Financial, spatial and ecological limits to fossil fuel emission offsetting

Alain Naef, Nina L. Friggens, Patrick Njeukam[1]

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Burning all the reserves of the 200 largest fossil fuel companies could generate up to 673GtCO_2. We only have a 400GtCO_2 emissions budget to remain under 1.5°C global warming by 2050 according to the IPCC. Rapid action is needed to cut, or as a last resort, offset these emissions. It remains unclear who will pay to offset these emissions and how to proceed. Here we show that if the cost of offsetting is above $150 per ton of CO_2, all large fossil fuel companies would have a negative market value. Using the social cost of carbon to give a valuation of fossil fuel companies, we find that they have a negative value for society. Fossil fuel companies could decide to offset their emissions by afforestation (a cheaper alternative and the most used technology today). We measure how much space would be needed to offset all the emissions from current fossil fuel reserves. We show that offsetting all reserves would require covering the equivalent of the whole of North and Central America with only trees, removing all of the people and cultivated land. Afforestation, while more economical could disrupt existing ecosystems that provide important ecosystem services.

Fossil fuel companies own vast fossil reserves. The burning of fossil fuel accounts for 94% of global fuel emissions (cement and other industry uses make up the rest) and the burning of fossil fuel represents 89.6% of global emissions.[1] In recent communications, fossil fuel companies have started to mention offsetting emissions from their activities. Shell, for example, plans to "offset emissions of around 120 million tons a year by 2030".[2,3] Carbon offsetting could potentially compensate for carbon emissions, yet the topic is debated.[4–9] We asked two questions: Is carbon offsetting economically viable? How much space is needed for afforestation to compensate for carbon emissions?

[1] Alain Naef, Department of Economics, ESSEC Business School, Paris, Nina L. Friggens, Department of Geography, University of Exeter, Patrick Njeukam, student, ESSEC Business School.

This article focusses on the 200 largest holders of fossil fuel reserves. Looking at their reserves today, we calculated the cost and land surface needed for offsetting carbon emissions from burning all their current reserves. Fossil fuel companies currently hold 182 Gt of carbon (equivalent to 673 Gt of CO_2e) in their reserves, as reported by Fossil Free Funds CU200. These reserves, recorded on their balance sheets as part of their economic value, would release 673 Gt of CO_2e if extracted and burned. This far exceeds the 400 Gt CO_2e remaining in our carbon budget. [10,11] It is estimated that 60% of oil and fossil methane gas, and 90% of coal must remain unextracted to keep within a 1.5 °C carbon budget.[12] But fossil fuel companies have no incentive to stop extraction and burning of fossil fuels, and regulations to stop them are slow to be put in place. These companies have put reserves on their balance sheet, which is a financial commitment on their part to burn these reserves.

Our study takes a global look at the question of fossil fuel offsetting. This has the advantage of giving general answers to the questions posed. The downside of this approach is that we - rely on many simplifying assumptions. These assumptions are laid out in the appendix.

We focus on offsetting in this paper because IPCC scenarios all contain an offsetting or negative emissions element, along with emission reduction. Also, fossil fuel companies have started communicating on offsetting, and this paper asks what it means if they were to take offsetting seriously. We focus on many forms of negative emissions such as Carbon Capture and Storage (CCS), carbon markets or offsetting through afforestation. The idea is to understand the limits of negative emissions. This to show the importance of reducing emissions instead. Our analysis aligns with existing policies, including the IPCC framework, which emphasises the necessity of reducing emissions before considering offsetting. However, the case of fossil fuel companies is unique, as their value a companies is closely linked to the value of their fossil reserves, making decarbonisation difficult and leading to a risk of stranded assets.[13,14]

Our paper first looks at the financial viability of an offsetting approach. We show that offsetting is though carbon markets or direct air capture is prohibitively expensive. We then single out afforestation, currently the cheapest offsetting technology. Afforestation in this paper is defined throughout this paper as the natural regeneration of forests in areas currently without tree cover. The estimates we use are for natural regeneration of forests and not for agroforestry.[15] We show that this technology would use more space than was previously thought. In the literature review we also show that even if policymakers were willing to sacrifice this space for afforestation, there would still be ecological limitations to be taken into account before starting afforestation at the scale needed. We conclude, in line with a large literature, that the best would be to not burn fossil fuel in the first place and simply leave them in the ground. Instead of burning them and then offsetting them.

First, our paper examines the literature of the social cost of carbon. The social cost of carbon computes the marginal cost of the impacts caused by emitting an additional ton of carbon emissions [16,17]. It is also at the heart of the Dynamic Integrated model of Climate and the Economy (DICE) models.[18,19] The method presented here does not offer a social cost of carbon, but rather computes at which social cost of carbon it becomes no longer economically viable for society to operate fossil fuel companies. We find that at the current estimated social cost of carbon, running fossil fuel companies is not economically viable.[20] That is, if an additional ton of CO_2 cost society around $190, it would not be economically viable to run any of the 200 largest fossil fuel companies. The harm they will cause by burning their oil, gas and coal reserves is not worth their economic value as assets.

The second literature this paper touches upon is that of stranded assets. This literature is focused with a similar question on the value of fossil fuel companies. Rich countries have more to lose if fossil assets become stranded. They estimate the net present value of future lost profits in the oil and gas sector at $1 trillion.[13] States highly dependent on oil and gas revenue could see government revenues drop by 51%.[21] In Latin America and the Caribbean around 66-81% of proven and unproven reserves (3P) might not be exploitable.[22] In order to remain within a 1.5 C scenario, 60% of oil and gas reserves would need to remain in the ground and 90% of coal reserves.[23] Our findings support this view by showing that the social cost of extracting all fossil reserves exceeds the economic value of these reserves. We show that it makes economic sense to leave fossil fuel reserves in the ground.

Finally, our paper explores the literature on the offsetting potential of our planet. This literature focuses largely on offsetting by afforestation as does our paper. A paper has recently claimed that there is enough space to offset 200 tons of carbon.[24] These estimates usually stay consistent whether using satellite or ground-sourced data. Estimate of the global capture potential are at around 226 Gt.[25] That would be just more than all fossil fuel reserves of the 200 largest fossil fuel companies. The difference in our approach, is that instead of calculating how much space is available, we ask how much space we need. In illustrative maps, we show how much space would be needed to offset historical emissions, and how much space to offset future planned emissions by fossil fuel companies. This is a new contribution to the literature and highlights some of the shortcomings of afforestation as an offsetting solution.

Our paper relies on a series of simplifying assumptions, which allow for broad reaching conclusions but are also limitations. We outline the broadest assumption here and present them in more detail in the paper. The first is that we focus on reserves of fossil fuel companies, not their emissions. This is a simplification because fossil fuel companies do not directly burn coal, oil and gas but simply sell it. Yet, we still think this assumption is valid as the future global temperature depend in part on the extraction of these resources.

Second, we focus primarily on afforestation in this paper, acknowledging that this leaves out other critical approaches such as preventing deforestation, restoring forests, and improving forest management. We made this choice because afforestation is the primary method used by most commercial offset solution providers, and it offers a relatively straightforward way to measure offsets. However, we stress that these other forest-based solutions remain central to tackling climate change and should not be overlooked.

Similarly, while this study focuses on afforestation, while other nature-based solutions such as mangrove restoration or peatland conservation are equally important. These were excluded from our calculations for simplification but should absolutely be considered by policymakers.

In terms of afforestation, we limit our calculations to afforestation by natural regeneration, as defined in the literature.[15] This approach assumes that afforestation competes for land use with other purposes, such as agriculture or housing. However, some afforestation could be integrated with other land uses, such as planting more trees in urban areas or intercropping trees with agricultural crops.[24] While our approach simplifies these possibilities, it remains consistent with the scale of afforestation required to offset historical and future human emissions. Thus, this simplification does not diminish the overall validity of our findings.

Considerations of ecological limitations of emissions offsetting through afforestation

Here we offer insights in the literature on the limitation of afforestation as a way of offsetting carbon emissions. Our estimates of required and available land area for afforestation are based on the literature.[15,24] However the assumptions and approaches used in this type of work have been questioned.[26–28] For example, as well as having inherent value culturally, for biodiversity and for carbon sequestration, many un-forested land areas are not suitable for afforestation due to abiotic limitations.[29,30] Trees require suitable temperature, moisture, nutrients, aeration, appropriate radiation, and rooting environment, as well as the absence of adverse soil or climatic conditions. While we ignore these limitations for simplicity in our calculations below, they remain important. Some of the ecological limitations of emissions offsetting through afforestation are explored below.

Plant photosynthesis requires water to fix carbon and afforestation has been found to affect local hydrology.[31] Afforestation increases evapotranspiration compared to grasslands or shrublands potentially leading to lowered water tables and reduced stream flows.[32] If water availability is limited, any afforestation efforts may lead to ineffective carbon sequestration and limited offsetting potentials.

Trees and other plants require nitrogen, phosphorous, potassium and other essential micronutrients to grow and sequester carbon. Nutrient availability influences a whole range of ecosystem functions including plant growth and carbon cycling [33]. Soil nutrient status in natural or seminatural ecosystems have developed over centuries to millennia through natural biogeochemical processes such as pedogenesis (soil formation) and weathering. For example; most parts of the tropics are phosphorous limited and many temperate and high latitude ecosystems are nitrogen limited.[34,35] Because of this, insufficient nitrogen and/or phosphorous may limit the biomass increase and carbon sequestration potential of afforestation in nutrient limited areas.[36] Furthermore, long-term increased nutrient demands from afforestation can lead to decreased soil nutrient availability, thereby exacerbating nutrient limitation within the ecosystem.[37,38] The introduction of trees, with high productivity and nutrient demands into nutrient limited ecosystems, can introduce nutrient foraging or mining by symbiotic mycorrhizal fungi. Mycorrhizal fungi associations increase the nutrient supply to trees, but may lead to the breakdown of complex organic matter containing both essential nutrients and carbon. This carbon is then more vulnerable to be lost into the atmosphere through microbial decomposition, resulting in a loss of carbon from the soil in some forested areas.[39,40] Therefore, nutrient availability and the effect of afforestation on nutrient cycling must be carefully considered when planning afforestation projects to ensure the intended carbon sequestration outcomes and to avoid unintended consequences on ecosystem nutrient cycling.

In areas with high pre-existing soil carbon stores such as, peatlands, tundra or moorlands, afforestation may result in the loss of stored carbon to the atmosphere, likely due to changes in the soil microbial community and nutrient requirements of trees.[39,41,42]

Even when afforestation projects successfully sequester carbon, that tree biomass carbon store is temporary and limited to the life of the tree, unless the resulting timber is preserved. Furthermore, carbon stored in tree biomass is also vulnerable to be lost due to extreme weather events such as droughts, fires or hurricanes, or due to disease and to insect outbreaks. Afforestation may even exacerbate negative climate impacts such as increased fire risk or severity and lowering surface albedo in boreal and arctic regions leading to increased warming.[43–45]

Afforestation for carbon sequestration and emissions offsetting could pose a risk to food security due to reductions in land available for agriculture and food production. This risk is increased if afforestation becomes an economic alternative to agriculture due to the financial incentives of the offsetting market, resulting in productive agricultural land being converted into forests.[46] Several recent studies have found that land-based climate mitigation can put high levels of strain on food security.[47–49] There is wide spread agreement that climate stability should not be achieved at the cost of reduced food security, in line with the United Nations Sustainable Development Goals that promote zero hunger as well as climate action.[50] However, afforestation and reduction of agricultural land may lead to increasing food prices, reduced food availability and, consequently, negative impacts on populations at risk of hunger.[46] It is clear that these unintentional yet potentially dangerous side effects of financially incentivised afforestation for emissions offsetting should be considered carefully to avoid causing more harm than good.

The high level of focus on afforestation may erroneously imply that there is a single solution to the climate crisis. There is a growing body of work which suggests that the restoration and protection of peatlands, which store about twice as much carbon as global forest biomass, will play a key role in carbon sequestration and climate change mitigation policy.[51,52] The role and importance of blue carbon sequestered in oceans, coastal ecosystems and mangroves is gaining increasing recognition.[53,54] All of the various nature based solutions to fight climate change and sequester carbon are likely to have positive impacts if they are carried out in a considered, ecologically and socially robust manner.

RESULTS

Estimates of financial limits to offsetting and Net Environmental Valuation of fossil fuel companies

Fossil fuel companies sell oil, coal and gas. This produces positive economic value. But while doing so, they also generate CO_2, which economists call a negative externality. Externalities have been subject to a large literature.[55] Here we asked, what would be the value of these companies if they had to compensate financially for this externality? The value of a company is determined by its assets net of liabilities. For fossil fuel companies, assets include buildings, extraction machines and to a large part, fossil fuel reserves. Liabilities include loans, bonds issued and debt to shareholders. What is not accounted for in the liabilities of fossil fuel companies is the cost of offsetting their carbon emissions. Here we calculated the valuation of fossil fuel companies, net of that externality. That is their value if they had to fully compensate the CO_2 from burning their reserves (see the appendix for discussions of the limitation of this approach).

We refer to this metric as the Net Environmental Valuation. The Net Environmental Valuation represents the value of a fossil fuel company after subtracting the cost of offsetting its future emissions. This conceptual valuation is not a market valuation but helps understand the extent to which fossil fuel companies can bear environmental externalities. If a company's Net Environmental Valuation is negative at a given carbon price, it indicates that its societal value is negative. Currently, fossil fuel companies are not taxed on their scope 3 emissions (or the burning of the fossil fuel they extract), nor do they typically offset these emissions, though some do offset scope 1 emissions (emissions occurring during the extraction process). The Net Environmental Valuation explores the potential impact on a company's value if they were to offset scope 3 emissions or if a tax on these emissions were implemented. A strong assumption we make in this article is that fossil fuel companies would have to offset only downstream emissions from the product they sell (scope 3 emissions), and not their direct emissions from running their companies (scope 1 and 2 emissions), which are excluded from this study. Scope 3 emissions are the most important for fossil fuel companies, and they are therefore crucial for a successful transition. This is why we focus exclusively on these emissions.

Although the Net Environmental Valuation has no direct practical applications, it can be likened to a provision for liabilities in accounting. For example, a car manufacturer might set aside provisions for potential lawsuits. Similarly, if a global carbon tax on scope 3 emissions were established or if fossil fuel companies chose to offset these emissions, they would likely record a corresponding liability. The Net Environmental Valuation estimates the company's value after accounting for this potential cost. It is calculated by subtracting the cost of offsetting future CO2 emissions from the company's market capitalization, providing a new perspective on the valuation of fossil fuel companies. It is calculated as follows:

$$Net\ Ecological\ Value\ (NEV)_i^n = Market\ cap_n - (CO_2\ reserves_{CO_2}\ \times\ Offset\ price_i\ )$$

To estimate the offsetting cost of fossil fuel companies, we operate in two steps. First, we rely on estimates by Fossil Free Funds of the potential future CO_2 in the balance sheet of fossil fuel companies. The database contains data about the 200 companies owning the most fossil reserves (underground proven reserves, not burned or sold yet).

We do not choose a price of carbon in this paper, but there are estimations of what a ton of CO2 should cost to its emitter. The most used is the social cost of carbon. It calculates the marginal cost of the impacts resulting from emitting an additional ton of carbon. There are different estimates available. Estimate of the social cost of carbon are at around $185 per tonne of CO2.[20] The US inflation reduction act used a measure of $180 and the latest estimates by the Environmental Protection Agency (EPA) in the United States has set it at $190. We will use this last figure in the next section. Note that our approach comes with many limitations, which are all outlined in the methods section.

Keeping these limitations in mind, we run a simulation at prices from 0 to $150 as offsetting prices to find at which point all fossil fuel companies in our sample reached a negative Net Environmental Valuation. Note that as 150$ is under the social cost of carbon (around 190$), our findings also apply to the social cost of carbon.

CO_2 offsetting pricing has led to a large literature [56–58]. But here we take an approach requiring no a priori knowledge on carbon offsetting prices. We simulate carbon offsetting prices to find the point at which current major fossil fuel companies all reach a negative Net Environmental Valuation. At an offset price of $1/T$CO_2$e, 26% of companies reach a negative Net Environmental Valuation, at $8/T$CO_2$e, 50% of companies, and at $150/T$CO_2$e no company has a positive Net Environmental Valuation (Figure 1).

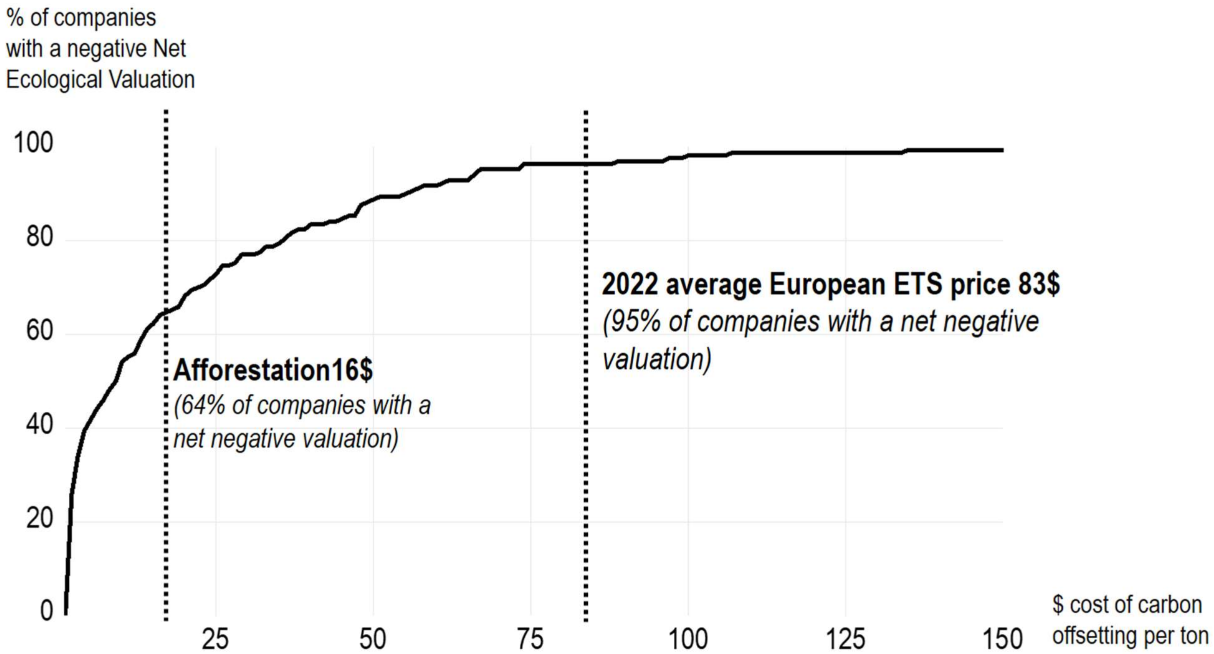


Figure 1: Simulation of Net Environmental Valuation for fossil fuel companies. For prices ranging from $1/t$CO_2$ to $150/t CO_2, the percentage of companies in the 200 largest traded fossil fuel companies that have a negative Net Environmental Valuation was evaluated. At $150/t CO_2, all fossil fuel companies have a negative Net Environmental Valuation. At the social cost of carbon (around 190$), all fossil fuel companies also have a negative Net Environmental Valuation.

In the supplementary materials, we analyse actual market offsetting prices. Our reference price for afforestation is $16 per ton of CO_2e. To estimate a carbon market price, we use the 2022 average cost of CO2 on the European ETS carbon offsetting market, which is $83. The European market is the largest offsetting market in the world and hence gives a good sense of a carbon price. For direct air capture, we rely on the current price around $1000 per ton for direct air capture by an existing and running offsetting plant in Iceland. We used these three reference prices to assess the Net Environmental Valuation of fossil fuel companies. Afforestation is the cheapest with the OECD estimating the cost starting at $16 per ton of CO_2e. At this cost, 36% of the companies in our data set would still have a positive market valuation if they tried to offset all the potential emissions of their current reserves (64% of companies would have a negative valuation). Using the 2022 average European carbon market price ($83), 95% of the companies would have a negative Net Environmental Valuation. Finally, using direct air capture at the current cost of the technology ($1000), all companies in the dataset would have a Net Environmental Valuation.

Aggregating the company results to global estimates offers perspective. If we sum up the total market capitalisation of the 200 largest oil, gas and coal companies in our sample, we get a total value for these companies of $7.01 trillion. But if we wanted to pay for the offsetting of these companies, it would cost $10.8 trillion (tree offsetting), $59.29 trillion (ETS Carbon Market) or $673.7 trillion (current direct air capture technology). These numbers are 11%, 62% and 701% of global GDP (see calculations in the appendix). This means that offsetting emissions of current reserves of fossil companies with direct air capture would cost up to seven years of global human economic production. All wealth generated by humans globally during a 7-year period would have to be reinvested into carbon offsetting. Looking at the cost of offsetting, the takeaway is that it is likely be more effective to stop these emissions in the first place rather than offsetting them.

Even if direct air capture technology drops to 150$/t CO_2e, the Net Environmental Valuation of fossil fuel companies would still be negative. Our survey in the appendix shows an average of studies estimating the price of direct air capture at around 400$/t$CO_2e$ (with a range from 94-1000$/t$CO_2e$). This means that if fossil fuel companies were to offset their emissions, direct air capture would unlikely offer a financially viable solution. The cheapest solution in monetary terms (afforestation), offsetting all current fossil fuel companies proven reserves would still cost $11 trillion with 36% of the largest fossil fuel companies having a negative Net Environmental Valuation. And this does not include the cost of acquiring the land required.

Looking at the largest fossil company in the world, Saudi Aramco, the valuation of the company at the time of writing is $2.2 trillion. Offsetting its reserves with afforestation would make its value be divided by four to only $482.9 billion. If it had to offset its emissions at the ETS average price at 83$, it would drop to a negative value of $6.6 trillion. If it was to offset its emissions at the current cost of direct air capture ($1000), the value of the company would fall at a staggering -$103.9 trillion (or a bit more than global GDP for comparison). This shows that offsetting is not an option for Saudi Aramco or any of the companies in our sample.

While our estimates consider real market cost of offsetting, we can also compute the Net Environmental Valuation of fossil fuel companies against the social price of carbon. This is not a market value like the prices we used before. Yet, it is a good measure of the current estimate of policymakers for the cost of emitting an additional ton of carbon. If we use any of these suggested prices for the social cost of carbon (180-190 for 2022), the Net Environmental Valuation of fossil fuel companies goes to 0. Put another way, if we think the social cost of carbon is at the right level, running a fossil fuel company is not a financially viable enterprise. Or if a government wanting to run one of these companies did a cost-benefit analysis, it should decide against running the company at this level of social cost of carbon. For now, the social cost of carbon has been mostly used for public investment projects. As Figure 1 shows, any social cost of carbon above $150 leads to the conclusion that running a fossil fuel company generates negative value for society.

Spatial limitations of emissions offsetting through afforestation

We provide estimates of the surface needed for afforestation by the largest fossil fuel companies. The largest 200 fossil fuel companies own 672Gt CO2e in reserves. How much space is needed to offset this CO2 by afforestation? We get a sense of the global carbon capture potential by estimating the maximum potential capture by afforestation on our planet. We also compare the potential future emission from the reserves of the largest fossil fuel companies with different countries to get a sense of the scale of offsetting needed. Our approach focuses on afforestation as a natural offsetting method but acknowledges key limitations, such as the limited availability of suitable land and the competing ecological, cultural, and economic values of un-forested areas. The simulations presented here abstract from these broader considerations, serving as an upper limit rather than a definitive guideline for offsetting potential. Furthermore, large-scale afforestation may have ecological impacts that could undermine its effectiveness, a topic explored further in the paper (the appendix offers more detailed limitations).

We try to estimate the maximum afforestation potential of our planet. This estimate is given as a hard physical limit of afforestation, not a recommendation. We then use this estimate to give the reader a sense of the space needed to offset future planned emissions by all fossil fuel companies, as well as historical human emissions. We are not the first to produce such estimates. Griscom et al. present a sequestration rate of 10.3 $GtCO_2$/year using 678 Mha by 2030, Lewis et al. find 154 $GtCO_2$ on 350 Mha over a time period of 70 years, and Bastin et al. show a potential of 752 $GtCO_2$ using 900 Mha without specifying a time period.[24,59,60] However, this last number is disputed [61,62] and it would potentially take over 100 years. Our contribution, however, is to offer a maximum rather than a realistic estimate. This shows the limitation of offsetting, which is the focus of this paper.

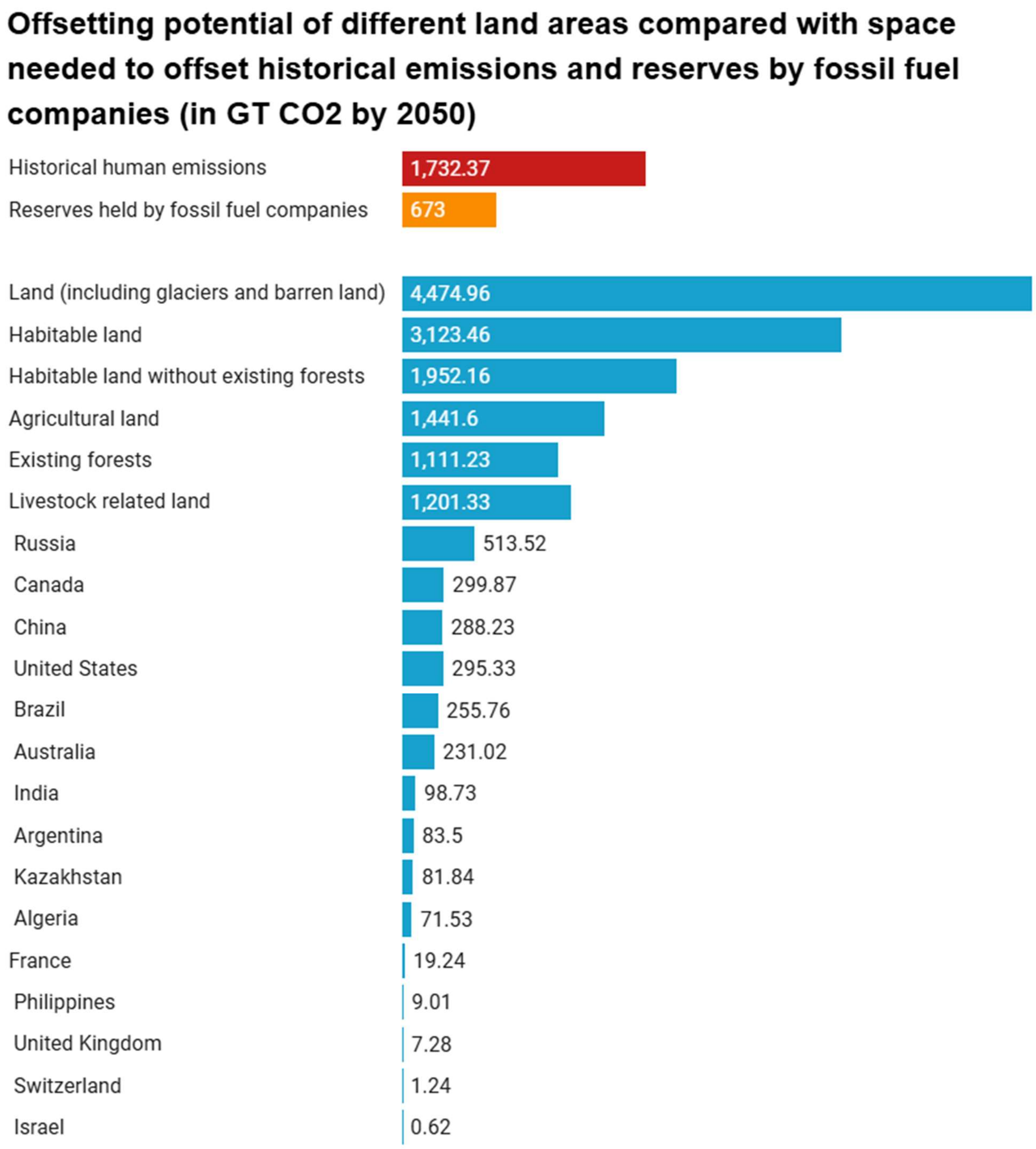
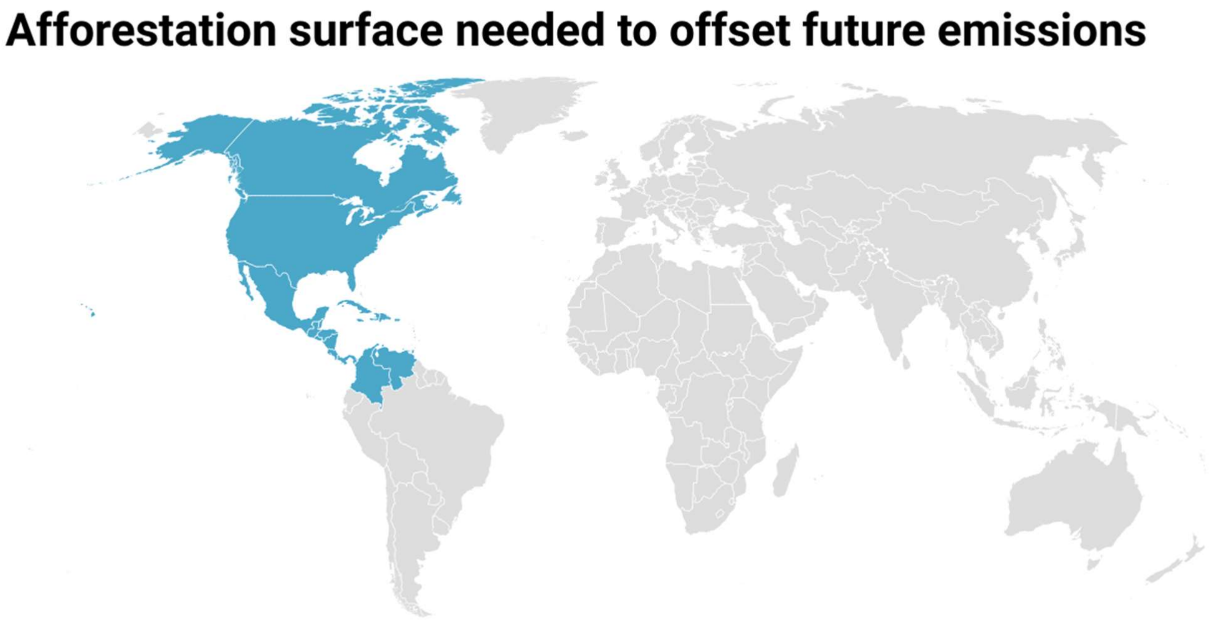


Figure 2 - Comparison of space needed to offset historical emissions and fossil fuel reserves by the 200 largest fossil fuel companies.
Note: Habitable land is a theoretical construct as given by the difference between total land mass removing the glacier (10% of the total land mass) and barren land (19% of the total land mass) such as deserts, dry salt flats, beaches, sand dunes and exposed rocks. The figures are from Hannah Ritchie and Max Roser (2013) - "Land Use". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/land-use'.

We ask a theoretical and abstract question, to better understand issue with offsetting by afforestation. How much CO_2 can our planet absorb through afforestation by 2050? And how much space is needed to offset future potential fossil fuel and past emissions through afforestation. To do this, we ran a thought experiment to show the maximum offsetting potential of our planet. We ask, how much CO_2 could our planet absorb if we removed everything (cities, roads, agricultural land, existing forest and everything that is on land), and replaced it with trees. This is of course not realistic, but doing so gives us the maximum offsetting potential of our planet. Appendix 6 gives the step-by-step calculations. Put simply, we take regional offsetting potential per hectare from the literature, and multiply it by the space on all continents, except Antarctica.[15] We use this to generate a total offsetting estimate for earths total land surface as well as an estimate per km^2.

We then use this last metric to compare the space needed with the size of different countries. Our comparisons in figure 3 (a and b) offer an idea of what the offsetting requirements represent in geographical terms. Offsetting all the emissions of all reserves of the 200 largest fossil fuel companies would take more land area than that of North America and and part of South America. (panel a). And if we tried to offset historical emissions from fossil fuel and cement, all agricultural land would have to be replaced by forests from now until 2050. In terms of land, it would cover all of North America, Western Europe and around three quarter of Africa (panel b). Note that these figures are not realistic, they are a representation. Think of them as an artist sketch. They are wrong as they suggest afforestation in places where trees cannot be planted, such as mountain tops, deserts or lakes. Their point is only to give the reader a visual understanding of the scale of the space needed to offset planned and past emissions. They are also very rough approximations, though as explained in the many assumptions of this paper, likely a lower band.

a)



b)

Figure 3 (a and b) – Illustration of the space needed to offset historical and future planned emissions by afforestation.

Note: data for afforestation per continent from Bernal et al. (2018) (see also the appendix, Table A6). Land surface' data from the United Nation for each country. The first map represents afforestation for future emissions which are estimates around 673 and the surface on the map would offset 673,70 GT CO_2. Historical emission are estimated around 1732.37 and the area on the map would offset 1732.43 GT CO_2. The slight mismatch is due to the fact that we only color entire countries on the map. Note that the surface is a simplification as it include all land on this surface, including barren land, mountain ranges or lakes. This is why this is not an accurate map but only a visual representation to give an order of magnitude.

Discussion

In this paper we showed the financial, spatial and ecological limitations of carbon offsetting. The issue is important as most climate scenarios include offsetting, alongside reduction in emissions. We focused mostly on fossil fuel companies, as they have started to communicate about offsetting as a solution to CO_2 emissions. While our findings come with many limitations and simplifications outlined in the paper and appendix, we offer global estimates of the practical limitations of carbon offsetting.

We show that there are financial limits to offsetting. If we take an offsetting price of the current price on the European ETS market (around $83 for 2022), 95% of fossil fuel companies would have a negative market value (we called it Net Environmental Valuation). If we wanted to offset the current fossil fuel reserves with afforestation by 2050, it would require afforestation on the equivalent whole of North America, necessitating the removal of all existing infrastructure, agricultural land, and urban areas. This would offset around 590 Gt CO_2 while fossil fuel companies have reserves that could generate 674 Gt CO_2. To offset all human historical emissions from fossil fuel and cement, more than half of our habitable land (or all non-barren land) would have to be covered by trees.

We show that even if afforestation has climate benefits, there are also many risks and limitations. Nutrient availability, water supply, temperature, soil suitability, and the suitability of different areas for afforestation should be carefully considered. Carbon stored in trees is temporary, vulnerable to loss due to extreme weather events, and must be preserved to retain sequestered carbon. In addition, afforestation for carbon sequestration could affect food security due to the reduction in land available for agriculture and the negative consequences of afforestation to biodiversity as it mainly involves monoculture.

Fossil fuel companies are becoming more engaged with offsetting, and policymakers are increasingly focused on net zero timelines and negative emissions targets. But what we show in this paper is that there is no way around emissions reduction. Technologies like direct air capture makes it prohibitively expensive to extract fossil fuel in the first place and offset it later, even in within the next decades. Afforestation, while financially more viable, poses unsurmountable challenges of land use and ecological limitations, in a world with a growing population in need for more living space and agricultural land. In short, it is economically cheaper to stop extracting fossil fuel, than to burn it an offset it later when the social cost of carbon is taken into account.

While we show that the priority is on emission reduction over naïve offsetting, this does not mean that forest conservation and restoration should not be a policy objective in and of themselves. Forests play a critical role in reducing human impact by sequestering carbon, conserving biodiversity, and maintaining ecological functions essential for life on earth. These natural climate solutions, though not a substitute for offsetting large scale emissions, are indispensable for addressing the multifaceted challenges of climate change and achieving a sustainable future.

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Methods

1. Limitations, important simplifications and caveats – financial limits

Our approach relies on a few important simplifications. The assumption is that fossil fuel companies would have to offset only downstream emissions from the product they sell (scope 3 emissions), and not their direct emissions from running their companies (scope 1 and 2 emissions), which are excluded from this study. Scope 3 emissions are the most important for fossil fuel companies, and they are therefore crucial for a successful transition. This is why we focus exclusively on these emissions. Also, we assume that fossil fuel companies would use all their fossil fuel reserves. This is because in terms of company valuation, the value of fossil fuel companies includes all assets and because fossil fuel companies are trying to burn as much of these reserves as they can [63]. But regulation or other factors could stop them from using all their reserves.

Another important caveat needs to be kept in mind when interpreting our results. We use potential emissions from reserves, and fossil fuel companies do not have as much control over these emissions as they do over the ones during their production process, for example. Another limitation of our Net Environmental Valuation is it that it only considers greenhouse gas emissions of fossil fuel companies. The impact of these companies on nature is much broader and also includes land use and other pollutions which are overlooked in this study. Our estimates of Net Environmental Valuation might also be too optimistic. Even companies with a positive Net Environmental Valuation might still not be liable to operate their business. A company having to pay as much as half of its entire market value in offsetting costs is likely to go bankrupt as well. Finally, also biasing our estimation downward, is that our afforestation cost does not include land purchase. An afforestation project in Manhattan would cost more than $16 per ton if land has to be purchased first. Despite all these caveats, our estimates are a first simple attempt at internalizing the carbon externality of fossil fuel companies.

There are issues with using the market valuation in the Net Environmental Valuation. Investors might already have priced in part of a price of carbon or offsetting. If investors believe that regulators will limit the use of fossil fuel, they will discount the value of fossil fuel companies. While this is a possibility, it is unlikely to be a short term possibility, as fossil fuel companies and investors know that demand for fossil is unlikely to drop globally over the next few decades [64].

Note that our database from Fossil Free Funds only presents data of proven reserves (1P) for ranking oil and gas companies. Proven reserves are the ones that are 90% likely to be extracted soon, usually in 10-15 years. Probable reserves have a 50% chance of extraction but they are excluded from this exercise. This means our calculations here are closer to a lower band. For coal, Fossil Free Funds uses the latest reported coal reserves from the S&P Global Database, after a reasonableness check. These reserves are the mineable part of a resource. They assign reserves to listed companies based on their ownership of each mine.

2. Limitations, important simplifications and caveats – spatial limits

Before diving into the approach presented here, let us first list some simplifying assumptions and limitations to our approach (in additions to the ones presented in the appendix for the first part). One limitation of our approach is to only use trees as natural offsetting methods. Offsetting by peatland restoration can likely generate better outcomes than afforestation, but estimates are harder to find and the practice is not available at a large scale commercially yet. It may not be feasible at a large scale due to climatic and hydrological limitations. Also, we only consider single offsetting projects. This assumes that all afforestation projects would never revert back to another land use, which is unlikely to be the case and will bias our estimates downward [65].

One major limitation of afforestation as a means of emissions offsetting is available and suitable land area. This breaks down into several key areas including; physical land area available, land suitable for tree growth, conflicts with other land-uses or ecosystem types and important food security implications. There is land on earth where afforestation is possible, but this land often belongs to someone. Ownership can be understood in a legal sense, but it can also be functional or emotional [66]. Land is rarely unutilised or devoid of ecological, cultural, or economic value.. It often serves a purpose for humans or animals, even when they do not have formal ownership of it. Un-forested land has inherent value culturally, for biodiversity, ecosystem services and for carbon sequestration which should not be forgotten [29,30]. Because of this it is important to take a broad ecological perspective on landscape restoration [67]. We abstract from these considerations here to only focus on surface needed, but these limitations would of course also play a role in the applicability of these offsetting simulations presented here. The simulations presented are therefore more of an upper limit of what can be done than a guideline. Furthermore, afforestation would need to be implemented at a scale which is likely to have ecological impacts that may undermine such offsetting efforts [36]. We further explore ecological limits of afforestation for carbon sequestration in the literature section in the body of the paper.

3. Cost as percentage of world GDP

The paper offers estimates of offsetting cost in percentage of GDP, here are how these are calculated. It is understood that, if the cost would be incurred, it would affect GDP and hence there would never be a cost going above GDP. These are given only as a benchmark in the same sense debt to GDP ratio are given for example.

200 largest fossil fuel companies tons of CO_2e	Carbon prices	Cost (in USD)	World GDP (in USD)	% of world GDP
6.7373E+11	16	10 779 672 640 000	96 100 000 000 000	11%
6.7373E+11	88	59 288 199 520 000	96 100 000 000 000	62%

	6.7373E+11	1000	673 729 540 000 000	96 100 000 000 000	701%
Source	CU200	See below	calculation	World Bank for 2021	calculation

Table A1 – global estimates of cost of offsetting the reserves by the 200 largest fossil fuel companies

4. Carbon offsetting price data overview

One of the goals of the paper is to have an understanding of the market value of carbon offsetting. This is the cost you would have to pay *today* if fossil fuel companies wanted to offset emissions. This price is likely to evolve if there is new offsetting technology available. The price might also increase if there is more demand for offsetting, regardless of technologies. Here we refrain from making projections of the future. Instead, we aim to empirically find a wide range of available carbon prices. This range can then be compared with the results in the main body of the paper where we look at Net Environmental Valuation of fossil fuel firms for to $150.

Below is our review of the different prices for our three offsetting methods: tree plantation, compensation certificate purchase on the European ETS market and direct air capture compensation. The point of our offsetting cost search is to have a realistic lower, middle and upper band and a mix of technologies. Our analysis in the main paper provides estimates for any price from 0 to $150.

Afforestation or tree Plantation

The cost of planting trees is estimated in a meta study between 10 and 100\$/tCO_2 in the United States.[68]. The OECD estimates the cost of forest conservation around 4-9\$/tCO_2 and 16-25\$/tCO_2 for afforestation.[69] In simulations, estimates between $5 and $100 are used [70]. We take the value of $16 from the OECD as a lower band.

Carbon market price: the price of the European Union Emissions Trading System 83.02\$/tCO_2

The European Union Emissions Trading System (EU ETS) is a CO_2 trading mechanism. It allows companies which generate less CO_2 than plan to sell excess CO_2 generation capacity. It is labelled as a "cap and trade" system, where the legislator sets a maximum CO_2 cap and private market participants can then trade these rights to emit CO_2. Trading happens on a centralised market, which allows to have a daily price of carbon.

European market price (an average of $83.02 in 2022, as of 20.07.2022): Companies exchange their emissions quotas on a carbon market with each other. They pay for the "extra" emissions caused by their activity, which is a form compensation or offsetting.

Direct air capture

Carbon capture and storage is a technology that involves removal and storage of CO_2 directly from the atmosphere. There are several technologies and research on the topic evolves fast. Here we offer a non-exhaustive review of prices we found to give a bracket of prices for direct air capture. Direct air capture also provides us with an upper band price that we use in this paper. This price is based on the cost of offsetting carbon today at the Ocra plant run by Climeworks, as this is one of the few sources of offsetting available today.

Note that direct air capture is also limited as it is not possible to directly capture CO_2 emissions produced by long-distance aviation and marine transport [71].

The table below provides a quick overview of the prices we found from existing projects or from estimates in the literature. The literature also offers a projection of around 200 USD/tCO_2 by around 2050.[72]s This would mean that according to their projection, even by 2050 technology would not allow for a positive Net Environmental Valuation for the fossil fuel companies analysis.

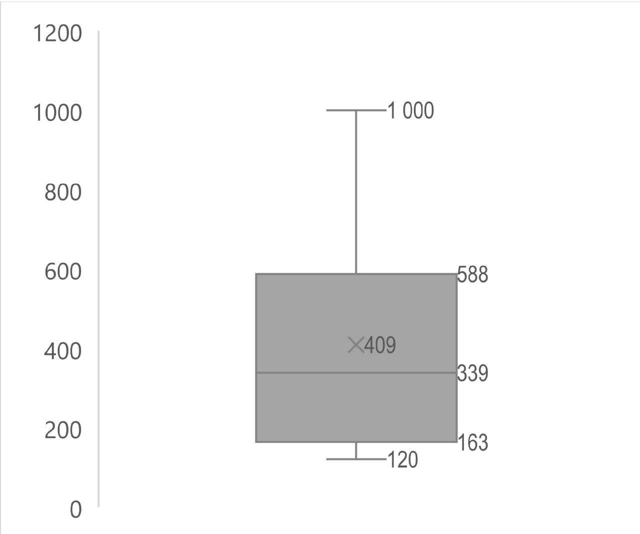

Fig. A1: Upper and lower band of major direct air capture costs. The figure shows the mean, median, min and max for direct air capture offsetting costs.

	Existing projects or companies				Theoretical estimates			
	Ocra plant, Climeworks[2]	Climeworks[73]	Carbon Engineering[74]	Global Thermostat[3]	Fasihi et al. 2019[71]	Keith et al. 2006[75]	Keith et al. 2018[74]	IEA[4]
Cost estimate	$1000	$600	$163	120	177.5	500	163	550
Cost min			$94		133		94	100
Cost max			$232		222		232	1000

Table A2 – Estimates of offsetting cost from the literature and current commercial providers

Looking at Figure A in comparison, we can see that the largest part of direct air capture fall outside of the $150 limit by which all fossil fuel companies attain a negative Net Environmental Valuation. In other term, regardless of direct air capture or technology, all fossil fuel companies would have a negative Net Environmental Valuation.

[2] Cost of 1000 euro (https://www.ft.com/content/8a942e30-0428-4567-8a6c-dc704ba3460a) worth close to $1000

[3] Data from the following source: https://singularityhub.com/2019/08/23/the-promise-of-direct-air-capture-making-stuff-out-of-thin-air/

[4] IEA report available here: https://www.iea.org/reports/direct-air-capture

5. Afforestation space needed for each fossil fuel company

Capture Rate database

We combine data from Bernal et al. (2018b) on land offsetting potential with the data from Bastin et al. (2019a) on available land for tree plantation. This last figure is compiled by the author for each country based on satellite pictures and a machine learning algorithm. Bernal et al. (2018b) provided us with data about the area available for Forest Landscape Restoration (FLR) Activities. FLR activities are activities that can be carried out in order to restore vegetation in an area such trees plantation, natural regeneration, agroforestry, mangrove regeneration and mangrove shrub. The paper also provided us with the carbon capture rate (amount of CO_2 that could be absorbed by the vegetation from an FLR activity) by year for each activity in tCO/year/ha (a range of the 20 first years, then another of the 40 following years), and these in 3259 regions in 177 countries. To get countries estimates for the capture rates, we assessed an average weighted by the available area for FLR Activities in each region. Then we obtained a dataframe containing the average capture rates for FLR Activities in each country

Calculation of the surface needed for compensation

To calculate the surface needed, we used estimates from the capture rates database we created. We computed the surface needed by 2050 (in 27 years) as this is the date of many net zero pledges, either by fossil fuel companies themselves, or by governments that regulate them. We also do another estimation over the lifecycle of a hectare of forest based on estimate by (Bernal et al. 2018b) The idea behind this second assumption is that an afforested or reforested plot of land will be a carbon sink until maturity. At maturity, our model here assumes that absorption stops, and that the hectare has a net zero effect as carbon sink. This is a simplification, but it allows for a clear model.

Our data is based on the following calculation made for each company's underground reserve:

$$Surface_{2050} = \frac{CO_2}{Absorption_{Tree\,Type}^{0-20\,years} \times 20 + Absorption_{Tree\,Type}^{20-60\,years} \times 8}$$

Table A3 shows the estimates for the largest 10 fossil fuel companies in hectares. Let us look at an example to define our approach. Take Saudi Aramco, a company mostly owned by the Saudi government. The company would need afforestation on 458 million hectares or 213% of the surface of Saudi Arabia to offset its future emissions. This means that the Saudi government would not have enough land in its own jurisdiction to offset the emissions of the company. It might therefore have to buy land abroad to offset its national oil production, which might lead to legal questions not investigated here. If the Saudi government instead decided to turn to direct air capture, it would cost more than the entire value of Saudi Aramco and it would become more economically viable to simply shut down Saudi Aramco.

Fossil fuel company	Country of registration	Area needed in registration country to offset reserves[a] (Mha)	Multiple of total country surface needed	Multiple of available reforestation surface in country
Saudi Aramco	Saudi Arabia	458	2.13	504.63
Coal India	India	293	0.89	29.6
Gazprom	Russia	251	0.15	1.66
Shaanxi Coal Industry	China	85	0.09	2.12
Adani Enterprises	India	81	0.25	8.1
China Shenhua Energy	China	61	0.06	1.52
Rosneft	Russia	119	0.07	0.79
Kailuan Energy Chemical	China	41	0.04	1.02
China Coal Energy	China	32	0.03	0.8
Exxaro Resources	South Africa	31	0.03	3.87

Table A3: Space needed by10 largest fossil fuel companies to offset their emissions in the country of head office and its available area.
[a] By forest regeneration as defined by Bastin et al. (2019)

Of the fossil fuel companies examined in Table A3 there is a huge range in area needed to offset their reserves from 31 – 458 Mha. This large range of area needed combined with the area available in the country of registration provides an estimate of whether each company can offset its reserves within its country of registration. This is the case with companies such as Roseneft or China Coal energy, but this is not the case for most of the companies listed. In fact Coal India requires almost 30 times the available reforestation area within its country of registration and Saudi Aramco requires almost more than 500 times the available reforestation area within its country of registration (Table 1). Note that the case of Saudi Aramco is extreme due to the largely ecologically unsuitable conditions for afforestation in Saudi Arabia.

6. Maximum global offsetting calculations

This section explains in details of how offsetting estimates are generated. These estimates rely on heavy assumptions. They are therefore to be taken with a lot of caution. If anything, they represent a maximum capture potential of the planet, more than a realistic policy to be implemented.

First, we take estimates of carbon capture by geography generated by Bernal et al. (2018b). Table A4 reproduces these from the original source, along with the 95% confidence interval.

Natural regeneration	Years 0-20 - Removal rate tCO_2 ha-1 year-1 (95% confidence interval)	Years 20-60 - Removal rate tCO_2 ha-1 year-1 (95% confidence interval)
Asia and Oceania Humid	11.9 (±3)	17.3 (±1.2)
Asia and Oceania Dry	10.3 (±1.7)	3.5 (±0.9)

Europe All	9.8 (±1.7)	4.5 (±0.8)
Africa Humid	17.4 (±2.1)	7.9 (±1.7)
North America Humid	11.1 (±3.3)	10.9 (±1.8)
North America Dry	9.1 (±2.1)	8.2 (±1.2)
Central America and Caribbean Humid	11.9 (±1.7)	7.1 (±1.5)
Central America and Caribbean Dry	10.4 (±1.4)	0.2 (±0.7)
South America Humid	18.8 (±2)	5.2 (±1.4)
South America Dry	13.8 (±3.3)	3.1 (±1.6)

Table A4 – tree absorption data from Bernal et al. (2018b)

Table A5 takes these numbers and multiplies them by the number of years until 2050. So that is 20 years at the growth rate from trees from 0-20 years estimated by Bernal et al. (2018b) and then 5 years at the rate 20-60 (accounting for the 25 years between 2025 and 2050). This is the amount per hectare that trees in different regions can absorb until 2050. Note that here we assume that all these projects will not be stopped by 2050, which is unlikely. This makes this number an overstatement.

	Removal rate by 2050 tCO_2 ha-1 (95% confidence interval)
Asia and Oceania Humid	390.5 (±66)
Asia and Oceania Dry	262 (±38.5)
Europe All	256.4 (±38)
Africa Humid	438 (±50.5)
North America Humid	351.5 (±75)
North America Dry	271 (±48)
Central America and Caribbean Humid	315 (±41.5)
Central America and Caribbean Dry	240.5 (±31.5)
South America Humid	449 (±47)
South America Dry	356.5 (±74)

Table A5 – Tree absorption potential by hectare (data from Bernal et al. (2018b) calculated until 2050

The next table, Table A6, then groups the different regions to get their CO_2 capture potential. Here there are two important simplifications. First we take the total landmass of these regions. We ignore anything that is already present on the land surface of these continents. This could be agricultural land, cities or other types of surfaces. It also excludes the fact that some of these landmasses might not be able to welcome trees. Again, the idea here is to reach a maximum offsetting potential rather than a recommended or realistic offsetting measure. The second simplification is that we take the average for each continent between humid and dry capture potential. While this is a gross oversimplification, taking only dry or only humid does not fundamentally change the results in a significant measure. We then take the total of the different continents to obtain a global potential CO_2 capture for the entire planet. Note that all estimates exclude Antarctica which is unlikely to have much of a CO_2 capture potential by afforestation.

The total obtained of 4300 is the absolute maximum that our planet could offset by 2050. Note that this number is also limited by the fact that it would imply replace current forests with new forests, which is likely to offset CO_2. But again, this number is an absolute physical maximum.

We also ran the same simulation until 2083, or 60 years from now. This is the maximum CO_2 capture potential according to Bernal et al. (2018b). The idea is that a forest would stop being a net CO_2 sink after 60 years. Imagine that trees would start to decompose an emit the CO_2 that they have captured into the atmosphere again. The maximum capture potential on the earth's landmass by 2083 is 8 092.35 (±1 354.3).

	A (in tCO_2 per km2) Removal rate by 2050 tCO_2 km-1 (95% confidence interval)	B (in km2) Continent area in km2	AxB (in $GtCO_2$) $GtCO_2$ removal by 2050 (95% confidence interval)
Asia and Oceania	27400(±5225)	53 125 000	1455 (±277.6)
Europe	21850 (±3800)	10 000 000	218.5 (±38)
Africa	38750 (±5050)	30 365 000	1176 (±153.3)
North America	4975 (±6150)	24 230 000	605 (±149)
Central America and Caribbean	24975 (±3650)	521 876	125.9 (±1.9)
South America	3475 (±6050)	17 814 000	617.7 (±107.8)
Total		136 055 876	4086 (±727.6)

Table A6 – Tree absorption potential by continent and global total

Finally, in an effort to make these number more relatable, we compare them to existing land surfaces. This last exercise is done only to give the reader an intelligible comparison. To do this, we take a value of average global capture potential by 2050. This number is in A6. It is 4086 Gt CO_2 for 136,055,876 km2. Or 30 033 T CO_2 per km2. We then compare, for illustration only, this number to surfaces known to the reader: countries. We also compare this to surfaces linked to human land use such as total agricultural surface, built land and so on.

Global historical CO_2 emissions data

Data from the Global Carbon Project (2022) offers global estimates of human emissions from fossil fuel and cement since 1850.[2] They estimate global CO_2 production at 472807.73 Mt of carbon, or 1732367.51 Mt CO_2 or 1732.37 Gt CO_2 since 1850. While there were emissions from the burning of fossil fuels from 1750 to 1850, these data offer a good approximation for global human emissions from the burning of fossil fuel and cement production.