. Back in the early 2000s, it already had an encounter with the offsetting market. The enthusiasm at the time was exuberant. Major banks such as Barclays proclaimed that carbon markets would grow to a value of \$1 trillion within the decade and eventually become ‘the

95 See <tomorrowsair.com>; <puro.earth>; <nori.com>.

world's biggest commodity market, if not 'the world's biggest market overall'.⁹⁶ In surveys carried out by Ecosystem Marketplace, an initiative that assembles information on this breed of fictional commodities, entrepreneurs uniformly proclaimed their faith in a steadily growing voluntary-offset market. By 2020, they prophesied, it could be trading up to 2.3 billion tons' worth of offsetting promises.⁹⁷ The reality turned out to be decisively more underwhelming. As belief in the capacity of politicians to tackle the climate crisis took a beating following the 2009 debacle in Copenhagen, so too did offset markets. What followed were years of credit oversupply, low prices, stagnation. The Clean Development Mechanism, or CDM – the UN's official, flagship offsetting market – turned into a drawn-out farce.⁹⁸ The market lost its sparkle but somehow refused to fizzle out completely. Now, with renewed climate urgency and the arrival on the stage of DAC and its carbon-removal cousins, it beckons once more. Polished and rebranded, carbon offsets have begotten a second life, but are they in any better shape than before?

In some ways, DAC has a clear advantage over its peers: it offers capital near-total control over the conditions of carbon removal. With DAC comes a solution to 'the problem of nature' that has long plagued the offsetting industry: the inevitable reversibility of biological sinks that keeps undermining claims of permanent sequestration; the long timescales it takes for trees to deliver; the unending uncertainties of accounting for carbon bound in vegetation.⁹⁹ From this vantage point, DAC appears like offsetting 2.0, the next frontier for 'ecosystem service' markets. Some of the technology's prophets – starting with Lackner – have long eyed such markets as a fount of finance.¹⁰⁰ In a previous life, Chichilnisky of Global Thermostat worked as an ideologue on their behalf; having contributed to the design of CDM, she has proclaimed herself the 'architect of the Carbon Market of the Kyoto Protocol' and repeatedly advocated for the inclusion of negative-emissions technologies in this very market so as to rescue it from redundancy. DAC would help achieve all that CDM initially promised but then failed to deliver – including, unsurprisingly, helping 'poor nations; they can capture more carbon than they emit' and sell the credits.¹⁰¹ Chichilnisky's altruistic dreams, however, seem to face some rather material obstacles. The offset market is awash with dirt-cheap offsetting

96 Kanter 2007.

97 Hamilton, Bayon, Turner and Higgins 2007; Peters-Stanley and Yin 2013.

98 For the critique of carbon-offset markets, see for example Lohmann 2009; McAfee 2012; Cames, Harthan, Füssler *et al.* 2016.

99 Cf. Boyd, Prudham and Schurman 2001; Prudham 2003; Mackey, Prentice, Steffen *et al.* 2013.

100 Lackner, Ziock and Grimes 1999, p. 11; Lackner, Wilson and Ziock 2001, pp. 35–7.

101 Chichilnisky and Sheeran 2009, pp. 6, 52–75, 108–11.

techniques and populated by actors infamous for their attempts to cut corners. Competing on these terms would require a drastic drop in DAC prices. Climeworks is currently selling offsets at the equivalent of €980 per ton of CO₂ (approximately what is emitted on a single return flight from London to New York). It is a well-endowed believer that opts for the deluxe DAC option over any of the budget virtue-signalling alternatives on offer. Here is another bridge to nowhere: direct air capture as the latest instalment of offsetting, the institutionalised mitigation deterrence that never goes out of fashion. For all its novelty, DAC appears as so much more of the same.

7 Suspended in Question Marks

Capital secretes fantasies about transcending the laws of matter and accumulating *in vacuo*. It projects an image of itself ‘as a power springing forth from its own womb’; but some way or other – and the ecological crisis represents a myriad of routes – it is brought down to earth.¹⁰² This will likely apply to DAC too. Can it become a closed loop of extracting the air by means of nothing but air? It comes up against a thermodynamic hurdle: the energy expended on removing a substance is, as a rule, inversely proportional to its concentration. Splitting carbon out of fine crude is easily done, since there is so much of it condensed in the liquid, but CO₂ molecules fly in the air like soot flakes in a gale: catching them demands effort. While DAC companies have disproven the pessimists who deemed this impossible, the process still consumes prodigious amounts of energy, in two phases in particular. Moving the air through the machines requires electricity, and CO₂ can be separated from the sorbent only if there is an influx of heat. The lower the heat requisite for the sorbent to give up its catch, the greater the efficiency; Climeworks and Global Thermostat have leapt ahead by pushing it below 100°C, which allows them to run on waste heat from industrial processes – the treatment of garbage from Zürich, in the case of Hinwil – of which there is no shortage. Where similar slack is absent, pumps or collectors powered by the sun can provide heat at these temperatures, which might, as the tech advances, be reduced further.¹⁰³ But even the cleanest of ovens do not, of course, come for free. DAC could tie up a significant share of the energy supply for process heat alone.¹⁰⁴ What of the electricity?

102 Marx 1991, p. 966.

103 See for example Creutzig, Breyer, Hilaire *et al.* 2019, p. 1809.

104 115 per cent of current natural (i.e. fossil) gas consumption, in the models of Fuhrman, McJeon, Patel *et al.* 2020, pp. 5–7.

All crystal balls are hazy, but some point to a massive chunk of power generation set aside for DAC, if it is to reach a scale that can affect the climate. To take down 30 gigaton of CO₂ per year – and thereby, on some assumptions, hold global warming below 2°C – it might, come the year 2100, gobble up electricity equivalent to more than half of what is produced in the world today.¹⁰⁵ Other estimates are starker still: a mere 1 gigaton per year could consume electricity on a par with what the US produced in 2017.¹⁰⁶ This may sound like a preposterous voracity, but it is worth noting that studies like this assume DAC being used to compensate for significant continued fossil-fuel combustion. A more radical fossil-fuel phaseout would reduce the scale of required removal; together with improved performance, it could help limit the electricity demands.¹⁰⁷ But if the goal is to remove past emissions rather than ‘just’ stabilise temperatures at 1.5 or 2°C, the scale tilts precipitously in the other direction again – the pile of historical stones being considerably larger. The process of removing them would need to be gradual, allowing energy demands to be stretched out over decades or even centuries.

Needless to say, a minimally rational world would shift to 100 per cent renewable electricity long before 2100. DAC in fact depends on it, because feeding it with fossil energy means so much more emissions to remove, forever chasing the tail.¹⁰⁸ Once renewables take over, however, there is room for manoeuvre. Grids that run exclusively on solar and wind are periodically inundated by a surfeit of electricity – days when there is no cloud in sight, or the wind is fierce, or both – and DAC units, particularly of the small-scale, modular kind, can be switched on at a moment’s notice. Spread across continents, on stand-by for sunny and windy days, they can shave off the surplus from the grids and use it for drawdown, gigaton by gigaton. Regions blessed with more sun and wind than anyone can exploit are poised to serve as DAC havens.¹⁰⁹ While this does not resolve DAC’s energy problem, it provides an opening for making it manageable.

If the curse of utilisation is lifted, where would the CO₂ be interred? Oil companies have, as we have seen, long injected it into aquifers. Depleted oil and gas reservoirs would be another option. Revenant of the fossil economy, the CO₂ could remain mobile for centuries down below. If the rock serving as the cap is stable and impermeable, it will stay; if not, it could seep to the surface, with potentially lethal consequences. Spectral and unexpected,

105 Realmonte, Drouet, Gambhir *et al.* 2019, p. 7; Chatterjee and Huang 2020, pp. 1–3.

106 Sekera and Lichtenberger 2020, pp. 1–28.

107 Creutzig, Breyer, Hilaire *et al.* 2019; Realmonte, Drouet, Gambhir *et al.* 2020.

108 Creutzig, Breyer, Hilaire *et al.* 2019; Chatterjee and Huang 2020.

109 Wohland, Witthaut and Schleussner 2018; Breyer, Fasihi and Aghahosseini 2020.

leaks of concentrated CO₂ have a way of catching their victims unawares. If they were to become frequent in a world of sequestration, the whole exercise would risk being defeated, but there are methods for keeping the lids in place – informed selection of reservoirs, reinforcement of caprocks, continuous monitoring – which is why this has become a routine procedure in the hidden abodes of oil production, so far without major mishaps.¹¹⁰

And then there is a safer insurance at hand: mineralisation. Stones do not seep. Several types of rock react with CO₂ and integrate it into their bodies, solid and immobile. In Iceland, the project to which Climeworks has attached its brand uses geothermal heat to drive the capture and then shoots the CO₂ into basalt rocks, where it turns into stone – not after centuries or millennia, as sceptics had forecast, but within less than two years.¹¹¹ Oman is another Eldorado awaiting the rush. Here a type of coarse rock that goes by the name of peridotite is exposed to the surface, where it drinks CO₂ like a sponge. If that natural process were to be accelerated and the Omani massif drenched in CO₂, the sultanate – some future for ground-rent in a carbon-negative world – could submerge a fair share of the emitted carbon.¹¹² Similar scraggy outcrops are found in Papua New Guinea and New Caledonia. By far the most common substratum for mineralisation, however, is basalt, which covers some one tenth of continental surface area and most of the ocean floor. To that could be added the mine tailings dotting the earth after the extraction of elements like nickel and platinum and diamonds. Highly reactive soups, they can be stirred to imbibe additional CO₂ (the world's leading diamond company, De Beers, founded by Cecil Rhodes, is gearing up for reuse of its tailings: there glitter carbon-negative jewels).¹¹³ Coal seams could have a brightening future too.

On this score, the constraints would indeed be few: ample geological stores wreathe the planet, not least its two largest economies, the US and China. The current consensus in the literature and 'space' alike is that storage capacity does not pose a limit to sequestration. There is enough room in the crust to fill it several times over with the stones from the past two centuries. But, again, getting the CO₂ into this state would not come without energy expenditure; depending on a number of variables – notably the need to grind or crush or otherwise treat the rock to make it more absorbent – mineralisation could

110 Kelemen, Benson, Pilorgé *et al.* 2019.

111 Matter, Stute, Snæbjörnsdóttir *et al.* 2016, pp. 1312–14; Kelemen, Benson, Pilorgé *et al.* 2019, pp. 2, 6, 14.

112 Kelemen, Aines, Bennett *et al.* 2018; Fountain 2018.

113 Mervine, Wilson, Power *et al.* 2018; Service 2020.

add its own hunger to the general demand.¹¹⁴ DAC plants would be built with steel and cement. They would require minimal land compared to BECCS, but build tens of thousands of them and they will certainly leave an imprint. Count in the land required to generate the required solar or wind energy, and the imprint quickly multiplies.¹¹⁵ Where would all the sorbents come from? Some are currently made with feedstock from fossil fuels; others are derived from renewable materials; none involve rare elements, but much of the minutiae is kept in the dark from science and society, as the start-ups obtain a competitive edge from the sorbents and jealously guard their secrets. How will they be disposed of when no longer recyclable? Heaps of those chemical sieves might be left lying around. When manufactured out of brine, they generate chlorine as a byproduct: how would several gigatons of that poison gas be dealt with? It became infamous as a chemical weapon courtesy of Fritz Haber and I.G. Farben. Ineluctably, an infrastructure on this scale – planetary by design and definition – will produce side effects in the biosphere, hard if not impossible to gauge *ex ante*.¹¹⁶

A forest of question-marks thus surrounds the universalisation of DAC. Some pertain to cost and price. The disheartening estimate of \$1,000 for capturing a ton of CO₂ circulated for some time.¹¹⁷ That was before Climeworks reached \$600 in Iceland (sequestration included), Carbon Engineering reported a span of \$100 to \$230 and Global Thermostat boasted of \$100, soon to be halved – and this without any company having initiated mass production.¹¹⁸ As of 2020, Climeworks still assembled its equipment by hand in essentially artisanal Swiss workshops. It is not an unwarranted belief that costs will bend downwards once manufacturing is transferred to assembly lines, automated and further pressed by refinements of a technology still in its infancy. Here is another advantage over BECCS: whereas the price of a captured ton will rise when land becomes scarcer, Ricardian style, the socially necessary labour-time for the production of DAC units will tend to fall, sharply, over the long run.¹¹⁹

But then there are uncertainties about maintenance and longevity and the cost of electricity, not to mention sequestration itself. One study ended up

114 Mac Dowell, Fennell, Shah and Maitland 2017, pp. 244–5; Kelemen, Benson, Pilorgé *et al.* 2019, p. 12; Fuhrman, McJeon, Patel *et al.* 2020, pp. 2–4.

115 Sekera and Lichtenberger 2020.

116 Gambhir and Tavoni 2019, p. 407; Realmonte, Drouet, Gambhir *et al.* 2019, pp. 7–8; Realmonte, Drouet, Gambhir *et al.* 2020, p. 1; Majumdar and Deutch 2018, pp. 806, 809; Creutzig, Breyer, Hilaire *et al.* 2019, p. 1808.

117 Based on House, Baclig, Ranjan *et al.* 2011.

118 The report of the cost-cutting feats of Carbon Engineering is Keith, Holmes, St Angelo and Heidel 2018. Climeworks: interview with representative; Global Thermostat: Soltoff 2019.

119 See, for example, Fasihi, Efimova and Breyer 2019; Creutzig, Breyer, Hilaire *et al.* 2019, pp. 1811–12.

in the ballpark of one to four trillion dollars for the storage of 125 gigaton of CO₂.¹²⁰ As of 2019, cumulative emissions since 1850 had reached 2,400 gigaton; by simple arithmetic, storing all of it could come with a mind-boggling price tag. Christian Parenti, author of the most cogent left-manifesto for DAC so far, has ventured the total figure of \$12 trillion for removing 40 gigaton – that is, \$12 trillion *every year* just to take back and sequester as much CO₂ as the world currently releases annually. But another scenario is ‘always more expensive’, he hastens to add. ‘That is permanent global economic collapse caused by rapidly rising seas, flooded coast cities, desertification of the globe’s key grain-exporting bread-baskets, colossal settlement-ravaging wildfires, proliferating disease, and attendant social breakdown.’¹²¹ Weighed thus, any removal technology might appear a bargain.

If this sounds like a challenge – energetic, material, environmental, logistical, financial – it grows larger by the day. The more fossil fuels are burnt, the more energy will be needed to catch the scattered soot. The higher the concentration of CO₂, the more Herculean the task to roll it back: the more sorbents to manufacture, scaffoldings to construct, reservoirs to locate, rocks to impregnate – the more resources, all in all, to feed into a sphere of the economy whose sole purpose would be to negate two centuries (or more) of climate destruction.¹²² Yet on the other hand, it is that very excess of CO₂ that calls for removal in the first place. We here approach what seems like a double bind for DAC. Imagine the concentration hits 1,000 ppm. At that point, removal by any means available – and this will include direct air capture – might be humanity’s best chance to cling to this planet. But by the same token, the enterprise would have become prohibitively expensive: it would consume so much productive capacity that little would be left for the species to live on. In more general terms, the curve of urgency will rise and that of feasibility fall, both linearly, for as long as emissions continue. It is relatively easy to go from 385 to 350, much harder to start from 450; but in the years of the former figure, carbon dioxide removal in general and direct air capture in particular did not appear exigent. This paradox has been known since the early musings of Hansen and Lackner.¹²³ The more critical the tech, the less likely that its mission can be accomplished. Its advocates can only hope that the curves cross at just the right time.

120 Kelemen, Benson, Pilorgé *et al.* 2019, p. 11.

121 Parenti 2020, p. 134.

122 See, for example, Supekar 2019; Friedmann 2019, p. 2.

123 Hansen, Sato, Kharecha *et al.* 2008, p. 14; Lackner, Brennan, Matter *et al.* 2012, p. 13161.

8 Seize the Means of Carbon Removal

An unavoidable question looms. We have seen how DAC is steadily proceeding in all the wrong directions – indeed has been doing so from its inception: rendering ideological and extractive services to fossil capital; feeding a frenzy of carbonous commodification where permanent storage appears as little more than an afterthought; burdening the planet with yet another source of phenomenal hunger for energy and resources and finances. Should we throw it out as a potential tool in the mitigation toolbox? Must the exclusive focus of the left remain on radical fossil-fuel phasedown, any suggestions for technological carbon removal rejected as buying into a sham? Or might there, despite all of the above, be use for DAC yet, provided we can detach it from its present capitalist perversions?

In Grant Price's *By the Feet of Men*, another of the dystopian cli-fi novels now ten a penny, northern Europe is a steaming sauna, overgrown by mutant vegetation and dotted with ruins, among which a smattering of humans scavenge to survive. Some descend into cannibalism. No price is too high for the most basic goods. Rumour has it, however, that scientists dug down in the deserts of Italy have developed a machine for reversing 'the Change'. A crew of half-decent men driving around subtropical Germany are assigned the mission to find and assist the scientists and bring their services to the world; but on their way south is a militarised wall. Behind it rules 'the Koalition'. With the help of 'artificial trees' and 'fan walls' and various other engineering feats, this corporate entity has managed to recreate pre-Change conditions on its Alpine turf. Anyone approaching risks being shot. Inside, the people labouring in factories bow to the tyrannic rule of the Koalition because the climate is at least bearable. 'But if we activate the machine, the land beyond the walls would become bountiful again. The Koalition's alternate reality would become obsolete. And they would lose their grip on the people.'¹²⁴ While muscular prose and a superfluity of post-apocalyptic violence make this a rather forgettable novel, it is noteworthy for delineating a faultline that might extend into the future: struggles over the means of carbon dioxide removal. At the start of the narrative, those means remain in private hands, but the crew is out to seize and socialise them.

In the case of DAC, 'we face', writes Parenti, 'what Marx described as a contradiction between the forces of production and the relations of production. The social relations of capital are now holding back the full potential of some of the most promising technologies that modern science has yet invented.'¹²⁵

¹²⁴ Price 2019, p. 67.

¹²⁵ Parenti 2020, p. 131.

This is, of course, some distance away from the orthodox rendering of the contradiction: DAC is not a motor of history about to smash through capital and drive humanity into communism. We are here offered a lesson *in media res* of the primacy of relations over forces. The historical sequence can then be crudely summed up: after having called forth productive forces that wreck the climate system, capitalist property relations are capturing another set of forces that could contribute to its stabilisation, so that they instead shore up those same relations and prolong the destruction to which they are prone. Here is, with Theodor Adorno, 'a simple reminder that the productive forces of technology are shackled and pushed in a very specific direction, and that the prevailing conditions prevent anything which might enable technology to break through this veil'. Instead of 'unswerving negation' – what negative emissions should be all about – we get one more way of 'sanctioning things as they are'.¹²⁶

Because capital has won the first round of climate struggles, for three decades successfully fending off threats to business-as-usual, we now face a second. It concerns not mitigation solely, but removal in addition. And precisely because 'this enemy has not ceased to be victorious', it is well-positioned to win again; while the climate movement and the left debate their strategies – Green New Deal or degrowth, full automation or rewilding, civil disobedience or sabotage – capital produces one *fait accompli* after another, soon likely to include a DAC plant coming to a roof or field near you. How can one keep up to speed with this machine? The first step must be to get on top of the ideology of it, and this means refusing to let any negative emissions, imagined or real, ever justify continued 'positive' ones.¹²⁷ There is an imminent danger that the entrance of DAC into climate models will excuse inaction in the short term, which is the one term that really matters; just like BECCS in the years of Paris, DAC is about to become the next illusion of a safe backstop. Decades hence, there will be a tech to sweep up the mess, so let's create more of it in the meantime: there is no exaggerating the irrationality of this gamble. Equally injudicious, not least from a thermodynamic perspective, is the notion of running two infrastructures in parallel – one for spewing out CO₂, another for washing it away – rather than just remodelling the first.¹²⁸ It would be resource squandering on an epic scale.

Winning the second round therefore demands a negation of its own, breaking the lame aspirations for DAC as waste management. Any headway in this round still rests on a total end to fossil fuels. The fact that there is too much CO₂

126 Adorno 2019, p. 136; Adorno 2014, p. 159. Cf. the analysis in Stuart, Gunderson and Petersen 2020.

127 Adorno would surely appreciate the vileness of the term.

128 See also Hamilton 2013.

in the atmosphere means precisely that there can be no more of it. Perhaps the greatest folly of banking on any substitute for ultra-radical emissions cuts is the presupposition that the climate system can be driven to a state of collapse and then wound back to the status quo ante, much as one turns a radiator up and down: but this system is not linear. If the West Antarctic ice sheet has drifted into the ocean or the Amazon rainforest desiccated, they will not be instantly resurrected by subtracting 10 or 50 ppm. The breakdown itself cannot be put into reverse gear.¹²⁹ All the same, three things remain indisputable: such breakdown becomes likelier the longer an excess of CO₂ stays in the atmosphere; without human intervention, it will linger for millennia; nothing guarantees that fossil capital is defeated and emissions cease this evening.

That composite of circumstances makes it inadvisable to write off carbon dioxide removal completely. As Buck argues in her landmark study *After Geoengineering: Climate Tragedy, Repair, and Restoration*, any blanket rejection now ‘comes off as an aesthetic luxury’.¹³⁰ Suggesting that this includes technologies such as DAC is sure to bring on a collective allergic reaction in the environmentalist left. A common objection, with Max Ajl, is that ‘technology is never socially innocent’ but irrevocably ‘bound to the specific historical class war deploying that technology to a specific end’ – in other words, trying to disentangle DAC from its capitalist roots is a misguided folly.¹³¹ We must disagree. If this were the case, then we might as well forget about renewable energy too. Its expansion in recent years has occurred in tandem with continued expansion of fossil-fuel infrastructure and often *de facto* worked as a supplement to – even a greenwashing of – business-as-usual. In the actually-existing capitalist world economy, solar, wind, geothermal and hydropower often do not displace fossil fuels but augment them.¹³² Anyone faintly acquainted with the production processes of these technologies is aware of the massive environmental and social costs involved.¹³³ But this is hardly a reason to abandon the position that what is really needed is precisely to negate business-as-usual by replacing fossil fuels with renewable energy, albeit in a constrained, collectivised, more responsible form – it’s only that capitalism appears unable to make this happen. Renewable energy and DAC here inhabit the same technological battlespace. Fossil capital deploys them to reproduce itself; the task for any counterforces is to instead arrange them so as to maintain a habitable planet.

129 See for example ICCINET 2019; Buck 2019, p. 236; Keith, Minh and Stolaroff 2006, p. 36.

130 Buck 2019, p. 39.

131 Ajl 2020.

132 The seminal paper here is York 2012.

133 For an elaboration of these costs in the case of solar power, see Mulvaney 2019.

But why not stick with the more ‘natural’, ‘low-tech’ carbon-removal alternatives on offer? A plethora of progressives are putting their money on them – think forest regeneration, soil carbon sequestration, mangrove restoration and the like. George Monbiot labours on their behalf under the already co-opted banner of ‘natural climate solutions’.¹³⁴ Troy Vettese goes for the socialist version of ‘half-earth rewilding’, a bold programme that aims to set aside half the planet’s surface as an undisturbed carbon sink.¹³⁵ We have already touched upon some problems with these schemes: their ability to counteract the continued stream of fossil emissions pouring into the sky runs into ecological limits. Furthermore, that ability is declining as a consequence of increasing temperatures, the downward flow of carbon at growing risk of reversal by wildfires and hypercharged soil bacteria.¹³⁶ The reasons for radical ecosystem restoration are many, but creating reliable, long-lived carbon sinks isn’t the best one. And despite the innocuous-sounding label, an intervention on this scale would pose challenges no less momentous than those faced by DAC – many of them eerily similar to those raised against BECCS.¹³⁷

A more convincing critique holds that it is wiser to allocate renewable energy directly to the substitution of fossil fuels than to something like DAC, and so any installing of the latter is an illogical, costly distraction.¹³⁸ There is merit to this argument; the trade-offs with alternative uses for scarce and resource-hungry renewables are real and need to be carefully considered – something that DAC proponents are rarely wont to do.¹³⁹ The feasible scale of any DAC deployment is likely to depend on it. But if one imagines any future role for DAC at all, one cannot put off its development until the moment of need. The technology cannot be summoned *ex nihilo* circa the year 2043; it would require, if only for sheer physical reasons, a few years to mature from bantam to climate-relevant scale. To pick up the slack after emissions have ceased, it must be advanced concurrently with the cuts.¹⁴⁰ The task of the second round is thus an unenviable compound: to do both things at once: bringing emissions to zero and preparing to go after what remains.

Any effects of the latter would necessarily take decades to manifest themselves. Lest there be any remaining illusions of DAC serving as a quick-fix

134 See for example <naturalclimate.solutions>.

135 Vettese 2018.

136 Wang, Zhuang, Outi *et al.* 2018; Wang, Zhang, Ju *et al.* 2020; Walker, Kaiser, Strasser *et al.* 2018; Bowman, Williamson, Abatzoglou *et al.* 2017.

137 For a good summary of these challenges, see Büscher and Fletcher 2020.

138 Jacobson 2019; Chatterjee and Huang 2020.

139 Sekera and Lichtenberger 2020, p. 13.

140 Cf. for example Beuttler, Charles and Wurzbacher 2019, p. 6; Creutzig, Breyer, Hilaire *et al.* 2019, p. 1807; Realmonde, Drouet, Gambhir *et al.* 2020, p. 2.

solution, consider a recent study that examined what ‘wartime-like’ mobilisation of the technology might do. Assuming governments plough up to 2 per cent of world GDP into DAC deployment every year after 2025, we could presumably pull down between 570 and 840 Gt of CO₂ by 2100 – about 20 times current annual emissions. The result? A temperature reduction of a meagre 0.1 to 0.2°C by end of century compared to a DAC-less world of continued emissions – not insubstantial from a climate-risk perspective, but hardly registering as a dent in the 2.5C warming that would still result.¹⁴¹ All diversions lead to the same conclusion: any DAC strategy that does not begin with ending that assumed world of continued emissions, with dismantling fossil capital as fast as humanely possible, is a wasted effort. At most, then, DAC can perform useful work in the background, its primary function to chip away at historical emissions, not cancel out present or anticipated ones – like the slow and tedious work of cleaning up after an oil-spill, futile before the leak has been stemmed. There is a politics of metaphors to engage in here. Much of the content of DAC is prefigured in it. The bathroom metaphor exonerates fossil-fuel production and condemns DAC to Sisyphean, ultimately impossible work; it also distorts the realities out of which the need for such a technology has arisen. Surely fossil capital approximates an officer revelling in his power closer than a girl waking up at night to take a leak – there is nothing innocent about it, but plenty of structural and gratuitous violence, and progress begins with its downfall.

None of these alternative trajectories is currently on the cards. We have seen how capital in general and fossil capital in particular co-opt and corrupt DAC along two lines: sequestration as a sewage system and utilisation as a business of air-mining. Who could unshackle it and push it in another direction? Both Buck and Parenti, two of the very few scholars of the left who have bothered about DAC, point to the state as the sole actor with a potential to mobilise resources for something of this scope. Less predictable, perhaps, is the clamour for state intervention from the leading start-ups and scientists championing DAC: no one else, they plead, can establish the subsidiary infrastructure (including pipelines conveying the CO₂ to oilfields for enhanced recovery).¹⁴² No one else could furnish the basic research (a dependence in place from its inception: the Los Alamos National Laboratory belongs to the US Department of Energy; Climeworks is a private spin-off from ETH Zürich; the Icelandic plant owes its existence to a public utility, and so on). And because of the implacable thermodynamic parameters, no one but the state could make commodities from the air undercut those derived from fossil fuels. Synthetic jet fuels might never

141 Hanna, Ahmed, Xu and Victor 2021; the temperature difference would be substantially larger over a longer period, however.

142 Edwards and Cella 2018.

outcompete the petroleum varieties of their own force, certainly not when oil prices are as low as in the wake of Covid-19. Only some heavy financial penalty on emitting CO₂ – a price, a tax, a rationing system – could make synfuels and other derivatives of DAC competitive across the board.¹⁴³

‘Policy needs to come in, and quickly’, is a mantra in the ‘space’.¹⁴⁴ Those who harbour hopes of a DAC-fuelled boom thereby find themselves in the awkward position of having to trust in the state as its catalyst. Omnipresent regulation must come to their aid and skew markets in favour of DAC, which means that its hyper-bourgeois boosters, as Buck wryly notes, suffer from ‘tremendous cognitive dissonance’.¹⁴⁵ It also raises the question of what exactly the state should do with DAC: pave the way for utilisation or open the shafts to sequestration. Doing both, on this count, is hardly viable. There is, as we have seen, no escaping the trade-offs: a quantum of DAC capacity allotted to diamonds or synfuels for the class of frequent flyers will be so much DAC capacity not devoted to removal. The more carbon in the air and the greater the burden to offload, the sharper these trade-offs will become.¹⁴⁶ The alternative is an aggressive pursuit of sequestration folded into a programme for ‘euthanizing the fossil fuel industry’, in Parenti’s words: and the two could be fully unified in one act. Private producers of fossil fuels could be nationalised and converted into organisations for capture and storage. This would, as Buck has argued, be the most logical solution: compelling the polluters to clean up their own mess; making good use of their geological and chemical expertise; transferring workers in a doomed industry to new jobs, without having them move one mile. The company formerly known as ExxonMobil: a public utility for drawing down all the emissions it has caused and then some.¹⁴⁷

A similar policy needs to come for the automobile industry. The apostles of DAC often calculate that 10 or 20 million DAC machines should be manufactured every year and argue that this is entirely within the realm of the feasible, since more than 70 million cars – devices of comparable size and sophistication – are turned out annually from the world’s factories. But the contention would be more credible if it came with the proposal that one fourth of the automobile industry be *converted* to DAC manufacturing (and the rest to other segments of the transition).¹⁴⁸ The state could force the pace of

143 As pointed out in Beuttler, Charles and Wurzbacher 2019, p. 5.

144 Interview with Climeworks representative; cf. for example Keith 2009, p. 1655; Lackner, Brennan, Matter *et al.* 2012, p. 13161.

145 Buck 2021.

146 As pointed out by Fuhrman, McJeon, Patel *et al.* 2020, p. 7.

147 Buck 2019, pp. 136, 203–6; Buck 2021.

148 For example, Lackner 2010, p. 71; Lackner, Brennan, Matter *et al.* 2012, p. 13159; Broecker 2013, p. 2; Realmonde, Drouet, Gambhir *et al.* 2019, p. 7.

development by acquiring the secrets from start-ups. It could open the valves of funding to improve the tech – yes, Manhattan Project-style – at maximum speed. Only the state could navigate the minefield of DAC energy and resource requirements and prevent unconscionable trade-offs. But most importantly, it is difficult to see any other actor that could release DAC from ‘the universal domination of mankind by exchange-value’ and let it work for something to which no such value can attach: a stable climate for all, impossible to bring to the market in a shining green bottle or white shoe.¹⁴⁹ States could supplement DAC with other forms of drawdown, provided these are compatible with progressive ambitions – natural forest regeneration on land taken from the hands of the meat industry, for instance. For the time being, however, it appears that direct air capture, mineralisation and sequestration could be an important part of removal. After zero-emissions, this process can start lifting the burden, stone after incremental stone, let the earth go free and heal the wounds to the best of its ability. But best-case scenarios are, of course, in very short supply in this overheating world. That is why the politics of carbon dioxide removal will be defining for decades to come.

Acknowledgements

We gratefully acknowledge research grant FORMAS 2018–01686, and thank Guy Finkill, Inge-Merete Hougaard, Kirstine Lund Christiansen, Nils Markusson, Natalia Rubiano Rivadeneira and the editors of *Historical Materialism* for comments and other input.

References

- Adorno, Theodor 2014 [1966], *Negative Dialectics*, translated by E.B. Ashton, London: Bloomsbury.
- Adorno, Theodor 2019 [2008], *Philosophical Elements of a Theory of Society*, Cambridge: Polity.
- Ajl, Max 2020, ‘Andreas Malm’s *Corona, Climate, Chronic Emergency*’, *Brooklyn Rail*, November, available at: <<https://brooklynrail.org/2020/11/field-notes/Corona-Climate-Chronic-Emergency>>.
- Al-Taie, Abdul Sattar 2020, ‘QF’s Research Fund Awards Grants to Projects Designed to Drive Qatar’s Socioeconomic Development’, *Albawaba*, 19 July, available at:

149 Adorno 2014, p. 178. Cf. Parenti 2020, pp. 136–7.

- <<https://www.albawaba.com/business/pr/qf%E2%80%99s-research-fund-awards-grants-projects-designed-drive-qatar%E2%80%99s-socioeconomic>>.
- Anderson, Kevin and Glen Peters 2016, 'The Trouble with Negative Emissions', *Science*, 354: 182–3, available at: <<http://smartstones.nl/wp-content/uploads/2016/12/Kevin-Anderson-2016.10.13-the-Trouble-with-Negative-Emissions-Science-2016.pdf>>.
- Audi USA 2014, 'New Audi E-Fuels Project: E-Diesel from Air, Water and Green Electricity', 14 November, available at: <<https://www.audiusa.com/>>.
- Azar, Christian, Kristian Lindgren, Erik Larson and Kenneth Möllersten 2006, 'Carbon Capture and Storage from Fossil Fuels and Biomass: Costs and Potential Role in Stabilizing the Atmosphere', *Climatic Change*, 74: 47–79.
- Bass, Thomas 1995, 'Robot, Build Thyself', *Discovery Magazine*, 1 October, available at: <<https://www.discovermagazine.com/technology/robot-build-thyself/>>.
- Benjamin, Walter 1996, *Selected Writings, Volume 1: 1913–1926*, edited by Marcus Bullock and Michael W. Jennings, Cambridge, MA: Harvard University Press.
- Beuttler, Christoph, Louise Charles and Jan Wurzbacher 2019, 'The Role of Direct Air Capture in Mitigation of Anthropogenic Greenhouse Gas Emissions', *Frontiers in Climate*, 1: 1–7.
- Biello, David 2016, 'World's Richest Man Picks Energy Miracles', *Scientific American*, 29 February, available at: <<https://www.scientificamerican.com/article/world-s-richest-man-picks-energy-miracles/>>.
- Biro, Andrew (ed.) 2011, *Critical Ecologies: The Frankfurt School and Contemporary Environmental Crises*, Toronto: University of Toronto Press.
- Bowman, David, Grant J. Williamson, John T. Abatzoglou *et al.* 2017, 'Human Exposure and Sensitivity to Globally Extreme Wildfire Events', *Nature Ecology and Evolution*, 1: 1–6.
- Boyd, William, Scott W. Prudham and Rachel A. Schurman 2001, 'Industrial Dynamics and the Problem of Nature', *Society and Natural Resources*, 14: 555–70.
- Breyer, Christian, Mahdi Fasihi and Arman Aghahosseini 2020, 'Carbon Dioxide Direct Air Capture for Effective Climate Change Mitigation Based on Renewable Electricity: A New Type of Energy System Sector Coupling', *Mitigation and Adaptation Strategies for Global Change*, 25: 43–65.
- Broecker, Wally 2013, 'Does Air Capture Constitute a Viable Backstop against a Bad CO₂ Trip?', *Elementa: Science of the Anthropocene*, 1: 1–3.
- Bruhn, Thomas, Henriette Naims and Barbara Olfe-Kräutlein 2016, 'Separating the Debate on CO₂ Utilisation from Carbon Capture and Storage', *Environmental Science and Policy*, 60: 38–43.
- Buck, Holly Jean 2019, *After Geoengineering: Climate Tragedy, Repair, and Restoration*, London: Verso.
- Buck, Holly Jean 2020, 'Should Carbon Removal be Treated as Waste Management? Lessons from the Cultural History of Waste', *Interface Focus*, 10: 1–8.

- Buck, Holly Jean 2021, 'Mining the Air: The Political Ecologies of Carbon-Negative Oil and the Circular Carbon Economy', *Environment and Planning E: Nature and Space*, forthcoming.
- Büscher, Bram and Robert Fletcher 2020, *The Conservation Revolution: Radical Ideas for Saving Nature beyond the Anthropocene*, London: Verso.
- Cames, Martin, Ralph O. Harthan, Jürg Füssler *et al.* 2016, 'How Additional Is the Clean Development Mechanism?', INFRAS and Stockholm Environment Institute, available at: <https://ec.europa.eu/clima/sites/clima/files/ets/docs/clean_dev_mechanism_en.pdf>.
- Carton, Wim 2019, "Fixing" Climate Change by Mortgaging the Future: Negative Emissions, Spatiotemporal Fixes, and the Political Economy of Delay', *Antipode*, 51: 750–69.
- Carton, Wim 2020, 'Carbon Unicorns and Fossil Futures: Whose Emission Reduction Pathways Is the IPCC Performing?', in Sapinski, Buck and Malm (eds.) 2020.
- Center for Negative Carbon Emissions 2018, 'Shell's New Energy and Research Technology (NERT) Group – Materials and Shapes for Advanced Filters Removing CO₂ from Wind', Arizona State University, available at: <<https://cnce.engineering.asu.edu/project/project-1-title/>>.
- Chancel, Lucas and Thomas Piketty 2015, 'Carbon and Inequality: From Kyoto to Paris', Paris School of Economics, 3 November, available at: <<http://piketty.pse.ens.fr/files/ChancelPiketty2015.pdf>>.
- Chatterjee, Sudipta and Kuo-Wei Huang 2020, 'Unrealistic Energy and Materials Requirement for Direct Air Capture in Deep Mitigation Pathways', *Nature Communications*, 11: 1–3.
- Chichilnisky, Graciela and Peter Eisenberger 2009, 'Energy Security, Economic Development and Global Warming: Addressing Short and Long Term Challenges', *International Journal of Green Economics*, 3: 414–46.
- Chichilnisky, Graciela and Kristen A. Sheeran 2009, *Saving Kyoto: An Insider's Guide to How it Works, Why it Matters and What it Means For The Future*, London: New Holland Publishers Ltd.
- Circular Carbon Network 2019, 'Why Now? Sparking a New Industrial Revolution', available at: <<https://circularcarbon.org/why-now/>>.
- Creutzig, Felix, Christian Breyer, Jérôme Hilaire *et al.* 2019, 'The Mutual Dependence of Negative Emission Technologies and Energy Systems', *Energy and Environmental Science*, 12: 1805–17.
- Davis, Carolyn 2020, 'Oxy Taking "Contrarian Approach" to Net-Zero Emissions by Developing Oil Resources, Reusing CO₂', *NGI Natural Gas Intelligence*, 13 November, available at: <<https://www.naturalgasintel.com/oxy-taking-contrarian-approach-to-net-zero-emissions-by-developing-oil-resources-reusing-co2/>>.
- Delamaide, Darrell 2020a, 'Lufthansa Backs Swiss Effort to Develop Carbon-Neutral Aviation Fuel', 24/7 *Wall Street*, 19 May, available at: <<https://247wallst.com/>>

- investing/2020/05/19/lufthansa-backs-swiss-effort-to-develop-carbon-neutral-aviation-fuel/>.
- Delamaide, Darrell 2020b, 'Norway's Water Power Key to Europe's Hydrogen Plan Fuel Venture', *Callaway Climate Insights*, 30 June, available at: <<https://www.callawayclimateinsights.com/p/norways-water-power-key-to-europes>>.
- Diamandis, Peter H. 2019, 'The Promise of Direct Air Capture: Making Stuff Out of Thin Air', *Singularity Hub*, 23 August, available at: <<https://singularityhub.com/2019/08/23/the-promise-of-direct-air-capture-making-stuff-out-of-thin-air/>>.
- Edwards, Ryan W.J. and Michael A. Cella 2018, 'Infrastructure to Enable Deployment of Carbon Capture, Utilization, and Storage in the United States', *PNAS*, 115: 8815–24.
- Eisenberger, Peter M. 2014, 'Chaos Control: Climate Stabilization by Closing the Global Carbon Cycle', *Energy and Environment*, 25: 971–90.
- Eisenberger, Peter M., Roger W. Cohen, Graciela Chichilnisky *et al.* 2009, 'Global Warming and Carbon-Negative Technology: Prospects for a Lower-Cost Route to a Lower-Risk Atmosphere', *Energy and Environment*, 20: 973–84.
- Elk Coast Institute 2020, 'Direct Air Capture Climate Mobilization Summit', unpublished booklet.
- Elliot, Rebecca 2020, 'Carbon Capture Wins Fans among Oil Giants', *Wall Street Journal*, 12 February, available at: <<https://www.wsj.com/articles/carbon-capture-is-winning-fans-among-oil-giants-11581516481>>.
- Elliott, S., K.S. Lackner, H.J. Ziock *et al.* 2001, 'Compensation of Atmospheric CO₂ Buildup through Engineered Chemical Sinkage', *Geophysical Research Letters*, 28: 1235–38.
- ExxonMobil 2019, 'ExxonMobil and Global Thermostat to Advance Breakthrough Atmospheric Carbon Capture Technology', 27 June, available at: <https://corporate.exxonmobil.com/News/Newsroom/News-releases/2019/0627_ExxonMobil-and-Global-Thermostat-to-advance-breakthrough-atmospheric--carbon-capture-technology>.
- Fasihi, Mahdi, Olga Efimova and Christian Breyer 2019, 'Techno-Economic Assessment of CO₂ Direct Air Capture Plants', *Journal of Cleaner Production*, 224: 957–80.
- Field, Christopher B. and Katharine J. Mach 2017, 'Rightsizing Carbon Dioxide Removal', *Science*, 356: 706–7.
- Fogel, Cathleen 2005, 'Biotic Carbon Sequestration and the Kyoto Protocol: The Construction of Global Knowledge by the Intergovernmental Panel on Climate Change', *International Environmental Agreements*, 5: 191–210.
- Fountain, Henry 2018, 'How Oman's Rocks Could Help Save the Planet', *New York Times*, 26 April, available at: <<https://www.nytimes.com/interactive/2018/04/26/climate/oman-rocks.html>>.

- Friedlingstein, Pierre, Michael O'Sullivan, Matthew W. Jones *et al.* 2020, 'Global Carbon Budget 2020', *Earth System Science Data*, 12: 3269–340.
- Friedman, Linda 2020, 'A Trillion Trees: How One Idea Triumphed over Trump's Climate Denialism', *New York Times*, 12 February, available at: <<https://www.nytimes.com/2020/02/12/climate/trump-trees-climate-change.html>>.
- Friedmann, S. Julio 2019, 'Engineered CO₂ Removal, Climate Restoration, and Humility', *Frontiers in Climate*, 1: 1–5.
- Fuhrman, Jay, Haewon McJeon, Pralit Patel *et al.* 2020, 'Food-Energy-Water Implications of Negative Emissions Technologies in a +1.5°C Future', *Nature Climate Change*, online first.
- Gambhir, Ajay and Massimo Tavoni 2019, 'Direct Air Capture and Sequestration: How It Works and How It Could Contribute to Climate-Change Mitigation', *One Earth*, 1: 405–9.
- Gertner, Jon 2019, 'The Tiny Swiss Company that Thinks it Can Help Stop Climate Change', *New York Times*, 12 February, available at: <<https://www.nytimes.com/2019/02/12/magazine/climeworks-business-climate-change.html>>.
- Goldman Sachs 2019, 'Carbonomics: The Future of Energy in the Age of Climate Change', 11 December, available at: <<https://www.goldmansachs.com/insights/pages/gs-research/carbonomics-f/report.pdf>>.
- Goldstein, Jesse 2018, *Planetary Improvement: Cleantech Entrepreneurship and the Contradictions of Green Capitalism*, Cambridge, MA: The MIT Press.
- Gov.uk 2020, 'PM: A New Deal for Britain', 30 June, available at: <<https://www.gov.uk/government/news/pm-a-new-deal-for-britain>>.
- Grasso Macola, Ilaria 2020, 'Q&A: A Look at Europe's First Renewable Aviation Fuel Plant with Climeworks', *Airport Technology*, 18 June, available at: <<https://www.airport-technology.com/features/qa-a-look-at-europes-first-renewable-aviation-fuel-plant-with-climeworks/>>.
- Hamilton, Clive 2013, *Earthmasters: The Dawn of the Age of Climate Engineering*, New Haven, CT: Yale University Press.
- Hamilton, Katherine, Ricardo Bayon, Guy Turner and Douglas Higgins 2007, *State of the Voluntary Carbon Markets 2007: Picking up Steam*, Ecosystem Marketplace and New Carbon Finance, available at: <<https://www.forest-trends.org/wp-content/uploads/2018/09/State-of-the-Voluntary-Carbon-Market-2007.pdf>>.
- Hanna, Ryan, Abdulla Ahmed, Xu Yangyang and David G. Victor 2021, 'Emergency Deployment of Direct Air Capture as a Response to the Climate Crisis', *Nature Communications*, 12: 1–13.
- Hansen, James, Makiko Sato, Pushker Kharecha *et al.* 2008, 'Target Atmospheric CO₂: Where Should Humanity Aim?', *Open Atmospheric Science Journal*, 2: 217–31.
- Hayes, Peter 2001, *Industry and Ideology: IG Farben in the Nazi Era*, New Edition, Cambridge: Cambridge University Press.

- Heck, Vera, Dieter Gerten, Wolfgang Lucht and Alexander Popp 2018, 'Biomass-based Negative Emissions Difficult to Reconcile with Planetary Boundaries', *Nature Climate Change*, 8: 151–5.
- House, Kurt Zenz, Antonio C. Baclig, Manya Ranjan *et al.* 2011, 'Economic and Energetic Analysis of Capturing CO₂ from Ambient Air', *PNAS*, 108: 20428–33.
- ICCINET 2019, 'Cryosphere 1.5°: Where Urgency and Ambition Meet', available at: <https://resources.mynewsdesk.com/image/upload/t_attachment/boozciloisj4qkiub6ji.pdf>.
- International Energy Forum 2020, 'The Circular Carbon Economy', *IEF Insight Brief*, available at: <<https://www.ief.org/programmes/circular-carbon-economy>>.
- IPCC 2018, *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, Geneva: IPCC.
- Ishimoto, Yuki, Masahiro Sugiyama, Etsushi Kato *et al.* 2017, 'Putting Costs of Direct Air Capture in Context', *Forum for Climate Engineering Assessment*, FCEA Working Paper Series, No. 2, available at: <<http://ceassessment.org/wp-content/uploads/2017/06/WPS-DAC.pdf>>.
- Jacobson, Mark Z. 2019, 'The Health and Climate Impacts of Carbon Capture and Direct Air Capture', *Energy and Environmental Science*, 12: 3567–74.
- Jones, Lee 2015, *Societies under Siege: Exploring How International Sanctions (Do Not) Work*, Oxford: Oxford University Press.
- Jones, Michael B. and Fabrizio Albanito 2020, 'Can Biomass Supply Meet the Demand of BECCS?', *Global Change Biology*, online first.
- Kane, Frank 2020, 'Circular Carbon Economy Holds Promise in Battle Against Global Warming', *Arab News*, 25 July, available at: <<https://www.arabnews.com/node/1709941/business-economy>>.
- Kang, Minsoo 2011, *Sublime Dreams of Living Machines: The Automaton in the European Imagination*, Cambridge, MA: Harvard University Press.
- Kanter, James 2007, 'In London's Financial World, Carbon Trading Is the New Big Thing', *New York Times*, 6 July, available at: <<https://www.nytimes.com/2007/07/06/business/worldbusiness/06carbon.html>>.
- Keith, David 2009, 'Why Capture CO₂ from the Atmosphere?', *Science*, 325: 1654–5.
- Keith, David W., Minh Ha-Duong and Joshua K. Stolaroff 2006, 'Climate Strategy with CO₂ Capture from the Air', *Climatic Change*, 74: 17–45.
- Keith, David W., Geoffrey Holmes, David St Angelo and Kenton Heidel 2018, 'A Process for Capturing CO₂ from the Atmosphere', *Joule*, 2: 1573–94.
- Kelemen, P.B., R. Aines, E. Bennett *et al.* 2018, 'In Situ Carbon Mineralization in Ultramafic Rocks: Natural Processes and Possible Engineering Methods', *Energy Procedia*, 146: 92–102.

- Kelemen, Peter, Sally M. Benson, H el ene Pilorg e *et al.* 2019, 'An Overview of the Status and Challenges of CO₂ Storage in Minerals and Geological Formations', *Frontiers in Climate*, 1: 1–20.
- Kobayashi-Solomon, Erik 2019a, 'A Historic Inflection Point in Capitalism's Battle against Climate Change', *Forbes*, 29 April, available at: <<https://www.forbes.com/sites/erikkobayashisolomon/2019/04/26/historic-inflection-point-mankinds-battle-against-climate-change/>>.
- Kobayashi-Solomon, Erik 2019b, 'Capitalism vs Climate Change: Front Line Interview I', *Forbes*, 21 May, available at: <<https://www.forbes.com/sites/erikkobayashisolomon/2019/05/21/capitalism-vs-climate-change-front-line-interview-i/>>.
- Krauss, Clifford 2019, 'Blamed for Climate Change, Oil Companies Invest in Carbon Removal', *New York Times*, 7 April, available at: <<https://www.nytimes.com/2019/04/07/business/energy-environment/climate-change-carbon-engineering.html>>.
- Kunzig, Robert and Wallace Broecker 2009, *Fixing Climate: The Story of Climate Science – and How to Stop Global Warming*, London: Profile.
- Lackner, Klaus 2003, 'A Guide to CO₂ Sequestration', *Science*, 300: 1677–8.
- Lackner, Klaus S. 2010, 'Washing Carbon Out of Thin Air', *Scientific American*, 302: 66–71.
- Lackner, Klaus S. and Christophe Jospe 2017, 'Climate Change Is a Waste Management Problem', *Issues in Science and Technology*, 33: 83–8.
- Lackner, K.S. and C.H. Wendt 1995, 'Exponential Growth of Large Self-Reproducing Machine Systems', *Mathematical and Computer Modelling*, 21: 55–81.
- Lackner, Klaus S., Christopher H. Wendt, Darryl P. Butt *et al.* 1995, 'Carbon Dioxide Disposal in Carbonate Minerals', *Energy*, 20: 1153–70.
- Lackner, Klaus, Hans-Joachim Ziock and Patrick Grimes 1999, 'Carbon Dioxide Extraction from Air: Is it an Option?', conference report, Los Alamos National Laboratory, <<https://www.osti.gov/biblio/20013487-carbon-dioxide-extraction-from-air-option>>.
- Lackner, Klaus S., Richard Wilson and Hans-Joachim Ziock 2001, 'Free-Market Approaches to Controlling Carbon Dioxide Emissions to the Atmosphere: A Discussion of the Scientific Basis', in *Global Warming and Energy Policy*, edited by Behram N. Kurşunođlu, Stephan L. Mintz and Arnold Perlmutter, New York: Springer.
- Lackner, Klaus S., Sarah Brennan, J urg M. Matter *et al.* 2012, 'The Urgency of the Development of CO₂ Capture from Ambient Air', *PNAS*, 109: 13156–62.
- Larsen, John, Whitney Herndon and Galen Hiltbrand 2020a, *Capturing New Business: The Market Opportunities Associated with Scale-Up of Direct Air Capture (DAC) Technology in the US*, Rhodium Group, available at: <<https://rhg.com/>>.
- Larsen, John, Whitney Herndon and Galen Hiltbrand 2020b, *Capturing New Jobs: The Employment Opportunities Associated with Scale-Up of Direct Air Capture (DAC) Technology in the US*, Rhodium Group, available at: <<https://rhg.com/>>.
- Leckel, Dieter 2009, 'Diesel Production from Fischer-Tropsch: The Past, the Present, and New Concepts', *Energy and Fuels*, 23: 2342–58.

- Lohmann, Larry 2009, 'Toward a Different Debate in Environmental Accounting: The Cases of Carbon and Cost-Benefit', *Accounting, Organizations and Society*, 34: 499–534.
- Lövbrand, Eva 2004, 'Bridging Political Expectations and Scientific Limitations in Climate Risk Management: On the Uncertain Effects of International Carbon Sink Policies', *Climatic Change*, 67: 449–60.
- Löwy, Michael 2009, 'Capitalism as Religion: Walter Benjamin and Max Weber', *Historical Materialism*, 17, 1: 60–73.
- Mac Dowell, Niall, Paul S. Fennell, Nilay Shah and Geoffrey C. Maitland 2017, 'The Role of CO₂ Capture and Utilization in Mitigating Climate Change', *Nature Climate Change*, 7: 243–9.
- Mackey, Brendan, Colin Prentice, Will Steffen *et al.* 2013, 'Untangling the Confusion around Land Carbon Science and Climate Change Mitigation Policy', *Nature Climate Change*, 3: 552–7.
- Majumdar, Arun and John Deutch 2018, 'Research Opportunities for CO₂ Utilization and Negative Emissions on the Gigatonne Scale', *Joule*, 2: 805–9.
- Malewar, Amit 2020, 'BMW Invests in Technology that Recycles CO₂ from the Air into Carbon-Neutral Gasoline', *Inceptive Mind*, 11 June, available at: <<https://www.inceptivemind.com/bmw-invests-prometheus-fuels-recycles-co2-air-carbon-neutral-gasoline/13746/>>.
- Mandel, Ernest 1978, *Late Capitalism*, London: Verso.
- Mandel, Ernest 1995, *Long Waves of Capitalist Development: A Marxist Interpretation*, London: Verso.
- Markusson, Nils, Duncan McLaren and David Tyfield 2018, 'Towards a Cultural Political Economy of Mitigation Deterrence by Negative Emissions Technologies (NETS)', *Global Sustainability*, 1: 1–9.
- Marx, Karl 1991 [1894], *Capital: A Critique of Political Economy. Volume Three*, translated by David Fernbach, Harmondsworth: Penguin.
- Matter, Juerg M., Martin Stute, Sandra Ó Snæbjörnsdóttir *et al.* 2016, 'Rapid Carbon Mineralization for Permanent Disposal of Anthropogenic Carbon Dioxide Emissions', *Science*, 352: 1312–14.
- McAfee, Kathleen 2012, 'The Contradictory Logic of Global Ecosystem Services Markets', *Development and Change*, 43: 105–31.
- McGinnis, Rob 2020, 'CO₂-to-Fuels Renewable Gasoline and Jet Fuel Can Soon Be Competitive with Fossil Fuels', *Joule*, 4: 509–11.
- McLaren, Duncan and Nils Markusson 2020, 'The Co-Evolution of Technological Promises, Modelling, Policies and Climate Change Targets', *Nature Climate Change*, 10: 392–7.
- McQueen, Noah, Peter Psarras, Hélène Pilorgé *et al.* 2020, 'Cost Analysis of Direct Air Capture and Sequestration Coupled to Low-Carbon Thermal Energy in the United States', *Environmental Science and Technology*, 54: 7542–51.

- Meadowcroft, James 2013, 'Exploring Negative Territory: Carbon Dioxide Removal and Climate Policy Initiatives', *Climatic Change*, 118: 137–49.
- Mervine, Evelyn M., Siobhan A. Wilson, Ian M. Power *et al.* 2018, 'Potential for Offsetting Diamond Mine Carbon Emissions through Mineral Carbonation of Processed Kimberlite: An Assessment of De Beers Mine Sites in South Africa and Canada', *Mineralogy and Petrology*, 112: 755–65.
- Morton, Evvan V. 2020, *Reframing the Climate Change Problem: Evaluating the Political, Technological, and Ethical Management of Carbon Dioxide Emissions in the United States*, PhD dissertation, Arizona State University, available at: <<https://repository.asu.edu/items/57290>>.
- Mulvaney, Dustin 2019, *Solar Power: Innovation, Sustainability, and Environmental Justice*, Berkeley, CA: University of California Press.
- NRG 2016, 'The Shoe without a Footprint', *YouTube*, 13 September, available at: <<https://www.youtube.com/watch?v=a03PbC8UdqQ>>.
- Obersteiner, Michael, Johannes Bednar, Fabian Wagner *et al.* 2018, 'How to Spend a Dwindling Greenhouse Gas Budget', *Nature Climate Change*, 8: 7–10.
- Oxfam 2015, 'Extreme Carbon Inequality', *Oxfam Media Briefing*, 2 December, available at: <https://www-cdn.oxfam.org/s3fs-public/file_attachments/mb-extreme-carbon-inequality-021215-en.pdf>.
- Oxfam 2020, 'Confronting Carbon Inequality', *Oxfam Media Briefing*, 21 September, available at: <<https://www.oxfam.org/en/research/confronting-carbon-inequality>>.
- Parenti, Christian 2020, 'A Left Defence of Carbon Dioxide Removal: The State Must Be Forced to Deploy Civilization-Saving Technology', in Sapinski, Buck and Malm (eds.) 2020.
- Peters-Stanley, Molly and Daphne Yin 2013, *Maneuvering the Mosaic: State of the Voluntary Carbon Markets 2013*, ForestTrends' Ecosystem Marketplace and Bloomberg New Energy Finance, available at: <<https://www.forest-trends.org/publications/maneuvering-the-mosaic-state-of-the-voluntary-carbon-markets-2013/>>.
- Price, Grant 2019, *By the Feet of Men*, Alresford: John Hunt Publishing.
- Prudham, Scott 2003, 'Taming Trees: Capital, Science, and Nature in Pacific Slope Tree Improvement', *Annals of the Association of American Geographers*, 93: 636–56.
- Rathi, Akshat 2019, 'A Tiny Tweak in California Law Is Creating a Strange Thing: Carbon-Negative Oil', *Quartz*, 1 July, available at: <<https://qz.com/1638096/the-story-behind-the-worlds-first-large-direct-air-capture-plant/>>.
- Realmonde, Giulia, Laurent Drouet, Ajay Gambhir *et al.* 2019, 'An Inter-Model Assessment of the Role of Direct Air Capture in Deep Mitigation Pathways', *Nature Communications*, 10: 1–12.
- Realmonde, Giulia, Laurent Drouet, Ajay Gambhir *et al.* 2020, 'Reply to "High Energy and Materials Requirement for Direct Air Capture Calls for Further Analysis and R&D"', *Nature Communications*, 11: 1–2.

- Repsol Foundation 2020, 'Direct Air Capture of CO₂' (Webinar), *YouTube*, 3 June, available at: <<https://www.youtube.com/watch?v=K2oSF1zydbg>>.
- Robinson, Kim Stanley 2020, 'Slowing Climate Change with Sewage Treatment for the Skies', *Bloomberg*, 13 December, available at: <<https://www.bloomberg.com/news/articles/2020-12-13/kim-stanley-robinson-direct-air-capture-is-a-public-good-for-climate-era>>.
- Rose, Charlie 2013, 'Charlie Rose Talks to ExxonMobil's Rex Tillerson', *Bloomberg*, 7 March, available at: <<https://www.bloomberg.com/news/articles/2013-03-07/charlie-rose-talks-to-exxonmobils-rex-tillerson>>.
- Sapinski, J.P., Holly Jean Buck and Andreas Malm (eds.) 2020, *Has It Come to This? The Promises and Perils of Geoengineering on the Brink*, New Brunswick, NJ: Rutgers University Press.
- Saudi Aramco 2020a, 'The Circular Carbon Economy', available at: <<https://www.aramco.com/en/making-a-difference/planet/the-circular-carbon-economy>>.
- Saudi Aramco 2020b, 'Technology Development: Carbon Management', available at: <<https://www.aramco.com/en/creating-value/technology-development/global-researchcenters/carbon-management>>.
- Seifritz, W. 1990, 'CO₂ Disposal by Means of Silicates', *Nature*, 345: 486.
- Sekera, June and Andreas Lichtenberger 2020, 'Assessing Carbon Capture: Public Policy, Science, and Societal Need', *Biophysical Economics and Sustainability*, 5: 1–28.
- Service, Robert F. 2019, 'This Former Playwright Aims to Turn Solar and Wind Power into Gasoline', *Science*, 3 July, available at: <<https://www.sciencemag.org/news/2019/07/former-playwright-aims-turn-solar-and-wind-power-gasoline>>.
- Service, Robert F. 2020, 'The Carbon Vault', *Science*, 369: 1156–9.
- Siegel, R.P. 2018, 'The Fizzy Math of Carbon Capture', *Grist*, 10 October, available at: <<https://grist.org/article/direct-air-carbon-capture-global-thermostat/>>.
- Soltoff, Ben 2019, 'Inside ExxonMobil's Hookup with Carbon Removal Venture Global Thermostat', *Green Biz*, 29 August, available at: <<https://www.greenbiz.com/article/inside-exxonmobils-hookup-carbon-removal-venture-global-thermostat>>.
- Stuart, Diana, Ryan Gunderson and Brian Petersen 2020, 'Carbon Geoengineering and the Metabolic Rift: Solution or Social Reproduction?', *Critical Sociology*, online first.
- Supekar, Sarang D., Tae-Hwan Lim and Steven J. Serklos 2019, 'Costs to Achieve Target Net Emissions Reductions in the US Electric Sector Using Direct Air Capture', *Environmental Research Letters*, 14: 1–11.
- Temple, James 2019a, 'Startups Looking to Suck CO₂ from the Air Are Suddenly Luring Big Bucks', *MIT Technology Review*, 2 May, available at: <<https://www.technologyreview.com/2019/05/02/135513/startups-looking-to-suck-co2-from-the-air-are-suddenly-luring-big-bucks/>>.
- Temple, James 2019b, 'Why the World's Biggest CO₂-Sucking Plant Would be Used to ... Err, Dig Up More Oil?', *MIT Technology Review*, 27 May, available at: <<https://www.technologyreview.com/2019/05/27/135513/why-the-worlds-biggest-co2-sucking-plant-would-be-used-to-err-dig-up-more-oil/>>.

- .technologyreview.com/2019/05/27/135203/why-the-worlds-biggest-cosub2-sub-sucking-plant-would-be-used-to-err-dig-up-more-oil/>.
- Total 2020, 'Total is Exploring Quantum Algorithms to Improve CO₂ Capture', 15 May, available at: <<https://www.total.com/media/news/news/total-exploring-quantum-algorithms-improve-co2-capture>>.
- Van Vuuren, Detlef, Michel G.J. Den Elzen, Paul L. Lucas *et al.* 2007, 'Stabilizing Greenhouse Gas Concentrations at Low Levels: An Assessment of Reduction Strategies and Costs', *Climatic Change*, 81: 119–59.
- Vettese, Troy 2018, 'To Freeze the Thames', *New Left Review*, 11, 111: 63–86.
- Walker, Tom, Christina Kaiser, Florian Strasser *et al.* 2018, 'Microbial Temperature Sensitivity and Biomass Change Explain Soil Carbon Loss with Warming', *Nature Climate Change*, 8: 885–89.
- Wang, Sirui, Zhuang Qianlai, Lähteenoja Outi *et al.* 2018, 'Potential Shift from a Carbon Sink to a Source in Amazonian Peatlands under a Changing Climate', *PNAS*, 115: 12407–12.
- Wang, Songhan, Zhang Yongguang, Ju Weimin *et al.* 2020, 'Recent Global Decline of CO₂ Fertilization Effects on Vegetation Photosynthesis', *Science*, 370: 1295–1300.
- Wilcox, Jennifer 2020, 'AirMiners Conference Series – Deep Dive on Direct Air Capture with Dr. Jennifer Wilcox', organised by airminers.org, *YouTube*, 17 June, available at: <<https://www.youtube.com/watch?v=XguPodnZ7g0>>.
- Wilcox, Jennifer, Peter C. Psarras and Simona Liguori 2017, 'Assessment of Reasonable Opportunities for Direct Air Capture', *Environmental Research Letters*, 12: 1–7.
- Wohland, Jan, Dirk Witthaut and Carl-Friedrich Schleussner 2018, 'Negative Emission Potential of Direct Air Capture Powered by Renewable Excess Electricity in Europe', *Earth's Future*, 6: 1380–4.
- Wright, Oliver 2020, 'Dominic Cummings Wins £100m to Save Planet by Sucking CO₂ from Air', *The Times* (London), 3 July, available at: <<https://www.thetimes.co.uk/article/dominic-cummings-wins-100m-to-save-planet-by-sucking-co2-from-air-8qv3mzjx8>>.
- York, Richard 2012, 'Do Alternative Energy Sources Displace Fossil Fuels?', *Nature Climate Change*, 2: 441–43.