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A novel burden-sharing approach: allocating responsibility for carbon dioxide removal to the Carbon Majors.

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Nadia Bates
Berlin, January 2023

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"It is unethical for a bearer of great causal responsibility who is able to repair or alleviate a very harmful situation to which she is actively contributing to ignore her obligations to stop contributing to harm." (Cuomo, 2011, p. 705)

Introduction

The premise for this master thesis is based on two scientific facts that are widely supported in the literature: the transient climate response to cumulative CO2 emissions (TCRE) (Collins et al., 2013), and the unavoidable implementation of carbon dioxide removal (CDR) in order to not exceed the Paris Agreement Long Term Temperature Target of limiting global warming to 1.5 degrees, a condition that crucially also holds for pathways with *no or limited climate overshoot* (Rogelj et al., 2018, Fajardy et al., 2019).

Whilst the allocation of the remaining CO2 budget and subsequent trading of carbon credits has been relatively well covered in the literature in the context of CO2 emission *mitigation*, the discussion is less thorough in the context of CO2 *removal* (Fajardy and Mac Dowell, 2020) and even sparser when concepts of equity and fairness are incorporated in burden sharing approaches. Fyson et al. (2020) begin to fill this gap, conducting an analysis of possibilities for sharing the global CDR burden by implementing different equity-based approaches. This offers an insightful alternative to the common approach of using the least-cost-distributions produced by optimization primed integrated assessment models (IAMs), which rely on normative assumptions that costs should be held at a minimum by balancing potentially negative impact of mitigation on economic growth against the reduction of future climate damages (Frisch, 2013). Whilst IAMs provide an economically efficient pathway for regionally disaggregated CDR deployment, they do not consider equitable allocation of responsibility regarding the large scale deployment or financing of CDR, exemplified by the findings that applying different equity considerations shifted responsibilities between low-emitting countries with high CDR potential and high emitting countries bv a magnitude in the range of hundreds of Gt CO2 (Fyson, 2020). Thus, whilst there is a consensus from the scientific modelling community that the deployment of CDR is inevitable, there is still relatively little guidance in the literature on *how* this will be achieved and, more importantly for the purpose of this thesis, *by whom*.

This, the lack of identifying responsible agents, is a problem, as climate change, commonly identified as a “Free Rider Problem”, suffers from the fallacy of the self-interest of nations and entities being prioritised over mitigation efforts to protect the common good of a (stable) global climate (e.g. Nordhaus, 2015; Cullity, 2006). This is demonstrated by the overwhelming inability of countries to cooperate in international agreements to produce binding and specific targets (e.g. Roy et al., 2020). This realisation supports the endeavour that particular entities should be targeted and called upon to explicitly take on a substantial portion of responsibility for operationalising CDR on the scale required to increase the chance of meeting the long term temperature goal of the Paris Agreement. Similarities can be drawn with the tobacco industry, where increased scrutiny and transparency of the damage done by the industry had far-reaching impacts on the consumption of these products (e.g. Whitehouse, 2015). Parallels have been drawn between the two industries regarding the marketing of harmful products, spreading of misinformation and deliberately misleading the public (this is expanded upon in section 2.3.3), further justifying holding this group of entities- the fossil fuel companies- to account.

In light of this, the group of entities that this thesis will focus on is the *Carbon Majors* (Heede, 2014a,b), a collection of the largest investor, state-owned and nation state producers of oil, gas and coal globally. This choice of target group is justified by the fact that the production and consumption of fossil fuels constitutes the main anthropogenic source of global CO2 (e.g. Olivier and Peters, 2020). Between 2008-2017, emissions from fossil fuels made up 87% of total global emissions, with the remaining 13% stemming from activities related to land use change (Le Quéré et al., 2018). Heede`s groundbreaking research attributes historic emissions *to the carbon producing entities themselves*, as opposed to collecting GHG data at a country level (Griffin and Heede, 2017). According to the research, 90 of the largest fossil fuel and cement producers have been responsible for nearly two-thirds of carbon dioxide emissions since the 1750s (Heede, 2014a,b). Crucially, many of these entities continued to operate and produce harmful emissions, *after* the scientific basis for climate change had been established, which, it can be argued, was as early as 1965, when climate

scientists communicated the risk that carbon dioxide pollution posed for the climate to president Johnson (Revelle et al., 1965). Even after the publication of the first IPCC report in 1990, which marked an international consensus regarding the threat of climate change, most companies did little to change their production processes.
At the time of writing, there has been **no documentation** in the literature of a burden-sharing analysis being conducted for the carbon majors specifically regarding their responsibility for CDR. **The objectives of this thesis therefor are to:**

- ➢ Begin to tackle this gap in the literature through focusing exclusively on a group of entities- the Carbon Majors - that has, to date, been exempt from binding climate change targets and assessing their proportional responsibility in a global context.
- ➢ Provide quantitative values (projections) for the amount of CDR that should be deployed by the Carbon Majors by 2050 and 2100, based on their historic, cumulative CO_2 emissions. This is valuable, as self-proposed and voluntary net zero pledges within the fossil fuel industry are frequently criticised as being too vague and lacking in near-term action (Fankhausen, 2021).
- ➢ Compare how these projected values vary across types of entities (nation states, state-owned companies (SOE) and investor owned companies (IOC)) and within these groups.
- ➢ Demonstrate how CDR projections vary across 1.5°C compatible SSPs, emphasising the importance of early climate action to avoid highly ambitious CDR deployment.
- ➢ Assess the feasibility of Carbon Majors deploying projected CDR quantities by discussing deployment challenges and comparing current action to projected future deployment.
- ➢ Contribute towards the ethical discussion regarding the responsibility major global fossil fuel companies have for climate change mitigation.

Due to model constraints and limitations (see chapter 6), the values provided by the analysis regarding the quantitative amount of CDR obligations in cumulative Mt CO_2 removed by 2050 and 2100 respectively should be viewed more as **providing a broad overview of the range of cumulative CDR amounts required by the different model/pathway combination and the substantial proportion of which, according to**

the line of argument presented in this paper, should be taken on by the Carbon Majors. The purpose of this thesis is thus to provide a **useful resource for highlighting the ethical discussion around allocating responsibility for CDR to the Carbon Majors as well as providing quantitative projections of the range of the amount of CDR required by mid and end of the current century.**
To my knowledge, a burden sharing approach analysis regarding CDR responsibilities specifically for the "Carbon Majors" has not been conducted to this date and thus constitutes the purpose of this thesis.

Chapter 1 will cover the scientific basis for the necessity of CDR in 1.5°C pathways as well as defining what is meant by CDR for the purpose of this thesis.
Chapter 2 delves into an ethical discussion on burden-sharing in regards to CDR. After a brief overview of burden-sharing approaches in the literature, the new approach is introduced, targeting the Carbon Majors by drawing on the principle of **negative responsibility** and uncovering the multitude of characteristics and activities that make this group of entities blameworthy.
Chapter 3 will describe the datasets used and the methodology deployed. Here the data and models used in the analysis and the methodology implemented will be presented.
In Chapter 4, the results of the data analysis will be highlighted. Chapter 5 will open up the discussion. Results will be interpreted and contextualised by scrutinising the current climate change mitigation activities and proposed pledges of the Carbon Majors, compared to their *expected* share of CDR deployment based on their historic emission production activities, as projected by the IAMs. To limit the scope, only the top five Carbon Majors (IOC and SOEs) are analysed.
The discussion will then be widened, critically discussing the feasibility of large scale CDR deployment, particularly focusing on governance challenges. The suitability of the Carbon Majors as a target group will be discussed and alternative culprits, for example the world's billionaires, the *super rich*, will be proposed. Finally, alternatives to CDR deployment will be discussed, drawing on the Societal Transformation Scenario proposed by Kuhnhenn (2018), as well as other pathways attempting to avoid or limit CDR deployment (Holz et al., 2018, Van Vuuren et al., 2018, Grubler et al., 2018).

The conclusion will highlight limitations of the data analysis and subsequent insights drawn. The research will be reflected on and recommendations for future work on the topic will be proposed.

Chapter 1: The scientific basis for CDR in 1.5°C pathways

1.1 Setting the Scene: Linking cumulative CO2 emissions to global mean temperature change

Global warming is the product of the cumulative build up of greenhouse gases (GHG) in the atmosphere. The quasi linear relationship between emission of CO2 and the increase in global temperature implies that the climate response to cumulative CO2 emissions is also linear (e.g. Matthews et al., 2009, Allen et al., 2009). This relationship is described as the transient climate response to cumulative CO2 emissions (TCRE) (Collins et al., 2013). CO2, whilst not being the sole contributor to anthropogenic warming, can be classified as the most important GHG due to its ability to produce temperature changes that are practically irreversible by natural processes in the context of timescales relevant to human societies (Matthews et al., 2018). This irreversibility also implies that even if CO2 emissions were stopped imminently, a substantial percentage of climate change and associated impacts, such as sea level rise, would take place nonetheless (Solomon, 2010). In comparison, GHGs such as Methane or hydrofluorocarbons, also known as short-lived climate pollutants (SLCPs), have limited lifetimes and could *theoretically* be continuously emitted at low, stable levels forever (Rogelj, 2015).

The cumulative nature of CO2 emissions suggest that rather than focusing on the rate of emissions in a given year (flow), the challenge of long-term climate change mitigation is best described as a stock problem (Millar et al., 2016), with the stock referring to the concentration of GHGs in the atmosphere.

1.2 The "what": the carbon budget

The sixth assessment IPCC report unequivocally states that *human* influence has warmed the atmosphere, ocean and land and that the scale of recent changes in the climate system are unprecedented (IPCC, 2021).

Acknowledging this human impact and the constant global response of temperature to cumulative CO2 emissions explained in the previous section, supports the claim that, in order to stabilise global temperatures, *net* anthropogenic CO2 emissions must be reduced to zero (Matthews and Caldeira 2008). In other words, any global temperature target is associated with a finite total amount of allowable CO2 emissions. This finite amount of CO2 emissions, linked to staying below a specific temperature target, has been coined the *carbon budget* in the literature (Allen et al., 2009, Meinshausen et al., 2009, Zickfeld et al., 2009). Thus, high emissions *now* require reduction of a similar calibre in *future* decades (Collins et al., 2013). *Net* Zero stabilises global temperature only if any continued emissions are balanced out by a permanent removal of CO2 (Allen et al., 2020). The IPCC and recent literature offer a variety of methods used to estimate the size of this carbon budget. Despite the neatness of the concept, a range of estimates of future carbon budgets has been published in the literature, mainly due to variations in the definitions and calculations leading to these budgets (Rogelj et al., 2016). Whilst a carbon budget reflecting CO2 induced warming is the simplest to quantify, it should be interpreted with caution for application in the real world, as it ignores the significant impact of non-CO2 induced warming (Rogelj et al., 2016).

It should also be noted that the concept of Net Zero is frequently confused or misinterpreted in the literature, such as equating it to net-zero CO2-*equivalent* emissions or describing specific trajectories consistent with a specific temperature goal (e.g. 1.5 °C). The latter however runs the risk of focusing too much on the specific temperature goal, concealing the fact that ceasing global warming at whatever temperature goal is reliant on achieving net-zero CO2 emissions and decreasing non-CO2 radiative forcing (Fankhausen et al. 2021). Whilst Net Zero Carbon or Carbon Neutral refers to balancing the emissions and removals of *CO2 only*, Net Zero Emissions or Climate Neutral refers to balancing the emissions and removals of *all* greenhouse gases (Peters, 2021). The danger with these various interpretations is that they obscure the necessity of *maintaining* a state of balance over *decades.* Preserving this state of balance over time is not conducive to compensatory action such as relying more on certain climate drivers or carbon pools (Fankhausen et al., 2021). Essentially, it is not possible to achieve a state of net zero (carbon or GHG) by solely offsetting emissions through CDR. Radical reductions in fossil fuel emissions in the *short term* are essential (Peters, 2021). The potential danger of over relying on CDR at the expense of emission reduction will be addressed in chapter 5.

1.2.1 Path Independence

It is worth highlighting that the carbon budget has been claimed, with the help of carbon-cycle and climate models such as MAGICC, to be *independent* of the path that is chosen to reach the temperature targets and the associated point where emissions reach net zero (Zickfeld et al., 2009, Meinshausen et al., 2009). In other words, as long as all pathways reach the *same cumulative CO2 emissions* by the *end* of the century, temperature projections are more or less identical (Rogelj, 2016). This is exemplified in **Figure 1.**

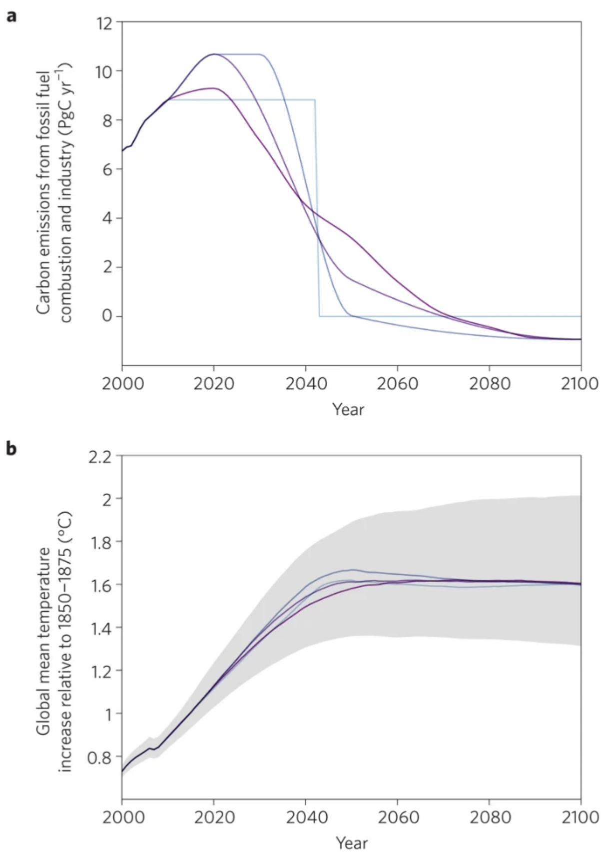


***Figure 1:** Proportionality of global-mean temperature increase to cumulative emissions of CO2, taken from Collins et al. (2013).*

1.2.2 Overshoot Scenarios

Recent literature, however, has questioned the aforementioned independence in the context of overshoot-scenarios. Overshoot scenarios are pathways that temporarily exceed the desired temperature target and consequently rely on *lower* stabilisation levels later on (Matthews & Solomon, 2013). Geophysically, this can only be achieved by deliberately removing CO2 from the atmosphere and subsequent *net negative* emissions (Tokaraska, 2019). Due to the near linear relationship between total cumulative CO2 emitted and global mean temperature rise, high overshoot scenarios and associated smaller emissions reductions in the short term, require deeper long term reductions to meet the specified temperature target. However, the impact of overshoot scenarios on components of the climate system beside global temperature increase, such as sea level rise, ocean acidification and marine net primary productivity are expected to be significant. This is due to the fact that the carbon cycle, unlike the global mean temperature response, *does* indeed exhibit path dependency, with significant implications for environmental change in areas *beyond* global mean temperature rise (Tokaraska, 2019). Whilst for low-overshoot scenarios this effect is expected to be somewhat offset by path dependence in the thermal response of the ocean, for pathways with large overshoots, the impact is much greater (Tokaraska, 2019).
Besides the largely unknown potential impacts on the climate system in dimensions other than global temperature rise, a delay in GHG reductions in the context of a high-overshoot scenario, perpetuates our carbon-intensive lifestyles and heightens the risk of economic and institutional lock in, making the attainment of the temperature target even less likely (Rogelj, 2018).

1.2.3 Short-Lived-Climate-Pollutants (non-CO2)

As mentioned in the introduction, short-lived climate pollutants (SLCPs) could, theoretically, be emitted at low, stable levels forever (Rogelj, 2015). However, in practice, calculating a carbon budget without taking into account the behaviour of non-CO2 gases is impractical and incongruent with reality. This is because the rate of emissions of these SLCPs is significant for near-term climate warming (e.g. Zhongming et al., 2021) ,which becomes especially relevant at the time of peak warming (Rogelj, 2016). Ignoring these SLCPs runs the risk of activating tipping points and inducing irreversible feedback loops in the climate system. Although, for the purpose of this thesis, CO_2 emissions only will be assessed, it is important to highlight the role of these SLCPs, as well as the opportunities they can offer for immediate impact on rising temperatures and consequent safeguarding against potential tipping points (Zhongming et al., 2021). The rate of emissions of SLCPs is directly affected by climate policy, such as changes in agricultural practices. Given the short-lived nature of these pollutants, it is more effective to focus on their present-day emission rate (with adjustment for their long-term impact), as opposed to their cumulative build up over time (Fankhauser et al. 2021). However, the current design of most climate policy, which uses a 100 year time horizon for measuring the impacts of climate change, by default neglects the positive role SLCP mitigation could play (Zhongming et al., 2021).

1.3 Defining Mitigation as CDR

Although the UNFCCC includes the IPCC definition of CDR in the mitigation of climate change, CDR has traditionally been considered separate from mitigation in the literature (Honegger et al., 2021). This separation is likely to be a product of the relative novelty of CDR and the conceptual confusion with geoengineering, commonly occurring when talking about large scale CDR deployment (Honegger et al., 2021).
For the purpose of this thesis, the mitigation burden is explicitly referring to the implementation of CDR. Following on from the approach used in Fyson et al., (2020), the analysis in this thesis will focus on possibilities for sharing this CDR burden, whilst assuming that the reduction of emissions will align with the cost-optimal distribution outlined by the respective pathways.

1.3.1 What is CDR?

At this point, it seems appropriate to clarify what is meant by CDR for the purpose of this paper. CDR is sometimes used interchangeably in the literature with terms such as Greenhouse Gas Removal or Negative Emission Technology. However, this neglects the fact that CO_2 does not impact the climate in the same way or with the same magnitude as other greenhouse gases, predominantly due to their different accumulation rates and lifetimes in the atmosphere.

Simply stated, CDR includes processes that take CO2 out of the atmosphere to stop it contributing to climate change and put it somewhere else, to prevent this from happening (Preston Aragonès et al., 2020). The IPCC, in its special report on Global Warming of 1.5°C, defines it as the "process of removing CO2 from the atmosphere" and makes the link to negative emissions by describing these as the outcome or achievements of CDR (de Coninck et al., 2018). The following definition by Tanzer and Ramirez (2019) provides four principles that can act as guidelines for deciding whether a process can be classed as CDR or not:

1) Carbon Dioxide needs to be physically removed from the atmosphere.

2) The removed carbon is stored in a permanent manner (or at least with the intention of permanence!). Geological storage generally entails this permanence but other forms of storage require continuous management to ensure the carbon is stored securely and for the long term.

3) Any GHGs involved in the removal or storage process (upstream and downstream) are estimated and included in the emissions balance. This is crucial to ensure an adequate representation of the overall process and is a prerequisite for the following principle to also hold:

4) The total amount of carbon dioxide removed by the process is greater than the total amount emitted.

CDR can broadly be separated into two main types:

1) enhancing existing natural processes that already remove carbon, also referred to as carbon sinks and

2) chemical processes that capture carbon and permanently store it somewhere (de Coninck et al., 2018).

It is useful to distinguish CDR from other commonly used terms in the literature including geoengineering and carbon capture. Whilst CDR actually reduces the warming effect of CO2 on the earth by actively removing it from the atmosphere, geoengineering does not change the concentration of GHG in the atmosphere but only focuses on the *symptoms* of climate change (Wilcox et al., 2021). Carbon Capture, unlike CDR, is a point source method for capturing carbon from emissions sources

before it can reach the atmosphere. CDR however has the potential to target non-point sources and sectors that are currently hard to mitigate such as agriculture.
Carbon Dioxide Removal can complement and compensate for what cannot be achieved by emission reduction alone through a portfolio of methods: increasing natural carbon sinks, creating new carbon sinks or through a combination of natural uptake and engineered storage (Keller et al., 2018). In this thesis, two CDR options will be considered: afforestation (establishment of forest on land where there was no forest prior) and reforestation (the planting of trees on land recently deforested, (IPCC, 2000)), hereafter referred to as A/R *and* bioenergy with carbon capture and storage (BECCS), a combination of two climate change mitigation technologies: Carbon Capture and Sequestration (CCS) and the use of biomass as an energy source (Fajardy and MacDowell, 2017), through which CO2 absorbing biomass is burnt and the emissions released by the process captured and stored underground in long-term reservoirs (Brack and King, 2020). Both CDR options will be described in more detail in chapter 3.
Of course the range of possible CDR strategies presented here is not exhaustive, not mentioning engineering options such as Direct Air Capture (DAC) or Solar Radiation Management (SRM). However, for the purpose of this thesis, it will suffice, as **other forms of CDR beyond those described above are rarely included in most current model pathways** (Fyson et al., 2020). Following Fyson et al., (2020), **for the purpose of this paper, CDR will be treated as the sum of negative emissions from bioenergy with carbon capture and storage and land-based sequestration, with the latter including both afforestation and reforestation**. As other CDR forms do not feature in most model pathways, it is assumed that implementing alternative CDR portfolios would not significantly alter the total amount of CDR required in the pathways (Fyson et al., 2020).

1.3.2 The role of CDR in 1.5 pathways

Crucially for the purpose of this paper, it should be highlighted that **all analysed pathways that result in a maximum warming of 1.5 °C degrees rely on CDR to some extent to reduce residual emissions for which mitigation is currently not**

available or very difficult and to incur net negative emissions to decrease warming after a temporary overshoot (Rogelj et al., 2018). Furthermore, a move to a low-carbon energy system would take time and the pace of this change also affects the need for CDR. The International Energy Agency (IEA) predicts that, in order to meet sustainability goals globally, fossil fuel will continue to be needed to meet an increasing demand in energy (Hastings, 2020). Thus, the need for CDR becomes ever more pertinent, as continued combustion cannot be accompanied by a release of CO2 into the atmosphere of similar magnitude (Hastings, 2020). The amount of CDR required to meet the 1.5 °C temperature target therefore depends on the pace of global emission reduction over the next century. The four illustrative model pathways that limit warming to 1.5 °C set out by the SR1.5 (IPCC, 2018a) all rely on contribution from CDR from a variety of sources, though primary reliance is on BECCS and changes in land use cover including afforestation and reforestation (Brack and King, 2020). The dominance of BECCS in IAMs and subsequent IPCC reports can partially be explained by the fact that quantifying it at various carbon prices is fairly simple in comparison to other CDR options (Smith and Porter, 2018). Furthermore, IAMs favour BECCS due to the structure of most models: assuming perfect knowledge of future technologies, cost-optimal design and discount rates utilised, which give more weight to present day expenditure versus future costs (Brack and King, 2002). The challenges of using IAMs for projecting CDR will be expanded upon in chapter 6, when limitations of this paper are discussed.

Dramatic and imminent reductions in global emissions significantly decrease the reliance on CDR for the likelihood of meeting the Paris Agreement goal (Strefler et al., 2018). This is exemplified in **Figure 2**, where we see that pathways with high-overshoot (S5), in which emission reduction are delayed, require a much larger amount of CDR to compensate for this. Despite this knowledge, the bulk of the debate regarding the necessity for CDR has remained within academia and is only beginning to enter policy discussions (Fuss et al., 2020).

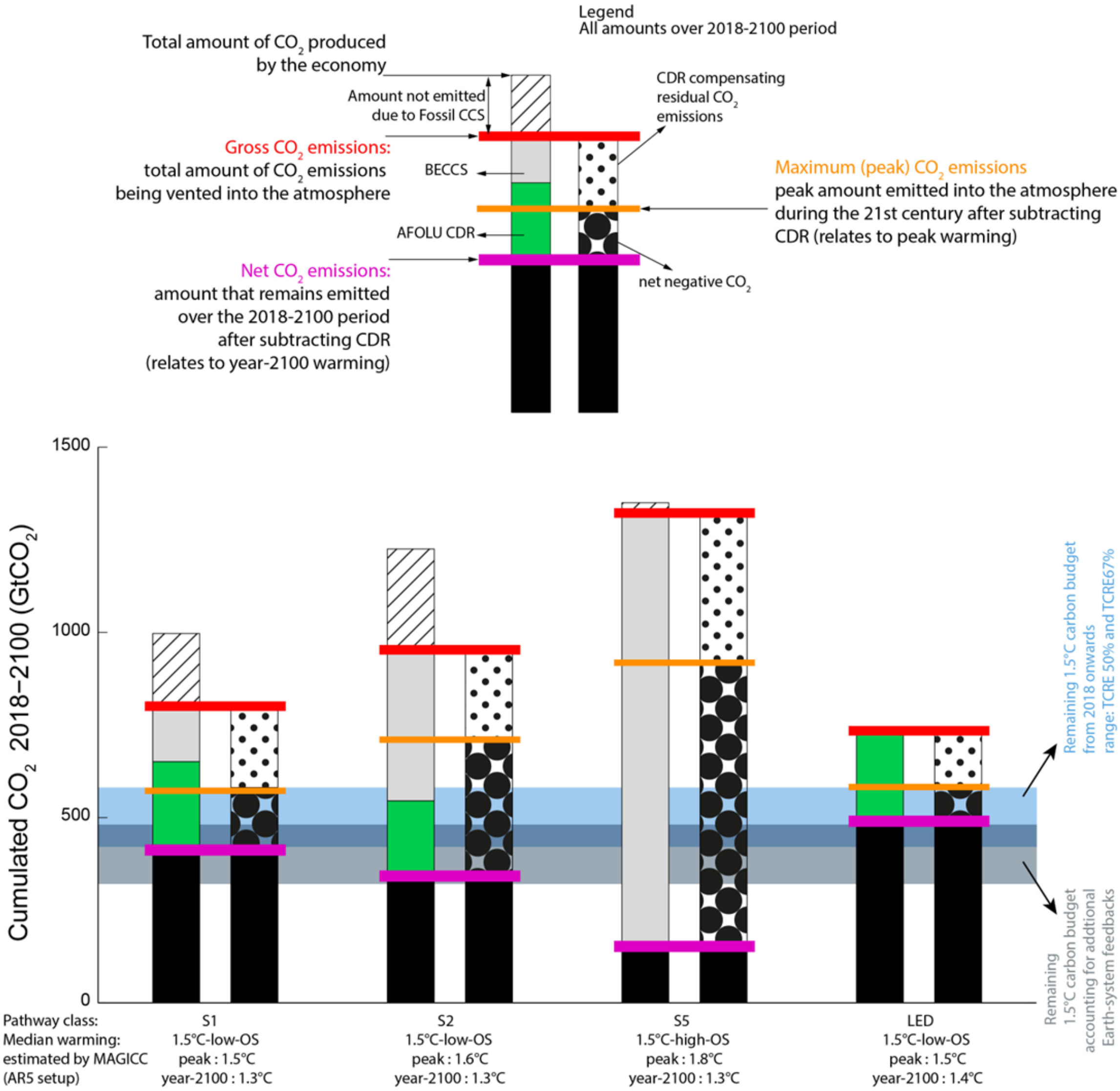


Figure 2*: Accounting of cumulative CO2 emissions for the four 1.5°C-consistent pathway archetypes, depicting the range of magnitude of CDR required across pathways with varying degree of overshoot and temperature at peak emission, taken from SR1.5 Chapter 2 (Rogelj et al. 2018).*

1.4 Separating the "what" from the "how" - building the research question

1.4.1 The "what" - the role of historic emissions in the carbon budget

The cumulative nature of CO_2 emissions in the atmosphere is a complicating factor when attempts are made to allocate responsibility for reducing CO_2 emissions to stay within a determined carbon budget. If warming was determined by an annual rate of emissions, it would arguably be simpler to identify scapegoats and design policies accordingly, as those polluting the most currently would be deemed the most responsible. However, acknowledging the concept of the carbon budget makes it inevitable to examine *historical* data of greenhouse gas emissions - those emissions that have contributed to the stock *over time*.
In light of this, the question becomes less focused on identifying the largest emitters of GHG *currently,* and more about discovering who has contributed most to the stock of CO_2 in the atmosphere *overall.*
As mentioned previously, the concept of a carbon budget is tied to a specific temperature target, at which point the stock is used up and no further emissions can be generated. The long-term temperature goal of the Paris Agreement established 1.5 °C as the long term warming limit. This essentially operationalises the objective of preventing dangerous anthropogenic interference with the climate system, the main goal stated by the UNFCCC in 1992. However, it is important to bear in mind that these scientifically produced targets, whilst providing important information for science-based political decisions, omit critical discourse on questions of responsibility and values, amongst other factors (Schleussner et al., 2016). This will be addressed in the following section.

The concept of the carbon budget and net zero stems from physical climate science, however, ultimately it is the social, political and economic institutions that determine how and when it is invoked and who have to grapple with the fact that these scientific concepts do not exist in isolation (Fankhauser et al., 2021). Furthermore, the size of the respective carbon budget is not specified for individual countries, let alone for non-state entities, such as companies (Fankhauser et al. 2021).

Understanding that climate change is a result of the build up or "stock" of CO_2 in the atmosphere as opposed to the rate of, or "flow" of emissions in each year, is an essential prerequisite for any attempt to conduct a burden sharing analysis regarding future CO2 mitigation strategies, assuming that the burden sharing analysis is based on the commonly used “polluter pays principle”, an environmental guideline that attributes the cost, prevention, control and remediation of pollution to the polluter (Maguire, 2012), as opposed to e.g. a capability approach, in which a greater capacity to act or pay translates into taking on a greater share of the mitigation burden (den Elzen, 2015).

1.4.2 The “how” - sharing the global CDR burden?

Accepting the need for CDR in all pathways, as illustrated in section 1.3.2, the question is less about *what* needs to happen and more about *how* it is achieved and specifically for the purpose of this thesis; *who* should shoulder the greatest responsibility. Whilst the *how* refers to questions regarding the extent of reliance on CDR, timing of deployment and what portfolio of technologies is utilised (Mace, 2021), the *who* seeks to elect a certain group or *groups* of entities in society which should be held largely responsible and subsequently finance and manage the CDR strategies implemented.

How one should spread the cost of climate change mitigation and adaptation across nations and generations has been a prominent feature in debates on climate change, but clear answers are still lacking (Page, 2008). If one can agree that, at least when talking about mitigation and adaptation efforts, the present generation is the only appropriate target audience, given that past generations can no longer act and future generations cannot and should not shoulder *all* responsibility (even though proponents of high discount rates seem to think so!), then one still is confronted with a range of agents and entities to whom responsibility could be allocated to (Page, 2008). To offer some background knowledge on how questions regarding burden sharing have been tackled in the past, the next chapter will provide a brief overview of some of the burden sharing approaches in the literature and then highlight the rationale behind choosing the Carbon Majors as a target group.

Chapter 2: An ethical discussion on climate mitigation burden sharing

2.1 A brief overview of burden sharing approaches in the literature

The literature of burden-sharing schemes in the context of climate change is rich and principles of equity and fairness have increasingly been incorporated, in step with a growing emphasis on these principles in the development of climate policy (Leimbach and Giannousakis, 2019). Zhou and Wang (2016), amongst many others, provide an overview of burden-sharing-schemes, highlighting fairness and efficiency as major initial principles of allocation criteria. They then separate common CO2 allocation methods into four groups which they name: indicator, optimization, game theoretic and hybrid approaches. Relevant to this thesis, they also note that most of the criteria are implemented for allocating CO2 emissions at a *country* level (Zhou and Wang, 2016), which confirms the value of this thesis in addressing the issue of burden sharing at a *company* level. Fairness plays a dominant role in the choice and design of policy frameworks for CO2 allocation and the indicator approach is the most commonly used allocation method, primarily due to it being easily implemented and understood. If efficiency is prioritised, optimization is the most suitable indicator to be used (Zhou and Wang, 2016), confirmed by the design of IAMs. Höhne et al., (2014), corroborate the impact of the choice of equity principle on the outcome of the allocation methods and subsequent distributional impact, especially at a regional level. A recent analysis by Rajamani et al., (2021) added an interesting perspective to the discussion by testing 168 nationally determined contributions (NDCs) to the Paris Agreement against criteria obtained from environmental law, concluding that some NDCs are based on indicators that are *not* aligned with the principles of environmental law, notably those based on minimising costs or *grandfathering.* Thus, the analysis provides states with a benchmark for assessing whether their NDCs are adequate on a global stage in the context of environmental law (Rajamani et al., 2021).

For the purpose of this thesis, two common allocation principles will be briefly expanded upon: The Polluter Pays Principle (PPP) and the Ability to Pay Principle (APP). Whilst both employ the initial principle of fairness, they differ in the choice of indicator to implement the allocation method, with the first selecting historic emissions and the latter current resource availability.

2.1.1 Polluter pays principle (PPP)

The PPP has been widely implemented and incorporated in international agreements. The OECD, the European Council of Ministers and the Commission of Global Governance have all recommended the adoption of the principle on numerous occasions (Caney, 2005). Debates regarding the cost of climate change tend to invoke the PPP, claiming that historical accountability is a just tool for allocating responsibility (e.g. Shue, 1999; Neumayer, 2000). The traditional PPP is limited to identifying *specific* (negative) *consequences* that are the results of a *specific act.* Consequently, the responsible actors should pay for the results of their action. However, in reality and especially in the climate change debate, it is useful to marginally adjust the PPP as we are (in this case) dealing with a group of polluting entities and it is not possible to link specific activities to an exact amount of pollution. It is therefore appropriate to create a more indirect link between the group of polluting entities and the pollution they produce as an aggregate (Caney, 2005). It is however still possible to differentiate responsibility within the group, so that those who pollute more than others are deemed more responsible and consequently should pay a higher cost (Caney, 2005). Traditional analysis that implements the polluter pays principle treats nation states as the principal agents. Consequently countries that have a large record of historical emissions should be responsible for the bulk of emissions reduction in the future. As Caney (2005) points out, arriving at this conclusion might be the result of a process of eliminating other possibilities including individual agents, economic corporations and international institutions. Caney (2005) argues that reasons for this could be that tracing GHG emissions back to individual agents or corporations is not always possible or extremely difficult. Furthermore, Caney (2005) argues that individual agents and corporations exist within the state and can therefore not be treated as separate from it. However, **as this thesis demonstrates, substantial detailed information *can* be and *has* been gathered on the emissions produced by the combustion of fossil fuels by**

major global oil, gas and cement companies. Additionally, the other counter-argument provided by Caney (2005), that corporations exist within the state and are therefore subject to the regulations of the state, does, in my mind, not allow sufficiently for the fact that most major global oil and gas companies operate internationally and therefor their emissions cannot be exclusively allocated to single nation-states. Furthermore, as the analysis in his thesis will show, their contributions to global CO2 emission are of such a magnitude that is indeed justifiable to apply the PPP to the companies within the Carbon Major database.

A crucial objection made by Caney (2005) to applying the PPP retrospectively to nation states is that it actually violates the principle itself, as it does not make the *actual* polluters pay (as these individuals and entities are partially no longer alive). However, Shue (1999) and Neumayer (2000) both object by stating that present generations are to some degree related to previous generations and therefore cannot be claimed to be void of any responsibility and more importantly, present generations continue to benefit from the activities of past agents, which include the negative externalities they caused. The latter point however seemingly invokes a second principle, the "Beneficiary pays" principle (BPP) , which suggests that those nations that have benefitted from a high rate of consumption of fossil fuels in the past, must reduce their consumption and/or pay a price for the higher standard of living they obtained through past consumption (Caney, 2005). However, without wanting to digress too much into the realms of philosophy, an interesting point is made about the BPP by Caney (2005), drawing on philosophical insights from Parfit (1984), which essentially argues that the BBP is flawed because the individuals who currently benefit from the past activities that contributed to the build up of greenhouse gases in the atmosphere would theoretically not exist if these activities and circumstances had not taken place and therefore claiming that they would have had an inferior quality of life had this been the case seems somewhat redundant. Parfit refers to this conundrum as the "*non-identity problem"* (1984), which highlights that we cannot make people pay for something they have benefitted from, as without said event or innovation they would not exist today (Caney, 2005).

If, however, one moves from an individualist to a collectivist position, the previous argument no longer holds as consistently. If we allocate the responsibility to collective entities such as nation states, we no longer face the situation that the agent or entity would not exist if a certain chain of events had not taken place, and therefore cannot be exempt from making some kind of payment to make up for past discrepancies (Caney,

2005). In addition, contrary to Parfit's argument in the previous paragraph, the argument that one cannot compare individuals' standards of living if certain events did not occur does not hold from a collectivist approach, as the existence of countries would not be impacted in the same way (Caney, 2005). However, a final remark made by Caney (2005) highlights the the problem with the collectivist approach is that, by treating individuals as a homogenous entity, one cannot account for the fact that some individuals would have objected to or acted against past activities, and so arguably should not be held responsible for the consequences.
From the discourse presented by Caney (2005), one can conclude that the individualist perspective of the PPP is only useful when assessing responsibility of individuals currently alive, whereas a collectivist approach can encompass past generations as well. The argument of ignorance, claiming that past generations (up to a point) were unaware of the dangerous consequences of their actions, thus only holds from a collectivist perspective (Caney, 2005).

The analysis in this thesis utilises the PPP, as will be explained in chapter 3, by calculating future mitigation shares for companies by taking into account their historic emissions over a specific timeframe.

2.1.2 Ability to pay principle

Under the Ability to Pay Principle (APP) the burden of climate change mitigation is allocated to those with the highest productive capacity, which can be measured for nations by GDP and for companies by annual revenue. Weijers et al., (2010) claim that this is effective, as it results in those who have benefitted the most from polluting activities also being the ones to pay for historic GHG emissions. Said bluntly, the APP disregards the question of who caused or is causing the harm, but targets those entities who have the greatest capacity to *rectify* the harm (Caney, 2010). However, essentially letting poorer nations "off the hook" eliminates any incentive for them to reduce their GHG emissions, with potentially disastrous consequences for the global climate. Furthermore, the principle can also be criticised, as, by treating all rich nations (or companies) the same, it does not allow for differentiation between those who knowingly and continuously produced GHG emissions and those who did not (Weijers et al., 2010), though arguably it is quite hard to imagine how someone could unknowingly pollute, especially after 1990, the year from which the analysis presented in this thesis begins. Caney (2010) therefore calls for a modified version of the APP, in which a distinction is made within the groupy of those able to pay between those who became rich through exploiting the earth's climate and those who gained wealth without endangering life on earth (again, this seems like quite an implausible scenario). In the light of this thesis, the Carbon Majors clearly fall into the former group, as they indisputably made their wealth by producing carbon intensive products whose production and consumption produces CO2 emissions.

A comparison between these two principles will be drawn in chapter 4, highlighting how companies who are making the highest profits currently are not necessarily companies who have the highest historic CO2 pollution track record.

2.2 The main contributors / the research focus

The following section will justify the choice of selecting the Carbon Majors as a target group for taking on a large share of the CDR burden by highlighting the challenges with limiting the allocation of said burden to nation states as well as calling attention to the history and characteristics of the Carbon Majors that underscore their culpability for exacerbating global climate change.

2.2.1 Exploring the how- a note on responsibility

The dominant focus in philosophical discussions regarding the ethics of climate change tends to rest on the responsibilities of nations, with the finger often being pointed at wealthier nations who have profited more from the continuous combustion of fossil fuels and subsequently should shoulder a greater burden of the challenge of reducing GHGs
(e.g. Gardiner 2004; Michaelson, 2021). However, policy and agreements at national or international level often do not adequately incorporate other non-state actors that

contribute significantly to the production of greenhouse gases, one of the most prominent groups being corporations.

In the discussion on responsibility, individuals, as consumers, are often cited as exacerbating the problem through their continuous demand for fossil fuel intensive products, a narrative often encouraged by the fossil fuel companies themselves. However, instead of framing this as being an active choice individuals make, it can be argued that they have been *locked into* this carbon-intensive system by the fossil fuel producing entities themselves. The term carbon or fossil-fuel lock-in (Unruh, 2000) describes the persistence of carbon-intensive technological systems over time, preventing lower carbon alternatives becoming more ubiquitous (Erickson et al., 2015). This is significant, because if these entities were to alter their production processes or invest in renewables, all consumers dependent on their products would automatically be reducing their emissions, regardless of their personal stance on climate change (Cuomo, 2011).

Physical, economic and social constraints mutually reinforce each other, illustrating a severe case of path dependency based on large capital costs, infrastructure lifetimes and the interdependence of social and technical systems (Seto et al., 2016). The "lock in" phenomenon is exacerbated by the fact that human beings are creatures of habit and generally are unlikely to select options that require changing said habits or involve investing significant resources (e.g finding an alternative energy supplier). Seto et al., (2016), claims that there are three, mutually reinforcing types of lock-ins: infrastructural, behavioural and institutional, which in conjunction create a collective inertia (Asayama, 2021). Our reliance on a fossil-fuel intense world is the product of the complex interaction of our institutions, governance systems, cognitive frames and social practices - demonstrating the extensive effort required to move society out of a sustained carbon lock-in (Asayama, 2021).

That being said, social norms and practices are also dynamic and can be responsive to sociotechnical changes and innovations. This is most commonly the case when a technological innovation becomes dominant, thereby crowding out previous practices. An example of this is the decline in cycling associated with the advent of the automobile industry, which dominated in terms of investment and roadspace and offered competitive advantages such as comfort and saving time (Seto et al., 2016).

Thus, whilst individuals are often reluctant to change their behaviour, socio technical innovations can positively impact their ability to do so.

In light of this, this thesis argues that it is necessary to focus on the contribution to the stock of CO2 emissions by a *specific* group of entities, as opposed to targeting nation states or the individuals living within it directly. The partial unsuitability of nation states as responsible agents will be expanded upon in the following section.

2.2.2 The (traditional) focus on the nation state and the problems with this

As mentioned earlier, the traditional approach in the discussion on responsibility for climate change mitigation has focused on the contributions of individual nation states. This is partly explained by the fact that the nation states represent a well suited entity to participate in international discourse about the protection and use of the global commons (Cuomo, 2011). Currently, countries emissions are calculated using a "bottom up approach", following international guidelines. Socioeconomic activities are combined with estimates of the emissions intensity of these activities. However, the accuracy of reporting required varies between countries, with developing countries being allowed to report less frequently, due to the large administrative burden of monitoring and collating the results (Rigby, 2021). An investigation by the Washington Post into 196 countries found that countries across the world are *under*reporting their GHG emissions significantly in some cases. 59% of the gap between reported and actual emissions (measured by other scientific datasets, see Minx et al., (2021), which combines various datasets, top-down atmospheric measurements and expert judgement) is linked to the methods countries employ to account emissions from the LULUCF sector, with countries including the carbon absorbing qualities of the land sector in their calculations, in order to offset emissions from the continuous burning of fossil fuels (Mooney et al., 2021). Furthermore, 45 countries have not submitted a report on updated GHG emissions since 2009 (Mooney et al., 2021). Basing mitigation strategies on inaccurate data presents an obvious problem, as percentage values of emissions reductions will be distorted if baselines are said to be lower than they actually are (Deng et al., 2021).

National inventories, such as those created by members of the UNFCCC are limited to emissions produced within those sovereign territories. However, this method of

emissions accounting neglects the emissions embodied in international trade (David and Caldeira, 2010) and highlights the potential for international carbon leakage and associated concerns over regional and historical inequity of emissions (David and Caldeira, 2010).
Analysing the emissions of nation states can also be misleading for other reasons. A nation´s cumulative emissions can be misrepresentative as they may be attributable to only a small part of the population, meaning that a small part of the population might be disproportionately contributing to the total CO2 emissions of that country (Barros and Wilk, 2021). This is also relevant for per capita emissions, which also need to be interpreted with caution, as they represent average values, generated by dividing a nation's total reported emissions, including all industrial and commercial emissions, by total population (Cuomo, 2011). This value is therefore not necessarily an adequate representation of the emissions of an average household or individual.
This, of course, is very relevant in the discussion on burden sharing. Should we put greater mitigation burdens on individual countries, even if their larger emissions share is actually only traceable to a relatively small group of individuals, in some cases?
Beyond the country level, data from the World Inequality Database shows how, in 2019, the top 10% of global emitters were responsible for roughly 48% of global CO2 emissions, whereas the bottom 50% were responsible for a mere 12% of global emissions in 2021 (Chancel, 2021). Furthermore, the responsibilities of nations cannot be entirely representative of the responsibility of individuals and corporations within it (Cuomo, 2011) as these can also transgress international boundaries and engage in behaviour that is not regulated by governmental decisions (Cuomo, 2011). Furthermore, GHG emissions reported by nations typically do not include a nation's military sector, although the ecological costs of military operations are significant (Gould, 2007) and military operations are often not subjected to environmental policy on the basis that they are facilitating the maintenance of essential national security (Gould, 2007). The Iraq war alone has been estimated to have created more than 141 million metric tons of carbon dioxide equivalent (Reisch et al., 2008).

Thus, a nation-based approach can obscure significant sources of emissions on a country level as well as disproportionately affect segments of the population that have contributed negligible amounts to the global carbon stock. Furthermore, a nation based approach is confronted with the difficulty of accommodating the huge global inequality regarding the relationship between countries GHG emissions and how vulnerable they are to the negative impacts of a changing climate (Althor et al., 2016). As such, countries who are less vulnerable are tempted to become free-riders and disincentivized to mitigate their own emissions (Althor et al. 2016). This notion begins to invoke the APP discussed previously, proposing that those who have the most resources, should take on a greater share of the burden of climate change mitigation (e.g. Shue, 1999). Finally, in the context of CDR, an analysis of long-term national climate strategies demonstrated that whilst CDR is considered necessary, national plans are inconsistent and highly variable regarding the level of detail and intended use of CDR (Buylova et al., 2021).

By abandoning the nation-based approach and selecting a group of entities who *per se* have the capability to fund mitigation action, this consideration becomes somewhat negligible, as arguably *within* the selected group, all entities have the ability to pay, based on their extensive annual revenues, as shown in **Figure 3** (Financial Times, 2022).

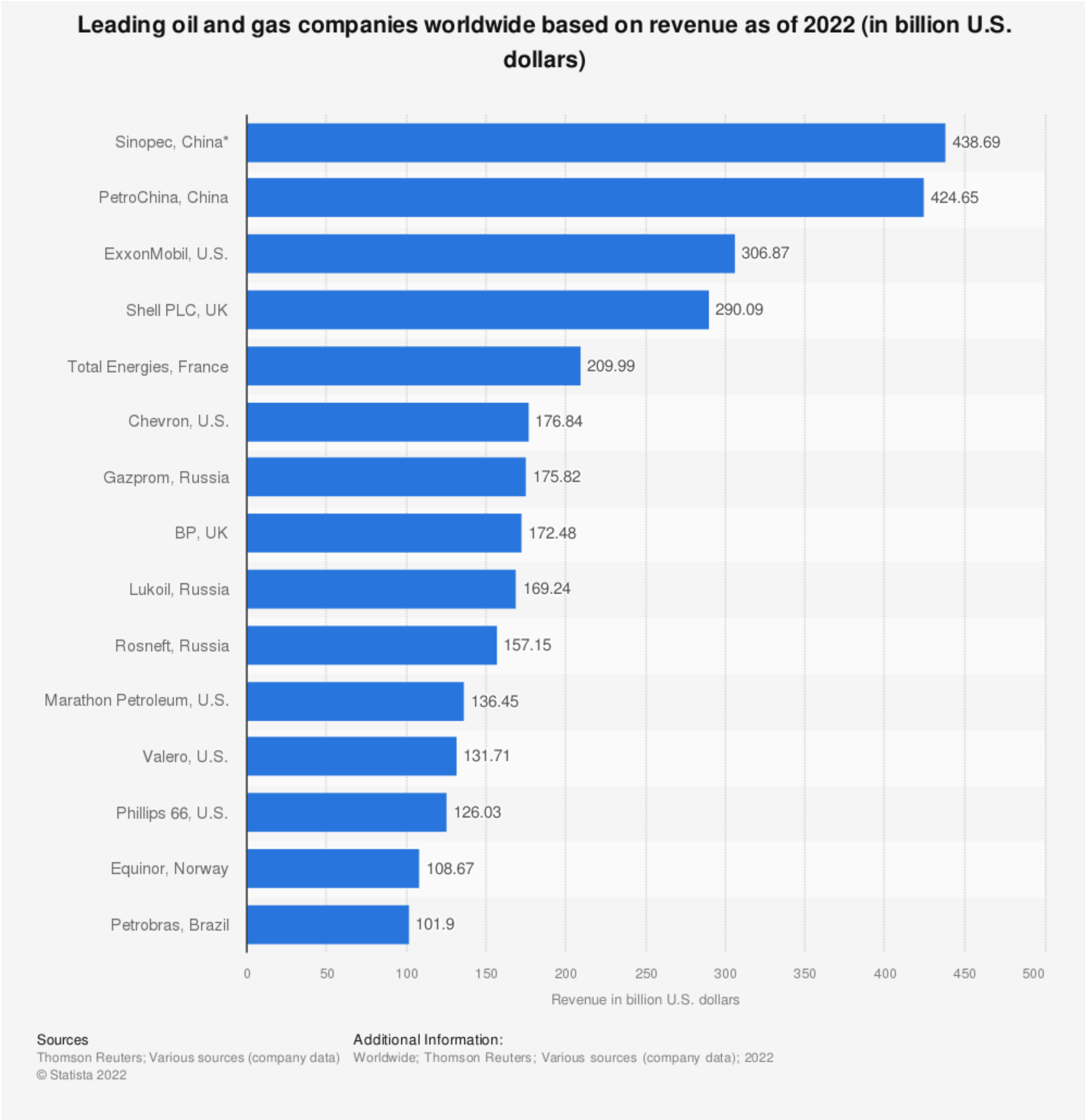


Figure 3: *The top (investor owned) Oil and Gas companies when ranked by their annual revenue in 2022 (Financial Times, 2022), taken from Statista. Original source: Thomson Reuters; Various sources (company data). Note: due to being a state-owned enterprise, Saudi Aramco was not included in this figure. The source notes that Saudi Aramco is the leading oil company worldwide based on daily oil production, at over nine million barrels per day.*

2.3. A new approach to burden sharing- targeting the Carbon Majors

Thus, there is another view emerging in the literature, one that acknowledges that "*nations and international bodies are not the only relevant parties with moral responsibilities related to climate change*" (Cuomo, 2011). Besides from individuals, households, communities and local governments, this also includes corporations.
At this point, it is useful to invoke the concept of "*common but differentiated responsibility*" (Sands, 1992 in Frumhoff et al., 2015) - the consensus that the production of historic carbon emissions has not been homogenous across nations and subsequently, financial profits linked to the production and consumption of fossil fuels also varies greatly between nations. This principle is grounded in a more general ethical consensus that one should allocate responsibility to an individual or collection of individuals (which could also be an entity, group of entities or nations) who created the problem in question (Frumhoff et al., 2015). This allocation becomes even more indisputable if the problem was created *knowingly* (Rawls, 1971). Whilst the concept seems intuitive, in reality, the problem at hand will be multifaceted, involve various players with competing interests and is subject to a multitude of interpretations.

Heede (2014) contributes a novel approach to the burden-sharing debate by tracing GHG emissions *directly to the carbon producing entities themselves*. By doing so, Heede draws attention to the fact that the traditional Annex 1 and non-Annex 1 divide does not account for the fact that nations and companies producing fossil fuels have gained substantial wealth by selling their products on the international market, and many of these nations traditionally belonged to the non-Annex 1 group. This suggests that these entities should therefore shoulder a proportion of the burden for the negative impacts their products have had and are having on the global climate and subsequently be held responsible for contributing towards mitigation efforts (Heede, 2014).

This group of entities will be described in detail in the method section when the datasets for the analysis are presented. However, at this stage, it is relevant to highlight the rationale for targeting this group. Essentially, this can be condensed to **three** major points:

1. the cumulative contribution of CO_2 emissions by this group of entities over time (invoking the *"Polluter Pays Principle")*,
2. the engagement of this group of entities in "*greenwashing*", spreading misinformation and misleading the public.
3. the fact that these entities have the financial and technological capacity to engage in and promote meaningful change and innovation on a large scale based on their extensive revenue and technological know-how (*invoking the Ability to Pay Principle).*

The final point is particularly significant for CDR strategies that involve geological storage, such as BECCS, as in-use oil fields can be suitable locations for carbon storage. However, one should be wary of conflating theoretical capacity with trusting the Carbon Majors to appropriately invest the resources in order to aid the low-carbon transition (Kenner and Heede, 2021).

Essentially, the combination of the three points highlighted above demonstrate that the Carbon Majors *knew* about the harmful effects of the CO_2 emissions stemming from their production processes and use of products, did *little or nothing to ameliorate the situation* and (in some cases) actively *lied* or *misled* the public about the effect of their activities. The relevance of these points and rationale for targeting this group of entities is further strengthened by a rapid increase in climate litigation globally in recent years, a branch of law using legal practice and precedent to hold governments and corporations accountable for their actions and demanding compliance and more stringent mitigation and adaptation goals (see section 2.3.2).
As Shue (2017) points out, the Carbon Majors need to take responsibility for the harm caused by their products by "... *by financing adaptation and participating in compensation for damage and loss in proportion to their knowing contribution to the disruptions...*" . For this to occur, their **proportional responsibility in a global context needs to be established.** This is one of the main goals of the data analysis of this paper.

The following section will further reinforce the claim that these companies should indeed be held responsible by invoking the principle of “negative responsibility”.

2.3.1 The principle of “negative responsibility”

As pointed out by Shue (2017), causal responsibility does not automatically translate into moral responsibility. For this to be the case, the causation must be blameworthy, which it becomes once a socially accepted principle is violated. A causation becomes blameworthy when it *was* possible to avoid the harm and/or if the possibility of causing the harm *was known* at the time the action occurred (Cuomo, 2011). According to Shue (2017, 2015), the Carbon Majors have continuously violated their negative responsibility of doing no harm, exacerbated by the fact that the scale of the harm is of monumental magnitude, threatening the ecological systems that human society depends on for its existence. The Carbon Majors have *actively* engaged in deceiving the public and hindering climate action, knowing that their products are causing harm (Frumhoff et al., 2015). As pointed out by Cuomo (2011), questions about blameworthiness become somewhat redundant when a non-trivial harm *continues* to be caused, when the morally right thing to do would be to end the causation of the harm immediately, even if this incurs extra effort or costs. The following section will provide evidence for the claim that the Carbon Majors were aware of the negative impacts their products were having and, in some cases, actively lied and misled the public on this topic.

2.3.2 Uncovering the evidence - identifying “blameworthiness”

Heede´s research (2014a) reveals that the 90 largest industrial Carbon producers have produced nearly *two-thirds* of all known industrial greenhouse gas emissions since 1751 (Heede 2014a). A popular counter argument to targeting this group of entities is to say that responsibility can only be attributed to an entity if there is *knowledge of the negative* impacts the activities of that entity are causing, which arguably in 1751 there was not. However, Heede is quick to point out that the bulk of these emissions of this group (more than half), have been produced since 1988, a date which neatly aligns with the establishment of the IPCC, whose purpose it is to provide regular scientific

assessments of the current state and knowledge of climate change. 1988 also marks the date when James Hansen, a leading climate scientist testified before Congress that the anthropogenic influence on the global climate had been confirmed by scientific data. Crucially for the purpose of this master thesis, actions following this date *cannot* be cleared of responsibility by claiming to have been carried out in the *absence* of knowledge, regarding the detrimental effects of fossil fuel production on the stability of the global climate (Mulvey et al., 2015).
Furthermore, the literature reveals that, within the fossil fuel industry, an awareness of the risks of climate change was present much earlier than the first publication of the IPCC report (Franta, 2018). Already by 1965, the US President's Science Advisory Committee acknowledged the pollutant nature of atmospheric CO2 (Revelle, 1965) and internal scientists at fossil fuel companies were at the forefront of realising the serious consequences of CO2 emissions (Banerjee, 2015). In their 1968 paper, Robinson and Robbins from the Stanford Research Institute (SRI) warned the American Petroleum Institute (API) of the increase in temperature and subsequent major changes in the world´s atmosphere on an unprecedented scale as a result of rising CO2 emissions (Robinson and Robbins, 1968).

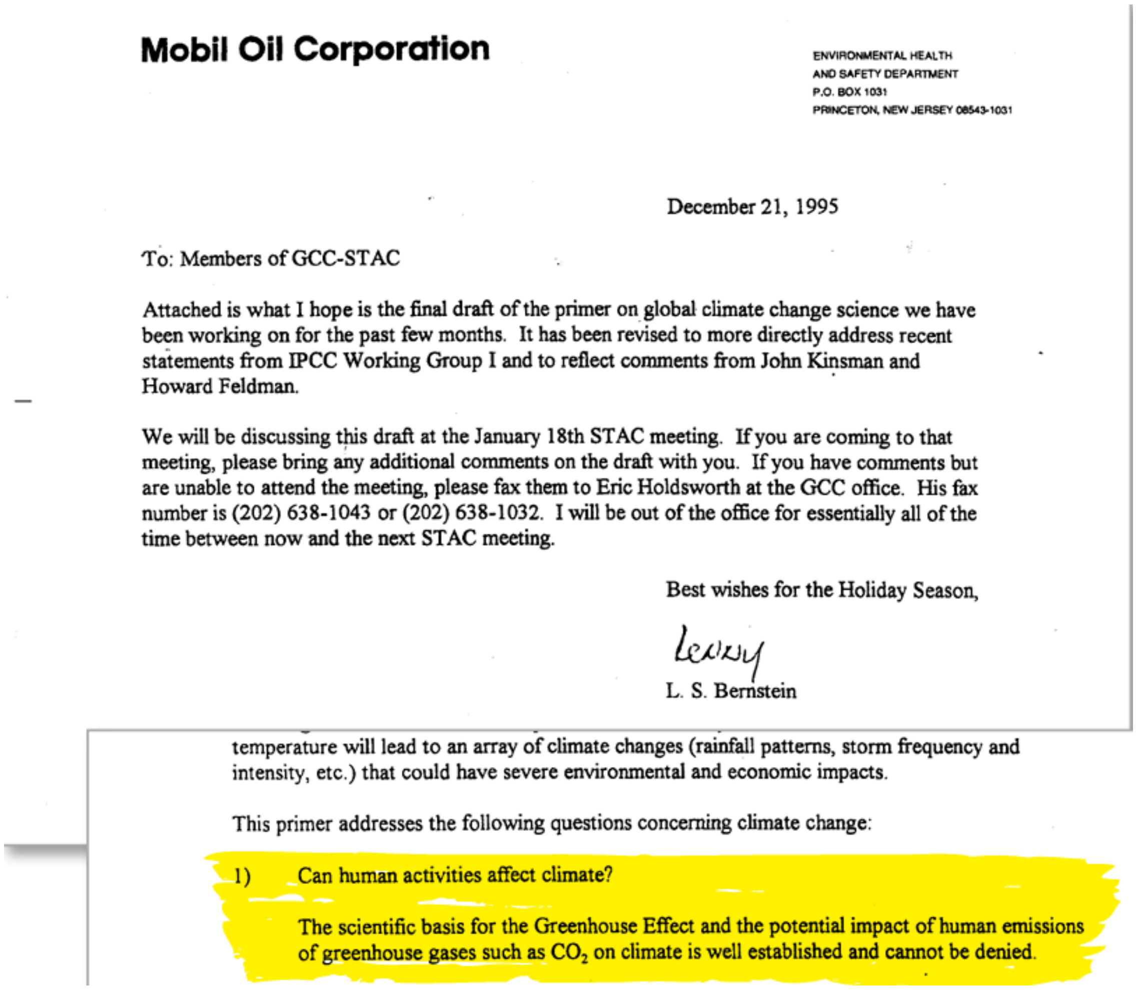
The rationale for targeting producers is collated into five key points by Frumhoff, Heede and Oreskes (2015) in their paper: "*The Climate Responsibilities of Industrial Carbon Producers*". First off, a large proportion of historic emissions can be linked to a relatively small number of producing entities. Second, these producing entities have the internal resources and know-how to be able to access and understand the scientific data. Third, they did not engage in or pursue more sustainable alternatives, instead they *continued* to explore new fossil fuel resources and promote their products. Currently, less than 1% of the fossil fuel companies capital expenditure is invested into low-carbon businesses (IEA, 2020). Fourth, they have actively denied scientific evidence and misled the public and fifth, they have received surprisingly little attention thus far from both academic and policy circles. Grasso (2020a) condenses this line of argument into four morally relevant facts that highlight the culpability of the Carbon Majors: Knowledge, Timing, Capacity and Denial. **The Carbon Majors are therefore in a position of unique agency, based on the notion that they made the *self-informed* choice to continue with the exploration and production of fossil fuels despite being fully aware of the harmful consequences.** Whilst temporary harm can be justified by *necessity*, the continued violation of the "doing no harm" principle by the Carbon Majors since 1965 reflected in their lacklustre ambition to modify their methods or products invokes the other side of the "doing no harm" principle, which can be simply stated as "clean up your own mess" (Shue, 2017). This is also embodied by the "polluter pays principle", which calls for those polluting to cease doing so and additionally compensate those who have been harmed by their actions (Baatz, 2013).

Furthermore, Ekwurzel et al., (2017), by implementing a simple climate model, is able to quantify the impacts of the GHG emissions produced by the Carbon Majors. The study shows that since 1980, emissions produced by the 90 Carbon Majors caused ~43% of the observed rise in atmospheric CO2, ~29–35% of the rise in global mean surface temperature (GMST), and ~11–14% of global sea level (GSL) rise (Ekwurzel et al., 2017) Framing the impacts of the continued production by these carbon producing entities in this quantitative way strengthens the argument that they should be held responsible for their past and present actions.

The case for targeting these companies is only strengthened by investigations that have showcased that they have worked consistently to block environmental laws and regulations that would otherwise curb the extraction and production of fossil fuels, in some cases via spreading misinformation about climate science (Mulvey et al., 2015) and continue to invest in and expand fossil fuel use (Frumhoff, Heede, and Oreskes 2015). A study carried out by the Union of Concerned Scientists (UCS) focusing on eight companies from Heede`s Carbon Major Dataset analyses each company´s climate related positions and actions between 2015 and 2016. Whilst there are differences between the companies, all eight companies studied need to increase efforts to distance themselves from the spread of climate disinformation and *no* company (at time of publication) has laid out a comprehensive pathway plan that envisions a world *free* from carbon pollution and meets the targets of the Paris Agreement.
A report named "*The Climate Deception Dossiers: internal fossil fuel industry memos reveal decades of corporate disinformation*" (Mulvey et al., 2015), represents a collection of internal company and trade association documents obtained through disclosure by invoking the Freedom of Information Act, emerging through lawsuits or by being leaked to the public. The documents provide evidence that the fossil fuel industry has deliberately spread misinformation on climate change science for decades

in the form of carefully planned campaigns. Letters and memos included in the report show that company executives chose to actively deceive the public despite being fully aware of the harm caused to the environment by their products (Mulvey et al., 2015). The evidence compiled in the report shows that major fossil fuel companies including BP, Chevron, ConocoPhillips, ExxonMobil, Peabody Energy, and Shell were aware of the detrimental impacts of their products much earlier than the commonly quoted date of 1989, as representatives of these companies were attending congressional hearings on climate science as early as 1977 (Davies 1990; Gifford 1990; Greenpeace 1990 in Mulvey et al., 2015). An internal assessment carried out by Exxon in 1979 forecasted an array of devastating climate change impacts by 2050, unless the majority of fossil fuels were left in the ground and clean energy systems replaced dirty sources by the 1990s (Knisley and Ferral, 1979).

Yet, in 1989 the Global Climate Coalition was founded, an international lobbyist group that publicly questioned the science of climate change and actively tried to obstruct actions to reduce GHG emissions. By the mid 1990s internal industry experts were well aware of the dangers posed by climate change (**Figure 4**) and facilitating climate change deception (**Figure 5**) evidenced in leaked documents.



Mobil Oil Corporation

ENVIRONMENTAL HEALTH
AND SAFETY DEPARTMENT
P.O. BOX 1031
PRINCETON, NEW JERSEY 08543-1031

December 21, 1995

To: Members of GCC-STAC

Attached is what I hope is the final draft of the primer on global climate change science we have been working on for the past few months. It has been revised to more directly address recent statements from IPCC Working Group I and to reflect comments from John Kinsman and Howard Feldman.

We will be discussing this draft at the January 18th STAC meeting. If you are coming to that meeting, please bring any additional comments on the draft with you. If you have comments but are unable to attend the meeting, please fax them to Eric Holdsworth at the GCC office. His fax number is (202) 638-1043 or (202) 638-1032. I will be out of the office for essentially all of the time between now and the next STAC meeting.

Best wishes for the Holiday Season,

L. S. Bernstein

temperature will lead to an array of climate changes (rainfall patterns, storm frequency and intensity, etc.) that could have severe environmental and economic impacts.

This primer addresses the following questions concerning climate change:

1) Can human activities affect climate?

The scientific basis for the Greenhouse Effect and the potential impact of human emissions of greenhouse gases such as CO_2 on climate is well established and cannot be denied.

Figure 4: *A Letter from L.S Bernstein to Members of GCC-STAC including an excerpt from the first page of the final draft of the Primer on Climate Change Science taken from Mulvey et al., 2015.*

measurement will be taken at one or more as-yet-to-be-determined intervals as the plan is implemented.

Victory Will Be Achieved When

- Average citizens "understand" (recognize) uncertainties in climate science; recognition of uncertainties becomes part of the "conventional wisdom"
- Media "understands" (recognizes) uncertainties in climate science.
- Media coverage reflects balance on climate science and recognition of the validity of viewpoints that challenge the current "conventional wisdom"
- Industry senior leadership understands uncertainties in climate science, making them stronger ambassadors to those who shape climate policy
- Those promoting the Kyoto treaty on the basis of extant science appear to be out of touch with reality.

Current Reality

Unless "climate change" becomes a non-issue, meaning that the Kyoto proposal is defeated and there are no further initiatives to thwart the threat of climate change, there may be no moment when we can declare victory for our efforts. It will be necessary to establish measurements for the science effort to track progress toward achieving the goal and strategic success.

Figure 5*: An excerpt from the American Petroleum Institute (1998): Global Climate Science Communications Team Action Plan internal strategy document outlining a roadmap to facilitate climate deception, with the goal of intentionally confusing the public (taken from Mulvey et al., 2015).*

The task of persuading the public was deliberately delegated to scientists *without* a long history in the debate on the credibility of climate change science and whose ties to the fossil fuel industry would be hidden, to maintain credibility in the eye of the public. These scientists would have to produce peer-reviewed papers that challenged the widely accepted consensus on climate change science (Mulvey et al., 2015). API´s deception strategies went beyond manipulating scientific publications, seeking to target teachers and schoolchildren in order to ensure that an acceptance of fossil fuels would be carried over into the next generation. This was achieved through creating online curriculums for elementary students which glorified the role of non-renewable energy sources such as oil, natural gas and coal by emphasising their convenience and affordability compared to most renewable energy sources (API, 2002). Deceitful behaviour was also uncovered through internal documents that demonstrated how fossil fuel companies created so-called "astroturf" groups, impersonating grassroot consumer movements in order to create the perception that there was opposition to proposed policies on climate change and renewable energy use (Union of Concerned Scientists, 2017). The culmination of this was the creation of fraudulent letters (13 in total uncovered by the investigation), written in the name of *existing* non-profit groups, with the purpose of influencing a vote on an important federal climate change legislation (Mulvey et al., 2015). Franta (2021), confirms the API´s propagation of false and misleading information about climate change as early as 1980, evidenced by a newly discovered document titled *"Two energy futures: a national choice for the 80s",* which essentially confirmed the pollutant nature of carbon dioxide and the causal relation between fossil fuels and global warming (Franta, 2021). The document also deemed the expansion of coal and synthetic coal production to be safe and causing *no* significant environmental damage (API, 1980). Before the publication of the document, a briefing was given by J. Laurmann, a Stanford University engineer, to representatives of the API, including major oil firms. The briefing communicated that a 2.5 degree celsius rise in global temperatures would have major economic consequences, in stark contrast to the message communicated to the public (Franta, 2021).

Besides the API, US coal companies were also involved in deceiving the public about climate science, employing similar tactics to the oil and gas companies. In 1991, the "Information Council on the Environment" (ICE) was founded, which ran advertisement campaigns that deliberately cherry picked data that brought claims of *cooling* temperatures into the public eye, purposefully creating confusion amongst the public. Internal Coal memos uncovered by Mulvey et al., (2015), reveal that the organisation *was* knowledgeable of the long term warming trend acknowledged by the majority of scientists globally. The memo also revealed that the advertisement campaigns were targeted towards specific groups of the population that were deemed to be more "susceptible", notably women and lower income groups (Mulvey et al., 2015). Such deceitful activities continued into the 21st century. The Environmental Protection Agency´s (EPA) clean power plan was attacked by a number of large companies, most prominently the giant coal company Peabody Energy whose coal production would have been limited by the implementation of the clean power plan (Goldman, 2015). The plan was also opposed by other prominent oil and gas industry trade groups representing BP, Chevron, ExxonMobil, and Shell. The American Legislative Exchange Council (ALEC) also continues to act as a prominent outlet for climate misinformation and design of policies that hinder climate action. ALEC´s current stance on climate change is critical, calling it a "historical phenomenon" and claiming that the "debate on natural versus anthropogenic cause" will continue (ALEC, 2015 in Mulvey, 2015). Its website today conveys this message a little more subtly, but the overall attitude remains clear. ALECs annual meetings have featured prominent climate change deniers and internal documents lay bare that ALEC´s task force held frequent closed door meetings which intend to brief state legislators with climate misinformation. These task forces were shown to include members of prominent oil and gas companies including BP, Chevron, ExxonMobil, Peabody Energy, and Shell (Myslinski, 2011). The authors point out that the data collected in this report build a compelling case targeting these companies and holding them accountable and responsible for a share of global warming damages.

In the light of these findings, investigations focusing on specific companies have taken a closer look at their climate communications. Supran and Oreskes (2017) investigated Exxon Mobil´s climate change communications from 1977-2014. After conducting a textual content analysis of 187 climate change communication documents covering a range of formats (internal reports, publications, advertorials etc.), the authors conclude that although Exxon advanced climate science *internally,* it promoted doubt about climate science in its communication with the public, primarily through its advertorials. On the basis of this discrepancy, the authors claim that Exxon Mobil misled the public. Supran and Oreskes (2017) believe that this kind of research can pave the way for challenging how we view the individual responsibilities of fossil fuel companies. This is further supported by the growing field of climate change litigation, which is increasing an awareness that companies cannot get away with continuing to engage in profit maximising activities that negatively impact the environment.

2.3.3 Climate Change Litigation

Another way for making the case that the Carbon Majors should take on a significant share of the mitigation burden is by drawing attention to the growing trend of climate change litigation, especially those cases targeting individual companies. Climate change litigation covers lawsuits that raise concern over law or fact related to climate change science and associated mitigation and adaptation efforts (Burger, 2017). Strategic climate litigation increases awareness of the role of major emitters and utilises the line of argument, that the activities of these companies produce emissions that are linked to climatic change. The 2021 report: "Global Trends in Climate Change litigation" (Setzer & Higham, 2021) highlights that there are currently 33 active cases against Carbon Major worldwide. The majority of these cases are trying to establish corporate liability for the historic contributions of these entities that have damaged the climate, typically by invoking claims that these companies engaged in misinformation and deception regarding their communication about their own activities and climate science more generally. A more recent trend in climate change litigation has seen claimants invoking human rights arguments when holding governments and increasingly also corporations accountable for climate change (Peel and Osofsky, 2018), based on the accusations that these entities are taking inadequate climate protection measures (Setzer and Higham, 2021). One of the most high profile of these cases that draws on human rights law is "*Milieudefensie et al. v. Royal Dutch Shell plc*", in which the court found that the Shell group´s total CO2 emissions were larger than the total emissions of the Netherlands and that the associated impacts on the climate in the Netherlands and the Wadden Region constituted a significant risk for the residents (Nollkaemper, 2021). In a groundbreaking and unprecedented move, the court acknowledged that Shell, informed by international human rights standards, (Khan, 2021), had a legal duty to reduce its GHG emissions in line with the Paris Agreement. The case strongly invoked Dutch tort law, requiring Shell to comply with international human rights obligations, interpreting them in such a way that the Shell group was held responsible for its entire value chain. As the 2015 Paris Agreement represents an internationally endorsed scientific basis, the court concluded that a 45% net reduction in CO2 emissions by 2030 relative to 2010 levels was the appropriate reduction target (Clifford Chance, 2021) and that the reduction of global CO2 emissions cannot be achieved without the participation of non-state actors (Nollkaemper, 2021). Shell´s claim that society as a whole, not just individual companies, should be held accountable for achieving the energy transition, was not found to be persuasive enough to rid Shell of any responsibility to act in line with its *individual partial* responsibility, recognising that individual actors are responsible for their *own* conduct and prevention of harmful effects (Nollkaemper, 2021).

Essentially, this case set a precedent for the **Paris Long Term Temperature goals to inform legal obligations and standards (Nollkaemper, 2021).** The case constituted the first time a company was held legally responsible by a court for its individual contribution to global greenhouse gas emissions (Setzer and Higham, 2021) and thus set a precedent for future trials.

A further growing field is value chain litigation, which essentially incorporates a company's entire value or supply chain in discussions of climate change and responsibility (Setzer and Higham, 2021). This has a significant impact on a company's scope 3 emissions, which are currently often emitted from annual reports or net zero climate pledges.

Finally, so called greenwashing cases have also increased, especially against energy companies. These cases highlight the discrepancies between a company's communication or discourse on climate change and the actual changes it has participated in or pledges it has taken on. One of the most prominent cases is the “State v. American Petroleum Institute", where the state of Minnesota brought charges of deception and misinformation against these major players in the oil and gas industry (Climatecasechart, 2020). The hope is that the direct (legal and administrative costs) and indirect costs (e.g. impact of market valuation an share price) incurred by the Carbon Majors as a result of an increase in climate litigation geared towards them will be of an order of magnitude large enough to instigate changes in policies and behaviour (Setzer, 2021).

The fact that there is a marked increase in climate litigation targeting major oil and gas companies supports the endeavour of this thesis to hold the carbon majors accountable for their cumulative CO2 emissions and efforts to operationalise CDR.

2.3.4 The relative lack of focus on this group of entities until now- the theory of the firm

The lack of focus on this particular group of entities until now can also be explained by the systems and mechanisms that govern them, which are largely voluntary of nature and do not compare to the more stringent emissions limits imposed by nations through a more top-down governance approach (Benjamin, 2016). Adding to this, norms prominent in the commercial environment, such as shareholder wealth maximisation as well as company law and theory do not create a climate where the reduction of GHG emissions is encouraged (Benjamin, 2016). The fact that transnational companies are *not* subject to the more stringent rules of nation states seems absurd in the light that emissions from carbon majors are of a significant magnitude.

The firm, in traditional economic theory, represents an entity that is formed by a number of private contracts that exist with minimal intervention or regulation by the state. As a result, generally, the main goal of a firm is to decrease transaction costs and increase profits. This fits neatly into the greater picture of traditional welfare theorems in economics, under which social welfare is increased through the maximisation of profits (Benjamin, 2016, 2021). However, disagreement about whether the focus lies on shareholder maximisation or maximising the firms´s value, as well as ambiguity regarding the short or long-term nature of this profit maximisation, has led to a tendency to prioritise short-term profitability, which frequently stands in conflict with social and environmental issues that are of a more long term nature (Benjamin, 2016). In economic terms, social efficiency regarding the firm is therefore quantified by increasing shareholder profits (Armour et al., 2009). Costs incurred by dealing with Climate Change are seen as wealth reducing, as they divert funds from investments which could bring shareholders more profit (Hsu and Wang, 2013). Consequently, shareholder wealth maximisation is pursued at the expense of negative externalities and the commodification of the environment (Greenfield and Smith, 2007). As a result, various other purposes and opportunities for firms are no longer acknowledged. Arguably, these shareholder-centric corporate norms are outdated and incompatible with the present climate emergency (Benjamin, 2021).

Chapter 3: Methods

3.1 Global CO2 Emissions 1990-2018

Data for global historical CO2 emissions is taken from the PRIMAP-hist version 2.2 database (Gütschow et al., 2021). This dataset is a combination of several published datasets that together create a comprehensive set of GHG emission pathways from

1850-2018, which cover every country and Kyoto gas. The dataset does not include emissions from international aviation and shipping and does not include emissions from land use, land use change and forestry (LULUCF).

The Dataset includes two “scenarios”: HISTCR and HISTTP. In the HISTCR scenario, country reported data is prioritised over data reported by third parties. In the HISTTP scenario, the reverse is true: third party data is prioritised over country reported data. Third party data is gathered from the CDIAC database (Boden et al., 2017), the FAOSTAT database (FAO, 2020), the Emission Database for Atmospheric Research (EDGAR) and the BP statistical review of world energy (British Petroleum, 2020). A combination of data sources is used to ensure that emission data for the entire time series can be provided. For example, the BP Review of World Energy is used in addition to the CDIAC database, as it is able to provide emission data for recent years, whereas, for example, the CDIAC database does not provide data beyond 2011 (Gütschow et al., 2016). Sources are prioritised, so that those of highest quality are selected for each unit of analysis. Following a similar methodology as that implemented by Le Quéré in his paper on the global carbon budget, the highest priority sources provide the absolute values and lower-priority sources are used for year-by-year growth rates that allow the time series to be extended (Gütschow et al., 2016).

For the purpose of this thesis, the HISTTP category is selected, in the hope to achieve a more objective and unbiased overview of global CO2 emissions over time (see the comment in section 1.5.2 on reporting errors by countries).

The database provides different options for grouping countries together. To capture global historic emissions, the code “EARTH” was selected for, representing aggregate emissions of all countries.

The dataset utilises the IPCC (2006) categories for emissions, as well as some aggregate sectors which are distinguished by the prefix IPCM instead of IPC. The data analysed for this paper is sourced from the category IPCMOEL, which represents national total emissions, excluding emissions from LULUCF.

The gas categories used in the database utilise the global warming potentials (GWP) from the IPCC second or fourth assessment report. For the purpose of this analysis, CO2 only is examined. The units are given in Gigagrams.

The reason why emissions from LULUCF are omitted relates to the high annual fluctuations in this sector, which complicates the combination of datasets as harmonisation of scales between datasets becomes challenging. Fluctuations in this sector exceed those from other sectors that are significant CO2 contributors and can, if aggregated with these other sectors, give the false impression of a trend development (Carbon Tracker). Including LULUCF data has been shown to lead to misinterpretation of the dataset, as sudden changes in emission time series were understood by users as changes in *actual* emissions as opposed to differences in underlying datasets. Providing detailed descriptions of the inconsistencies and limitations of the dataset did not suffice to eliminate these misinterpretations. The inclusion of LULUFC data would therefore not allow the PRIMAP database to meet its requirements of internal consistency and easy usability by a broad audience. This could be amended once the methodology and consistency of LULUFC datasets has improved, as stated by the authors on the PRIMAP-hist website (Gütschow et al., 2016).

It should also be noted that, for the sake of completeness, extrapolation is used to provide the relevant data for some gases and non-Annex 1 countries. Subsequently, short term emissions trends need to be interpreted with a degree of caution (Gütschow et al., 2016). For a full description of the uncertainties present in the individual dataset within the PRIMAP-hist national historical emissions time series as well as limitations regarding the methodology implemented, please refer to the dataset description paper by Gütschow et al., (2016). Notably however, the authors acknowledge that the integration of different datasets will inevitably lead to key differences as methodologies for estimating emissions, definitions of sectors, data and assumptions made about missing data points will all vary.

However, in general, the data coverage for CO2 from the database is of very good quality **and the consumption and production of fossil fuels and production of cement are identified as the largest emission sources**. The authors also state that, despite its shortcomings, the dataset provides a more holistics picture of the historical time series of countries' greenhouse gas emissions than could be provided by any individual source, confirming the usefulness of this dataset (Gütschow et al., 2016).

In order to adequately represent global CO2 emissions in my dataset and subsequently calculate the appropriate amount of CDR necessary to stay on a 1.5 trajectory, I believe it is necessary to include emissions from LULUCF. LULUCF refers to the net sum of CO2 emissions and removals resulting from all human induced changes in land use and land management (Minx et al., 2021). The bulk of CO2 emissions from this sector stem from forestry or changes in land use such as clearing or regrowing natural vegetation, as opposed to agriculture, which contributes larger shares of CH4 and N2O, than CO2 (Minx et al., 2021). This sector has been estimated by the IPCC 5th assessment report to be responsible for 20% to 25% of global greenhouse gas emissions (IPCC 2018, in). As the LULUCF sector includes both carbon storage and removals and is a significant contributor to global GHG emissions, inclusion of this sector in the analysis is vital to paint a representative picture. To do this, I draw upon the FAOSTAT database (FAO, 2020).

3.1.1 CO2 emissions from agriculture and land use

As previously explained, the PRIMAP database does not include GHG emissions from agriculture and land use. To adjust for this, this thesis incorporates data from the FAOSTAT database. For the sake of consistency with the other datasets, data is selected for the period: 1990-2018, although 2019 data is also available. The database was updated in June 2021, combining the previously separate datasets *Agriculture Total* and *Land Use Total* in a single database titled *Emissions Totals*, enabling both FAO and UNFCCC data to be visualised jointly for the first time (FAOSTAT Analytical Brief 25). Within this, the LULUCF entity was selected for the time span 1990-2018, filtering for CO2 emissions only, on a global scale (Area Code: World). LULUCF covers human activities that impact terrestrial carbon sinks, thereby incorporating emissions and removals of GHGs.

3.1.2 CO2 emissions from the Carbon Majors 1990-2018

The data for CO2 emissions for the Carbon Majors comes from Richard Heede`s *Carbon Major research*, which quantifies emissions of CO2 and CH4 traceable to the supply chains of the largest fossil fuel and cement companies that produce oil and natural gas liquids, natural gas, coal, and industrial cement, *as well as the combustion of these hydrocarbons that reach the global economy* (Heede, 2014a). The project traces emissions back to as early as 1854. For this analysis, a more recent version of the

database was provided by Richard Heede directly, including data up until 2018. The data provided will be shared as a spreadsheet in the digital version of this thesis.
In Heede´s research, fossil fuel producing entities were initially chosen based on production data on oil, natural gas and coal from published sources. The threshold for inclusion of a company was set at ≥8 million tonnes of carbon (MtC) per year. The database is kept up to date by adding new entities that meet the threshold as well as tracking mergers and acquisitions. For the latter, historic production is assigned to the extant company. The project reports companies' net production of crude oil and natural gas liquids. In the case where the company only reports data on gross production, net production is estimated by applying a net of gross percentage, in order to minimise the risk of overestimating emissions by relying on gross production data. Reporting is particularly poor for state owned companies, where it is often limited to total production data, which runs the aforementioned risk of potential double-counting.

An array of sources have been utilised by Heede (2014a,b) to minimise potential over-reporting. Heede´s task is further complicated by the fact that companies themselves have been shown to underreport their emissions. Bloomberg Green Analysis (2021) uncovered that the company topping the Carbon Major list, Saudi Aramco, understated its emission by 50% in 2019, as it disclosed only *wholly owned assets*, thereby excluding numerous assets located abroad. Saudi Aramco also does not disclose emissions from joint ventures, nor publicise scope 3 emissions (Rathi & Martin, 2021). This is just one prominent example that highlights the difficulty in compiling a dataset like the one produced by Heede (2014a,b). Gaps in the reported data of companies are completed through interpolation.

The project also subtracts the share of each fuel used for non- combustion purposes (i.e. for non-energy purposes such as steel production, fertilisers and petrochemicals) from the emissions it calculates (again, following IPCC guidelines) for individual companies, as these processes essentially store carbon. It is worth noting that since the increased use of plastic in the 1920s, non-energy uses have also increased. Thus, an overall sequestration rate applied to each year would be overestimating the values for data pre 1980s. However, the fact that half of all emissions have occurred since 1984 somewhat offsets this (Heede, 2014b). A detailed overview of the data on non-energy uses is provided in Heede (2014b).

Industrial emissions from cement production are also included, but limited to process emissions from calcining (as emission from fuel and electricity inputs are already accounted for in the fuel production of other carbon majors). The cement industry is a huge contributor to global CO2 emissions, producing around 8% of global CO2 emissions (Preston and Lehne, 2018). If represented by a country, the industry would follow in third place after the US and China. Cement is the most widely used human made material globally and the second most consumed resource after water (Rogers, 2018), used for the construction of housing, infrastructure and subsequently a key determinant of economic growth, creating direct employment and economic benefits to related industries (Devi et al., 2017 .

Compared to the power sector, cement companies have received less attention as the production process is harder to decarbonise as over 50% of emissions are directly linked to the production process itself and R&D into low-carbon cement has until now yielded few commercial results (Timperley, 2018; Preston and Lehne, 2018).

Given the key role that cement plays in enabling development and the difficulty in reducing emissions associated with its production, an interesting question remains if the emissions should be attributed to the producing companies or to the nations requiring it for infrastructure and housing.

Heede (2014a) recognises the ambition and subsequent uncertainties associated with the Carbon Majors project. Heede (2014a,b) notes that whilst the industrial emissions of CO2 of nations based on their fossil fuel *consumption* is relatively well established, sitting within a fairly narrow range of uncertainty (+/- 5% for one standard deviation (which equates to the IPCC range of "likely", Global Carbon Project, 2012), attributing emissions directly to the producers of fossil fuels is subject to a much wider uncertainty range, due to a reliance on the reporting accuracy of mult-national producers (Heede, 2014a). Adding to this, the carbon content of crude oils can vary substantially, yet for practicality, a general factor is applied to every barrel (Heede, 2014a), thus obscuring this diversity. This is especially prominent for coal, where the carbon content can vary from 32.8% (lignite coal) to 71.6% for anthracite (IPCC 2006 Guidelines for National GHG Inventories, Volume 2). Uncertainties are widely discussed and acknowledged in the Methods and Results Report (Heede, 2014a). An uncertainty range of +/- 10% is estimated for all historic emissions attributed to the Carbon Majors (Heede, 2014a).

For the purpose of this thesis, the CO_2 emissions of the Carbon Majors are analysed for the time period 1990-2018. This is for two reasons: First, 1990 is chosen as a starting point because this marks the date of the first assessment report of the intergovernmental panel on climate change (IPCC) being published, which presents the risks of human induced climate change by providing *evidence* of the phenomenon (Kimuyu, 2017). This is relevant, because it essentially nullifies any previous claims from the Carbon Majors that they were *not knowledgeable* about the impact of their products and can therefore not be held accountable for their consequences.
Second, LULUCF data is prone to uncertainty. Models are needed to separate emissions from the land carbon sink (Gasser et al., 2020) and two types of models are combined to estimate LULUCF emissions: dynamic global vegetation models (process-based) and bookkeeping models (parametric models), with contrasting strengths and weaknesses (Gasser et al., 2020). This is exacerbated by the fact that definition and calculation of LULUCF varies across models (Pongratz et al., 2014).These incongruities are naturally aggravated if the time period under analysis is extended.
Non-extant companies are omitted from the data, as the purpose of the thesis is to calculate future CDR share for the carbon major entities. Therefore, the companies for whom the shares are being calculated *need to still be in existence at time of writing.* Companies no longer in existence in the database include: British Coal; Cyprus Amax, USA; Czechoslovakia (coal); FSU (former Soviet Union) (oil and gas); Ruhrkohle AG and UK coal. Removing these companies from the database does not change the percentage share of global CO_2 of individual companies, as these are calculated by dividing each company by the *global* total, which remains unchanged. However, when separating the carbon majors into respective groups (Nation State, SOE and IOCs), omitting the non-extant companies will change the overall contribution of each group to global CO_2 emissions and subsequent CDR responsibility. However, as four out of the 7 no longer extant companies were in existence for five years or less in the time period under analysis, the impacts of these companies are deemed negligible enough to remove them from the analysis without making further adjustments. If one subtracts the sum of the cumulative emissions of the non-extant companies from the total cumulative CO_2 emissions from all Carbon Majors (incl. non-extant) over the period of analysis, one is left with a difference of 12.524,1 Mt CO_2, which constitutes less than 2% of the total CO_2 emissions generated by the Carbon Majors over the time period 1990-2018.

This is warranted as insignificant enough to justify the exclusion of the non-extant companies from the analysis without further adjustments.

3.2 Integrated Assessment Models

As noted in the introduction, CDR is necessary to balance out sources of emissions that are not possible to mitigate fully, predominantly stemming from human activity in energy and land-use sectors, through natural or technological based sinks (Schweizer et al., 2020).

In order to imagine the future and design pathways that meet global climate goals, scientists employ Integrated Assessment Models (IAMs), which represent geophysical, energy and economic systems as well as the interactions between them, essentially allowing storylines of future development to be quantified (Huppmann et al., 2018). IAMs project emissions based on possible future socio-economic developments, ranging from demographic changes to technological progress. Different types of policy interventions can also be accounted for in the models (Schweizer et al., 2020). Upon introduction of the Integrated Scenario Framework, the use of representative concentration pathways (RCPs) and shared-socio-economic pathways (SSPs) allowed emission scenarios to be modelled in two dimensions, resulting in output that represents particular RCP-SSP pairing (Schweizer et al., 2020). This integrated framework allows a reflection over a range of policy choices, taking into account differences in targets, timing (explored with RCPs) and quantitative and qualitative differences in socio-economic conditions (SSPs) (Schweizer et al., 2020). SSPs represent underlying societal values and commitments that prioritise certain trajectories for global socio-economic development and hereby lead to certain mitigation options being favoured over others. These underlying societal attitudes and developmental trajectories have significant impact on the reliance on and timing of a significant scale-up of CDR (Schweizer et al., 2020).

Thus, IAMs facilitate an understanding of how fast emissions need to be reduced to meet specific temperature goals, but also which portfolio of technologies can best achieve this goal. IAMs can only rule out infeasible pathways based on technological, economic and geophysical constraints (Jewell and Cherp, 2020). **However, what is deemed feasible in a modelling context does not necessarily translate into**

feasibility in the real world, as additional pervasive factors, such as political and social forces, can hinder implementation significantly (Riahi et al., 2015). Furthermore, it is important to acknowledge that IAMs, being optimization models, generally identify *least cost pathways*. This means that when CDR is used in a model, it is considered to be cheaper than direct emission abatement (Greenpeace, 2021), This is a result of the less time-bound nature of CDR compared to standard mitigation (which is applied at the point of emissions occurring) and the discounting of future costs associated with deploying it. From the perspective of an IAM, CDR represents just one candidate from an array of climate change mitigation strategies including, amongst others, renewable energy, nuclear power and efficiency improvements (Tavoni and Socolow, 2013). Other mitigation strategies, e.g. behaviour or lifestyle change which are significantly harder to model, are therefore arguably underappreciated as a result of the model structure.

IAMs differ substantially in their structure, objective function, assumptions and constraints. The amount of CDR projected by models covers a large range and any scenario used to project a future value for CDR is based on a particular bundle of assumptions (Schweizer et al., 2020). The limitation regarding IAMs will be further expanded on in chapter 6.

For this thesis, future amounts of CDR are projected by using the *IPCC SR1.5 Scenario Explorer Database* (Huppmann et al., 2019, Rogelj et al., 2018). The scenario ensemble is the product of single and multi-model studies, which share the common aim of limiting warming to 1.5°C or well below 2°C, resulting in a range of quantitative climate change mitigation pathways that support the IPCC 2018 "*Special Report on Global Warming of 1.5°C*" (SR1.5) (Huppmann et al., 2018, Rogelj et al., 2018b). For this thesis, scenarios limiting end of century warming to 1.9 Wm-2 (which translates into median year 2100 warming of 1.5°C) were selected, resulting in six IAMs being used in conjunction with five Shared Socioeconomic Pathways (SSPs) (Rogelj et al., 2018b). The SSPs provide a framework for the IAMs to explore the impact that socio-economic drivers have on, in this case, 1.5°C-consistent pathways (Rogelj et al., 2018b), covering five plausible futures regarding the evolution of society and ecosystems over this century, *not* including the impact of climate change or climate policies (O´Neill et al., 2014). **The analysis carried out in this master thesis utilises four of the five SSPs in combination with the models outlined below to illustrate**

the quantitative amount of cumulative CDR (limited to BECCS and A/R) necessary by 2050 and 2100 in order to attempt to not exceed a 1.5 temperature increase by end of the century (though temperatures may temporarily exceed this limit within the century). The pathways vary in terms of their challenges for adaptation and mitigation, exemplified by their reliance on technology and socio-economic developments. 1.5 consistent pathways could not be achieved in all model-SSP combinations, notably, SSP3, which is characterised by resurgent nationalism and regional conflicts, which hinders the abatement of GHG emissions through implementation barriers such as low institutional capacities in developing countries and low international cooperation (Popp et al., 2017, Rogelj et al., 2018b). Six IAMs in the database combined with the SSPs attempt to model scenarios limiting end of century warming to 1.5°C (with a 66% probability) (Rogelj et al., 2018b). The models included are AIM/CGE 2.0, IMAGE 3.0.1, MESSAGE-GLOBIOM 1.0 , REMIND-MAgPIE 1.5, WITCH-GLOBIOM 3.1. and GCAM4. All models succeeded in not exceeding the 1.5°C goal in SSP1, four were successful in SSP2, one in SSP4 and two in SSP5. **For the purpose of this thesis, adopting the approach used in Fyson et al. (2020), GCAM is excluded from the analysis as its projections for required CDR mid century are judged as unrealistic. This is also shown graphically in Figure 6.** CDR requirements for GCAM SSP5-19 are significantly higher by midcentury than for any of the other pathway/model combinations, peaking at over 30000 Mt CO2/yr.

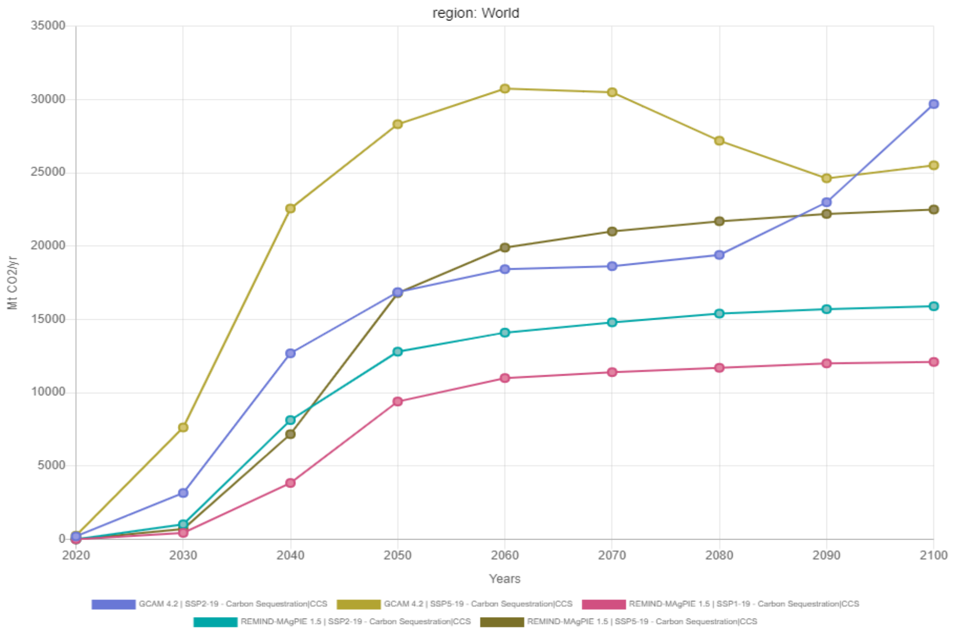


***Figure 6**: CDR projections from the IAMC 1.5 Scenario Explorer.*
Data for creating the graphic was taken from the IAMC 1.5 Scenario Explorer https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/ (Huppmann et al., 2019, Rogelj et al., 2018).

All information for the following model descriptions is taken from the IAMC webpage, and the IAMC wikipedia page.

3.2.1 AIM/CGE 2.0

AIM/CGE is a computable general equilibrium model, which incorporates all economic goods, the interactions between the production factors as well as the trade of goods and services. The focus of the model is to analyse future climate change mitigation and grasp the impact of this on economic conditions. The model disaggregates the energy system (supply versus demand) and the agricultural sector. The flexibility of the model design means it can be used at either a global or a regional scale (individual countries). The temporal scale of the model is 2005-2100 with a time step of one year.

3.2.2 IMAGE 3.0.1

The IMAGE 3.0.1 modelling framework simulates the interactions between human and natural systems and their consequences worldwide, with the objective of exploring the long-term dynamics of global change. Specifically, the model seeks to gain insights into the processes (and accompanying uncertainties) taking place within global environmental change and to provide possible response strategies by assessing available options. The framework is best applied for global and long term (2100) coverage in order to assess the impact of human activities on the natural environment, the provision of natural resources and ecosystem services. The model is able to consider negative side effects of natural resource use (emissions, resource depletion, quality reduction etc.) when making projections for future energy and natural resource use.

3.2.3 MESSAGE-GLOBIOM 1.0

MESSAGE is designed to optimise the energy system in order to meet energy demand at the lowest cost, whilst GLOBIOM provides input covering land use and the implications of land use availability on the cost of land-based carbon dioxide removal strategies. The framework is designed to assess energy and land system transformations in the face of climate change and other sustainability challenges (IXMP Scenario Explorer developed by IIASA, 2021).

3.2.4 REMIND MAgPIE 1.5

REMIND represents the future evolution of world economies, focusing on the energy sector and consequences this has on the global climate. The model works within population, technological, policy and climate constraints to determine an optimal mix of investments in the energy and economy sectors. REMIND is commonly used in conjunction with MAgPIE, a model which projects the impact of agricultural production on the environment. The strength of the model lies in its detailed depiction of the energy system as well as its ability to take into account system inertia and path dependencies within that system (REMIND — Potsdam Institute for Climate Impact Research, 2021).

3.2.5 WITCH GLOBIOM

WITCH dynamically models the interactions between the economy, technological options and climate change. The land use and forestry model GLOBIOM presents land-based mitigation options and the climate model MAGICC computes future climate projections. A damage function represents the impact of climate change on economic output, taking into account the rate of investments in adaptation (The WITCH team, 2019). WITCH can evaluate climate policies and their impact on economic systems on a global and regional scale. A strength of the model is its ability to characterise endogenous technological change

3.3 Model variables (input)

The two main CDR options for IAMs featured in the SR1.5 are in the land and energy sector. In the land sector, carbon is stored via afforestation and reforestation (A/R) in the forest and in the soil. In the energy sector, BECCS is the dominant option, (Hare et al., 2018). The extent of CDR deployed varies greatly between models due to underlying differences in model assumptions, such as demographic trends and speed of technological and socioeconomic change (Hare et al., 2018). BECCS had a history of being the dominant CDR measure in deep mitigation pathways, but, since the fifth IPCC Assessment report and the associated increase in the variation in underlying assumptions including socio-economic drivers, a larger and more diverse portfolio of CDR options has been made available and limitations regarding deployment of CDR measures (e.g. related to land-use) have been emphasised (Rogelj et al., 2018a)

The variables chosen to represent CDR options in this paper are "**Carbon Sequestration/CCS/Biomass**" and "**Carbon Sequestration|Land Use**" *or,* when the former is not available, negative values for **"Emissions/CO2/AFOLU**". "**CarbonSequestration/CCS/Biomass**" represents the total CO2 emissions captured from Bioenergy use and subsequently stored in geological deposits, reported as a positive number in Mt CO2/year. Following the approach used by Lee et al., (2021), **the amount of BECCS utilised in each pathway is used as a proxy for technological CDR. "Emissions/CO2/AFOLU**" represent CO2 emissions from agriculture, forestry and other land use, reported in Mt CO2/yr. Values can be positive or negative reflecting the potential for the AFOLU sector to act as both a source and sink of CO2 emissions (Smith et al. 2014). When available, the "**Carbon Sequestration/Land Use**" variable is prioritised over "**Emissions/CO2/AFOLU**". This refers to the total amount of carbon dioxide sequestered through land-based sinks (e.g. afforestation, soil carbon enhancement, biochar), in units of MtCO2/yr. However this variable is only available for the IMAGE SSP1-19 and MESSAGE-GLOBIOM SSP1 and SSP2-19 model-pathway combination. For the other models, in line with the IPCC SR1.5 methodology, ***net negative*** **AFOLU emissions** are used as a conservative proxy for terrestrial CDR options (Rogelj et al., 2018a). For the latter, positive values are emitted as these do not reflect CDR. For the sake of consistency with the other model output, net negative AFOLU emission values are turned into positive values to represent projected amounts of CDR deployment. Limitations of this approach are acknowledged, most importantly that it likely significantly underestimates emission removals from this sector (Rogelj et al., 2018a).The estimation is a lower bound because it does not include any CDR deployed before reaching net zero AFOLU CO2. Yet, baseline AFOLU CO2 emissions are also reduced by other interventions besides CDR such as reducing deforestation and preserving land carbon stocks. Currently, the literature on pathways is not able to separate these two processes and therefore the approximation is conservative (Rogelj et al., 2018a).

Thus, for the purpose of this thesis, CDR is treated as the sum of the negative emissions from bioenergy with carbon capture and storage and negative emissions from the AFOLU sector- afforestation and reforestation.

A portfolio of CDR options is chosen, as it is generally acknowledged that a large-scale deployment of a single CDR option is a somewhat risky strategy as all technologies have strengths and weaknesses (Fuss et al., 2020).

As mentioned in the introduction, the approach in Fyson et al., (2020) is followed, in that the assumption is made that the *total* amount of CDR projected would not differ much in different model portfolios, even if additional (more nascent) forms of CDR are included.

It is worth noting that efforts have been made to investigate whether the 1.5 temperature target could be achieved without invoking technological CDR to achieve this. This so-called Low Energy Demand (LED) (Grubler et al., 2018) scenario achieves this goal but only through a very ambitious global target of a drastic reduction of energy demand that would have to take place within the decade. This is supported by work from Edmondes et al. (2013) who stated that the 1.5 °C target could be achieved without BECCS CDR, but only under very stringent conditions including, amongst others, a carbon price in excess of \$500/tCO2 by 2040 (Schweizer et al., 2020). Alternative strategies for meeting the end century 1.5 temperature target will be expanded upon in chapter 5.

Regarding CDR, the models differ in respect to the moment in time when negative emissions are initiated and the amount and form of CDR required. For example, CO2 emissions from energy supply in the WITCH model become negative by 2030, whilst in the AIM model, this does not happen till 2050-2060 (Rogelj, 2018a).

3.3.1 CDR in the Land Sector-A/R

Afforestation refers to trees being planted on land which has not been afforested recently, with a value of 50 years or more usually used as reference. On the contrary, reforestation refers to the planting of trees on land recently deforested (IPCC; 2000). However, in the literature, the distinction between the two practices can be quite fuzzy and they are sometimes categorised together under "AR" (Fuss et al., 2018). Both practices can induce negative emissions through an increase in additional biomass which enable CO2 to be sequestered from the atmosphere (Fuss et al., 2018). Estimates for global sequestration potential and costs for AR vary widely (for an overview, see Fuss et al., 2018). The sequestration potential is not only the result of the planted trees, but also of the improved soil quality (Brack and King, 2020). Early studies suggested that over the period 1995-2050, the potential for carbon sequestration under maximum feasible afforestation and reforestation scenario amounts to 60-87 GtC (Brown et al., 1996), which subsequently translates into a 15-30 ppm reduction in atmospheric CO2 (House, 2002). These estimates should be viewed with caution as they do not take into account the effect of future climate change on forest growth (Sonntag et al., 2016). The study by Sonntag et al., (2016) also points out that the potential for reforestation as a CDR method is strongly dependent on the background climate and CO2 levels.
Concerns regarding the feasibility of AR as a CDR strategy include the effect that the changes in land cover can have on local *and non-local* climate via biogeophysical pathways and subsequent alterations in wide ranging climate circulation (e.g. Lejeune

et al., Boers et al., 2017). A prominent example is the change in albedo invoked by modifying land cover (e.g. Anderson et al., 2011). This is particularly significant for boreal forests in high latitudes, where increased forest cover could actually *increase* local warming and ice/snow cover loss, as dark trees substitute land cover that previously reflected the heat. For tropical regions, the loss of albedo effect is not an issue, as it is overshadowed by the greater potential for evaporative cooling through increased tree coverage (Fuss et al., 2018). Scaling up A/R is marked by trade-off: Whilst planting native species is beneficial for biodiversity, it can reduce carbon sequestration potential. Furthermore, this CDR strategy can compete with food and biofuel production for land and water resource availability (Davin and De Noblet-Ducoudré, 2010). Furthermore, although deployment of A/R is fairly low cost and achievable in the near-term, this is not associated with an immediate removal of CO2, as sequestration rates are biologically constrained and juvenile vegetation has lower total storage potential and sequestration rates (Brack and King, 2020).
Over time, AR becomes a less attractive CDR option as storage of CO2 is less permanent than for other CDR options (Smith et al., 2016) and is dependent on careful management of the reforested area as human induced changes in land use or natural disturbances can alter the sequestration potential of the area imminently.

3.3.2 CDR in the energy sector - BECCS

BECCS is a carbon removal technique that entails burning CO2 absorbing biomass, capturing the emissions released in the process and storing them underground in long-term reservoirs (Brack and King, 2020). The biomass utilised can be sourced from wood, energy crops, agricultural residues and organic waste.
BECCS plays an important role in long-term climate scenarios, with deployment usually rapidly increasing from mid-century. Scenarios in which mitigation is delayed see the sharpest increase in BECCS deployment, exemplified in the SSP5 pathway. However *all* SSPs feature BECCS to some extent (Fridahl and Lehtveer, 2018). The IPCC Special Report on 1.5 °C showed that, in order to stay well below the 2 °C target, emissions in 2030 would have to be drastically reduced, to about 50% of 2010 levels

(Köberle, 2019). Meeting near term targets is only realistic if CDR technologies are utilised that already exist, making BECCS a prime candidate for this purpose. BECCS is considered a popular choice as a mitigation option for IAMs due to its ability to, (in theory), make scenarios with ambitious mitigation targets feasible, as well as the fact that it is a versatile source of energy, as it can be used produce bioelectricity, liquid biofuels, charcoal, hydrogen, or biomaterials (Köberle, 2019). BECCS has the advantage that it can be utilised to decarbonise sectors that are traditionally hard to decarbonise such as freight transport, aviation and industry (Azar et al., 2013), which increases the chance of making ambitious climate scenarios feasible (Köberle, 2019). The versatility complements the cost-optimization structure of most IAMs, as they can replace secondary energy carriers with high marginal cost with bioenergy, which reduces the overall cost of the system (Azar et al., 2013).
The dominance of BECCS in IAMs is partly due to the existing structure of these models, but also, as previously mentioned, due to the use of high-discount rates, which essentially favour delaying stringent mitigation action on the basis that technological solutions will be cheaper to deploy in the future. On the other hand it could be argued that a high discount rate actually reflects the current state of affairs quite well, as the minimal efforts to reduce emissions so far could suggest that society *does indeed* embody a high discount rate (Köberle, 2018).

However, this high discount rate raises ethical concerns (disproportionately burdening future generations) and runs the risk of relying extensively on a NET that is not guaranteed to materialise at the time and scale required and is subject to significant governance and implementation challenges, such as land area required for storage (Lenzi et al., 2018). In addition to the discount rate, the dominance of BECCS in IAMs is also explained by the fact that IAMs have only *recently* started including CDR technologies other than BECCS and afforestation (Smith et al., 2014). Various studies found that when other NETs, such as Direct Air Carbon Capture Storage (DACCS) are included, the deployment of BECCS is substantially reduced (20-37%) across 1.5 °C and 2 °C scenarios (Realmonte et al., 2019).

Representation of **technological innovation** is a further factor to consider when assessing the dominance of one NET over another. Most IAMs do not give much weight to disruptive innovation or increases in energy efficiency. However, including low-carbon technology can reduce the deployment of BECCS in IAM projections. In addition to neglecting technological innovation, IAMs struggle to incorporate institutional and social innovations and subsequent behaviour change. Combining lifestyle changes with optimistic technological assumptions can reduce the need for CDR (Van Vuuren et al., 2018). In terms of cost-efficiency, the cost of BECCS may be underestimated due incomplete accounting of the costs of agricultural production, resulting in lower estimates of energy prices and subsequently makes BECCS appear more favourable in alignment with the cost-minimisation function of most IAMs (Köberle, 2018).

Further development and choice of constraints (e.g. what other NETs are included) in IAMS could diminish the role of BECCS in future scenarios (Köberle, 2018).
A paper by Bauer et al., (2020) provides an in-depth overview of the EMF33 comparison project which describes the ways in which models represent and deploy BECCS.

3.4 Data Processing

Data for the CO2 emissions attributed to the Carbon Majors was extrapolated from the spreadsheet provided by Heede (2020)[2] and formatted to select for the time period 1990-2018, filtering for CO2 emissions only. Cumulative emissions were calculated for said time period and no longer extant companies were removed, as was explained in section 3.1.2 , as these non-extant companies are not able to contribute towards CDR efforts. Their theoretical share (were they still in existence) was calculated to verify whether they had contributed an amount significant enough to warrant further action in the analysis. The sum of the cumulative emissions of all seven no longer extant companies represents just under 2% of the total Carbon Major CO2 emissions over the time period 1990-2018. This was deemed a substantially small share, so that no further action was taken to incorporate them into the analysis. Thus, when referring to total

[2] The data provided by Heede (2020) is attached in the digital version of this document as a spreadsheet.

Carbon Majors from now on, this should be interpreted to not include non-extant companies.

The data for global CO2 emissions in the same time period, obtained from the PRIMAP-hist national historical emissions time series, was also filtered for CO2 emissions values only. As explained in the data section, LULUCF emissions data from the FAOSTAT database were added, in order to provide a more complete and accurate depiction of global CO2 emissions. After converting the data sources to the same units (megatonnes), the two cumulative values were summed together. This allowed for the first calculation of the analysis to be carried out: identifying the proportional share of global CO2 emissions attributed to the Carbon Majors. In order to do so, the cumulative emissions from the Carbon Majors over the time period 1990-2018 were divided by the total global cumulative emissions over the same time period.

Individual values were then sorted by grouping the companies into the three categories: IOCs, SOEs and nation states, the same categories used by Heede (2014) in the initial analysis.

In the next steps, the CDR data was prepared for the analysis. As the data was received with values separated by 10 year intervals, the first step involved doing a linear interpolation to complete the missing values.

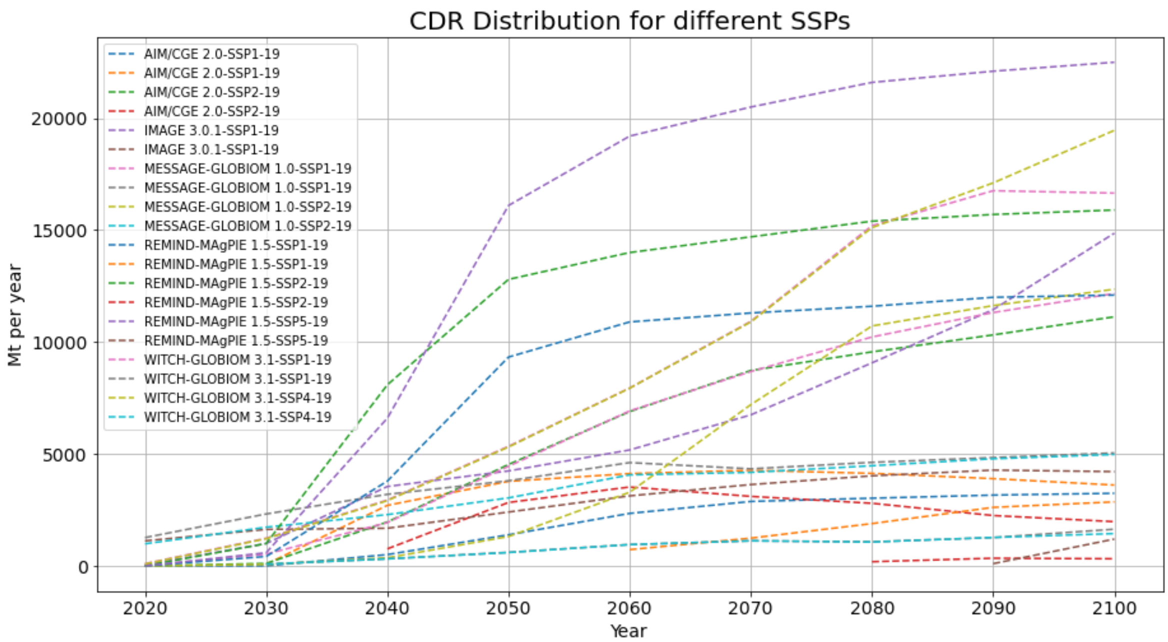


***Figure** 7: Visualisation of the interpolated CDR-data. Script for interpolation is attached in the digital version of this thesis.*

Next, cumulative values for the time period 2020-2050 and 2020-2100 were calculated per model, pathway and variable combination. Finally, individual values were summarised to provide one value per model and pathway combination (i.e. total CDR). In order to compare CDR projections between the different SSPs, Median values were calculated for SSPs for which there were results from multiple models (SSP1 and 2), whereas for SSP4 and 5, only two models were able to provide results, Witch-Globiom and Remind-MagPie respectively.
In the final step, the share of CDR attributed to the Carbon Majors was calculated by multiplying the CMs share of total CO2 emissions by the CDR values per pathway/variable/model combination. The fact that there are multiple pathway/variable/model combinations results in a number of possible values for CDR shares in 2050 and 2100 for each Carbon Major. Attributing shares of global CDR to individual companies represents a novel approach, as analysis thus far in the literature has focused on the responsibility of nation states (e.g. Fyson et al., 2020, Lee et al., 2021).

Chapter 4: Results

Cumulative CO2 emissions for the Carbon Majors in the time period 1990-2018 totalled 685.129 Mt. The value for cumulative global CO2 emissions totalled 833.900 Mt, reaching 866.493 Mt when the LULUCF emissions from the same time period were added.
When calculating the proportional shares of the Carbon Majors in respect to global CO2 emissions, it was identified that the Carbon Major´s total share of Global CO2 emissions amounts to 79,1% over the time period 1990-2018. Values for individual companies can be found in the attached excel sheets. When entities are grouped into categories, IOCs contribute 22,1% of global CO2 emissions, SOE contribute 31,1% of global emissions and Nation States contribute 25,8% of global CO2 emissions over the time period 1990-2018. These statistics are valid when non-extant companies are *not* included in the equation.

Figure 8 compares global CO2 emissions between 1990-2018 to those of the Carbon Majors over the same time period. Whilst the two graphs follow a similar trajectory, it is notable that the CO2 emissions from the Carbon Majors dip slightly in the early 1990s and between 2014-2017. This is better visualised in **Figure 9,** which shows the change in the Carbon Majors cumulative CO2 emissions over the time period 1990-2018. The decline in emissions between 1990-1993 can be explained by the collapse of the Soviet Union and subsequent fall of economic activity (Raupach et al., 2007). The decline seen between 2014-17 could in part be attributed to a reduction in China's coal consumption, prompted by a move to cleaner energy sources and a slowdown in economic growth over this period (Jackson et al., 2015). However, data uncertainty regarding China's coal burning activity means that this apparent dip needs to be viewed with a degree of caution (Weiss, 2015). **Yet, overall, the relative share of Carbon Major CO2 emissions stays fairly constant over time**. This is significant, as discussed earlier, the danger of continuously emitting high levels of CO2 emissions for the global climate was indisputably confirmed in the scientific community by 1990 and the publication of the first IPCC report, yet a reaction to this in the form of a *decrease in emissions* is not displayed in the data.

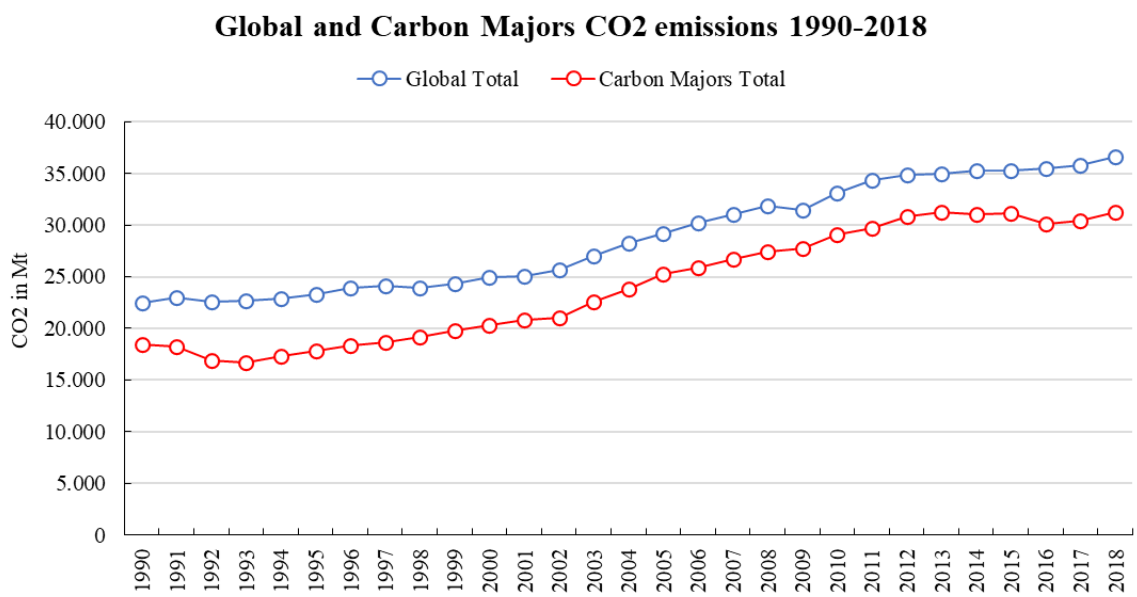


Figure 8*: global (blue) and carbon major (red) CO2 emissions 1990-2018 in Megatonnes (Mt).*

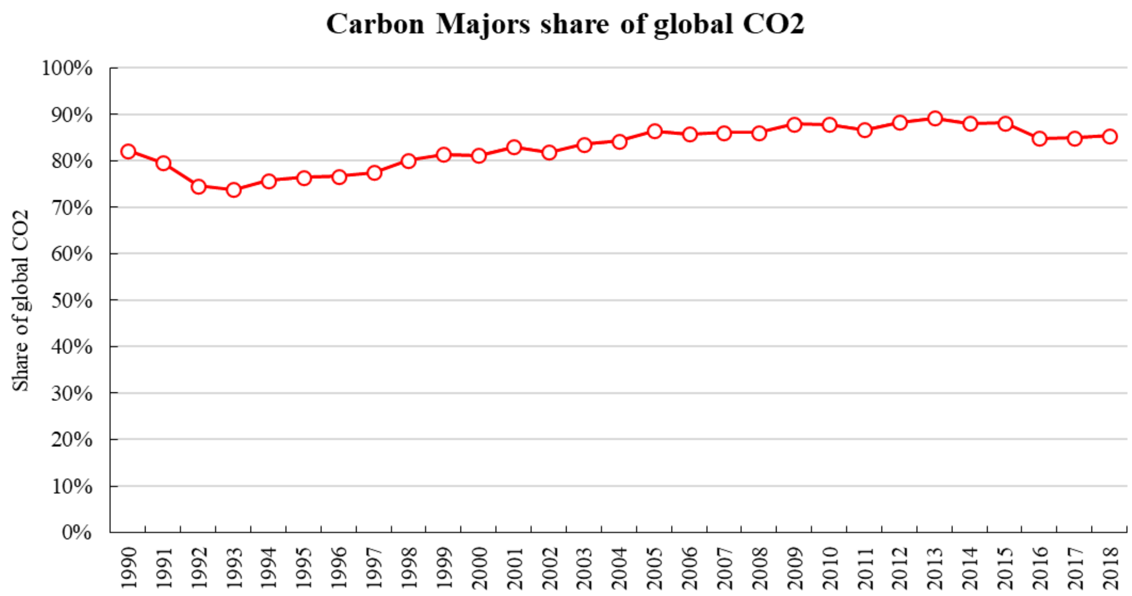


***Figure 9**: change in percentage of the Carbon Major share of total global CO2 emissions 1990-2018.*

Table 1 shows the share of global CO2 of the top twenty Investor Owned Companies (IOCs). Due to the large number of IOCs in the dataset (61), only the top 20 are displayed here for ease of visualisation. Even within the top 20 group there is significant variation, with Exxon Mobil´s share being more than 5 times as large as that of Petoro, Norway. Furthermore, the top 5 IOCs are responsible for nearly half of the total share of the top 20 companies combined. Whilst the bottom 50% of companies (within the top 20 IOCs) are responsible for only 2,8% of cumulative global CO2 emissions over the period, the top 5 IOCs contribute nearly 8% of total global cumulative emissions between 1990-2018. The top 5 contribute a share more than half as a large (7,94%) of global cumulative emissions than the rest of the IOCs combined (14,14%)

	Entities	cum. CO2 Emissions/Mt	share of Global CO2
1	ExxonMobil, USA	17117,9	1,98%
2	Royal Dutch Shell, The Netherlands	15375,4	1,77%
3	BP, UK	13480,4	1,56%
4	Chevron, USA	11845,3	1,37%
5	Peabody Energy, USA	11014,1	1,27%

6	Total, France	8587,0	0,99%
7	Rosneft, Russian Federation	7514,2	0,87%
8	BHP, Australia	7506,2	0,85%
9	ConocoPhillips, USA	7407,5	0,70%
10	Lukoil, Russia	6079,5	0,66%
11	Arch Coal, USA	5755,2	0,63%
12	Equinor, Norway	5424,8	0,61%
13	ENI, Italy	5293,7	0,57%
14	Contura Energy / ANR, USA	4956,9	0,54%
15	Anglo American, UK	4706,7	0,52%
16	Glencore, Switzerland	4521,4	0,48%
17	Repsol, Spain	4190,2	0,43%
18	CONSOL Energy, USA	3697,7	0,39%
19	RWE, Germany	3397,9	0,36%
20	Petoro. Norway	3150,9	0,36%

Table 1*: share of cumulative global CO2 of the top 20 IOCs over the time period 1990-2018. Source:Carbon Major Database (Heede, 2020)*

Table 2 shows the share of cumulative global CO2 by SOEs over the time period 1990-2018. Again, within this group we see substantial variation. The top five SOEs contribute a share of global CO2 (15,15%) that is *(slightly)* larger than that of the rest of the SOEs combined (15,06%). Even within the top five, Saudi Aramco and Gazprom make up a disproportionately large amount of the share, contributing 4,8% and 4% respectively.

	Entities	cum. CO2 emissions/Mt	share of Global CO2
1	Saudi Aramco, Saudi Arabia	41678,3	4,81%
2	Gazprom, Russia	34807,5	4,02%
3	National Iranian Oil Co.	21410,3	2,47%

4	Coal India, India	18395,7	2,12%
5	Petroleos Mexicanos (Pemex)	14971,5	1,73%
6	PetroChina, China	14550,1	1,68%
7	Abu Dhabi, United Arab Emirates	11112,9	1,28%
8	Petróleos de Venezuela (PDVSA)	10754,7	1,24%
9	Kuwait Petroleum Corp., Kuwait	8990,0	1,04%
10	Sonatrach, Algeria	8588,1	0,99%
11	Rosneft, Russian Federation	7514,2	0,87%
12	Iraq National Oil Co., Iraq	7374,1	0,85%
13	Petróleo Brasileiro (Petrobras), Brazil	7302,8	0,84%
14	Nigerian National Petroleum, Nigeria	6352,1	0,73%
15	Petronas, Malaysia	5839,1	0,67%
16	Qatar Petroleum, Qatar	5735,3	0,66%
17	Rio Tinto, UK	5289,2	0,61%
18	Libya National Oil Corp., Libya	4225,2	0,49%
19	Pertamina, Indonesia	4118,3	0,48%
20	Oil & Gas Corp., India	3682,7	0,43%
21	Sinopec, China	3299,6	0,38%
22	Sasol, South Africa	3132,4	0,36%
23	CNOOC (China National Offshore Oil Co.)	2970,8	0,34%
24	Petroleum Development Oman	2705,0	0,31%
25	Egyptian General Petroleum, Egypt	2641,4	0,30%
26	Sonangol, Angola	2475,9	0,29%
27	TurkmenGaz, Turkmenistan	2384,8	0,28%
28	Ecopetrol, Colombia	2335,1	0,27%
29	Singareni Collieries, India	1987,0	0,23%
30	Syrian Petroleum, Syria	1140,8	0,13%
31	Bahrain Petroleum Corp.	930,5	0,11%

32	Polish Oil & Gas Co., Poland	536,4	0,06%

Table 2: *share of cumulative global CO2 by SOEs over the time period 1990-2018.*

To put these values into perspective, **Table 3** shows the countries with a high share of global CO2 emissions. Comparing these percentage values with those of the top IOC and SOEs highlights the magnitude of the Carbon Major´s share of global CO2 emissions. Saudi Aramco, the top SOE emitting company, had higher annual emissions in 2018 than Indonesia, a country that ranked 5th place in the 2018 report "Fossil CO2 emissions of all world countries - 2018 Report" (Publications Office of the European Union) and Gazprom and National Iranian Oil had higher annual emissions than Japan. Whilst for IOCs the comparison is less dramatic, it is nonetheless remarkable how an investor owned company like Exxon produced roughly half the emissions of a country like Japan in 2018. One should also note that as we are comparing CO2 *equivalent* emissions for countries with CO2 *only* emissions for companies, comparisons should be drawn with a degree of caution.

country	CO2e* in 2018	SOE	CO2 in 2018	IOC	CO2 in 2018
Indonesia	1269.55Mt	Saudi Aramco	1797.62Mt	ExxonMobil	512.76 Mt
Japan	1074.08Mt	Gazprom	1243.82Mt	Shell	478.44Mt
Russia	1049.05Mt	National Iranian Oil	1108.45Mt	BP	486.59Mt
Brazil	812.02Mt	Coal India	1091.05Mt	Chevron	392.48Mt
Germany	680.06Mt	Petroleos Mexicanos	348.91Mt	Peabody Energy	358.01Mt

Table 3: *5 countries with high shares of global CO2 emissions from 2018 taken from "Historical GHG Emissions". Climate Watch., as well as the top 5 SOEs and IOCs from the Carbon Major Database (Heede, 2020). Note, the values for the countries are shown in CO2 equivalent, so comparison should be drawn with caution.*

Figure 10 shows the share of cumulative global CO2 of the six nation states included in this analysis for the time period 1990-2018. The graph clearly demonstrates China´s disproportionately large share (21,1%), nearly five times the size of those of the other nation states combined (4,75%). The nation states included in Heede´s original analysis represent states where investor-owned or state-owned enterprises have not been established or play a minor historical or quantitative role (Heede, 2014b). China´s significantly large share is partly attributed to a lack of historical data and verification of ownership structure, which led to all production being aggregated under the nation state (Heede, 2014a). In reality, there are a number of semi-autonomous coal mining entities, commonly controlled by provincial governments. However, ownership structure is often unclear. Further work is needed to disaggregate these production entities into state vs investor owned entities (Heede, 2014a).

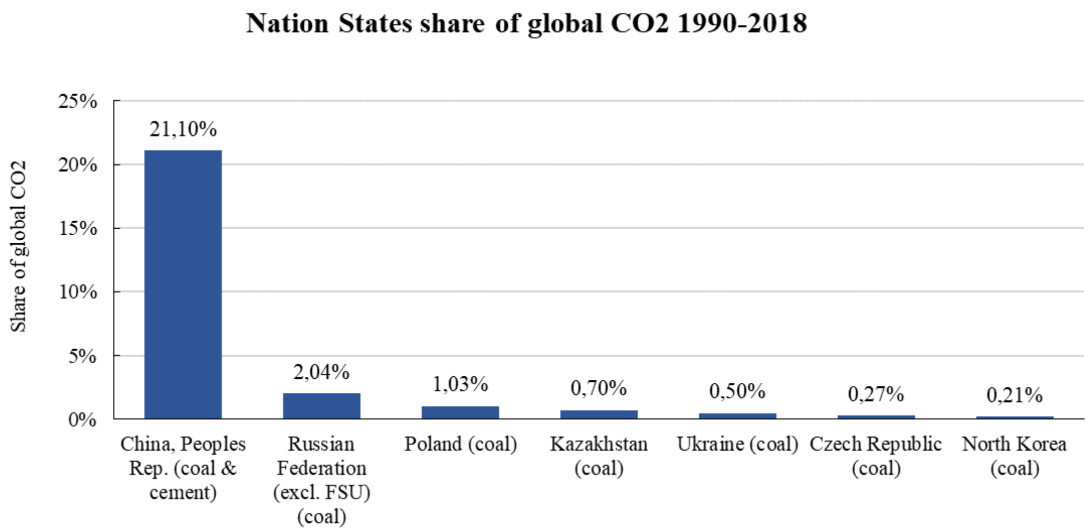


Figure 10*: share of cumulative global CO2 by Nation States over the time period 1990-2018.*

Moving on to the results for the CDR calculations, these will also be presented for each company-type group, beginning with the investor owned companies. Due to space constraints and ease of visually displaying the data, only the top 5 companies of each category and only CDR values for BECCS will be shown graphically here. Full datasets can be viewed in the excel spreadsheets attached in the appendix. BECCS is prioritised to be visualised as, being a technological CDR solution that deploys carbon capture and storage (CCS), it can be argued that fossil fuel companies are more amenable to engage with this CDR solution, based on their existing infrastructure and technological expertise. Individual values for each company can be gained from the complete spreadsheet attached in the appendix.

Figure 11 and **12** show the quantitative amount of BECCS contributions by 2050 and 2100 respectively, calculated for the top five IOCs across SSP1, SSP2, SSP4 and SSP5 in Mt CO2/year. Columns represent the median values for each pathway. The figure clearly shows the significant relative differences in magnitude of CDR required between SSP1, 2, 4 and 5. This is unsurprising, given the trajectory of SSP5 - *fossil fueled development*- a scenario which relies on intensive energy and resource consumption. Comparing **figures 11** and **12**, it becomes clear that the amount of BECCS required by 2100 is significantly larger, e.g. in the case of Exxon for SSP5, nearly 24,000 Mt CO2/year in 2100, compared to just over 3000 Mt CO2/year in 2050.

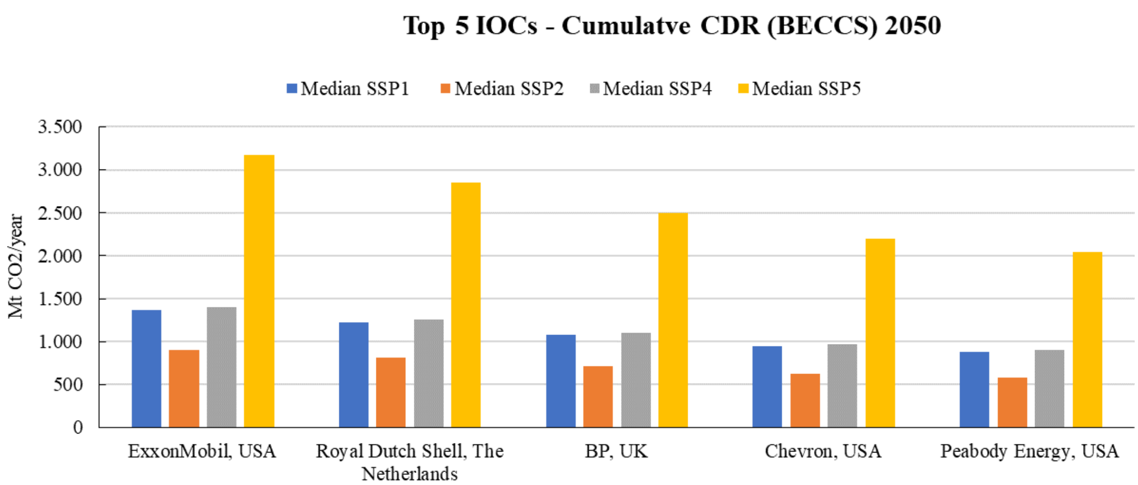


Figure 11*: cumulative CDR by 2050 projected for the top five IOCs in the Carbon Major database, per SSP. Columns represent the median values for each SSP. Note: for SSP4 and 5, due to model constraints, only one value was available.*

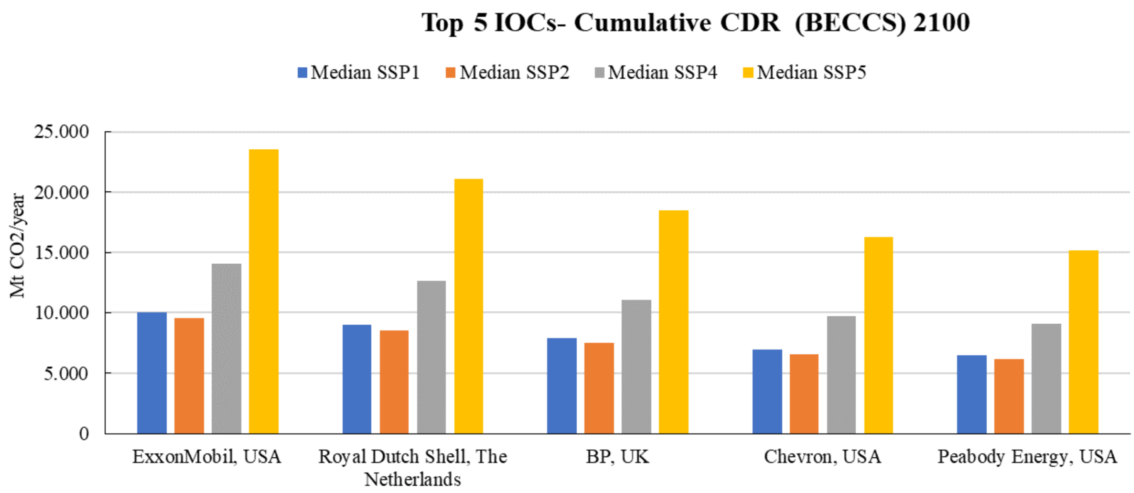


***Figure 12**: cumulative CDR by 2100 projected for the top five IOCs in the Carbon Major database, per SSP. Note the change in scale on the y-axis between the figures between figure 11 and 12.*

Figure 13 and **14** show the quantitative amount of BECCS contributions by 2050 and 2100 respectively, calculated for the top five SOEs across SSP1, SSP2, SSP4 and SSP5 in Mt CO2/year, following the same methodology as for the previous graphs. Insights drawn are similar to those of the previous figures, however the extremely large amount of CDR required by 2100 for Saudi Aramco, nearly 60,000 Mt CO/year, is remarkable.

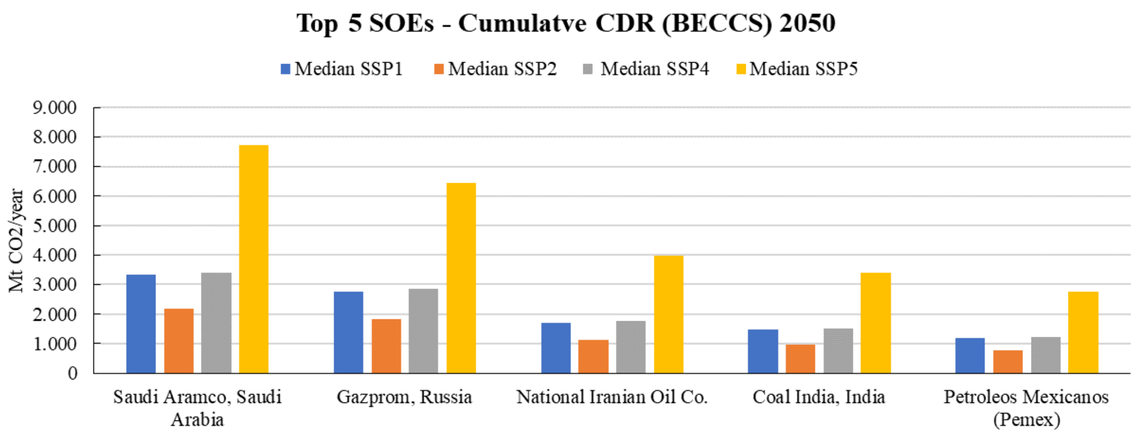


***Figure 13**: cumulative CDR by 2050 projected for the top five SOEs in the Carbon Major database, per SSP. Columns represent the median values for each SSP. Note: for SSP4 and 5, due to model constraints, only one value was available.*

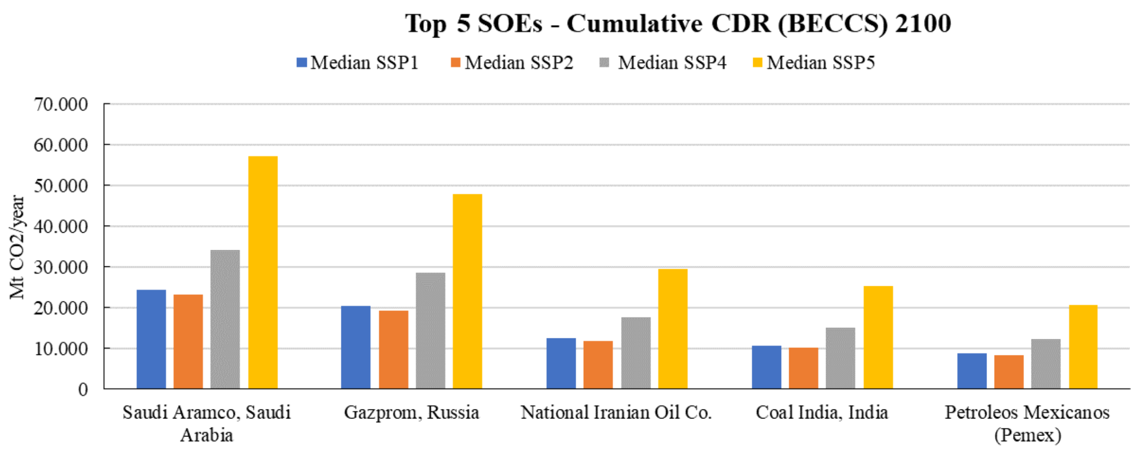
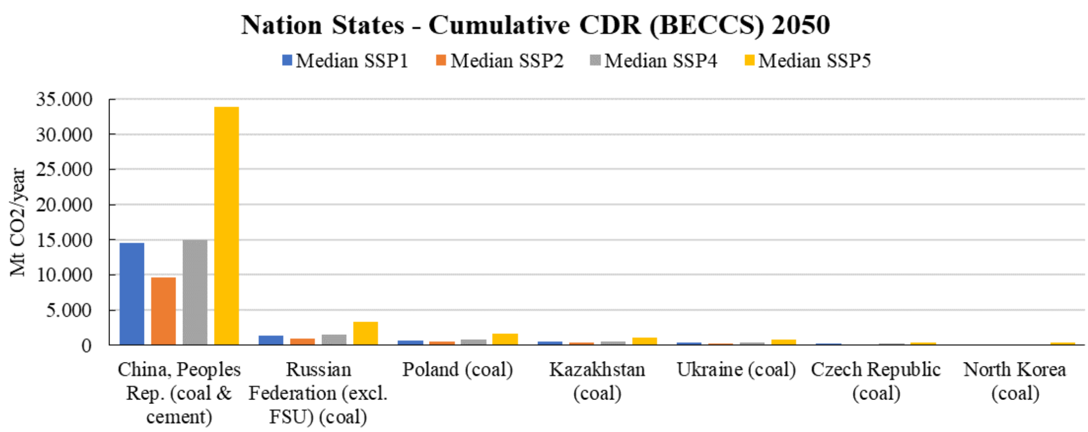


***Figure 14**: cumulative CDR by 2100 projected for the top five SOEs in the Carbon Major database, per SSP. Columns represent the median values for each SSP. Note: for SSP4 and 5, due to model constraints, only one value was available. Note also the change in scale on the y-axis between the figures between 13 and 14.*

Figure 15 and **16** show the quantitative amount of BECCS contributions by 2050 and 2100 respectively, calculated for the seven nations states across SSP1, SSP2, SSP4 and SSP5 in Mt CO2/year, following the same methodology as for the previous graphs.



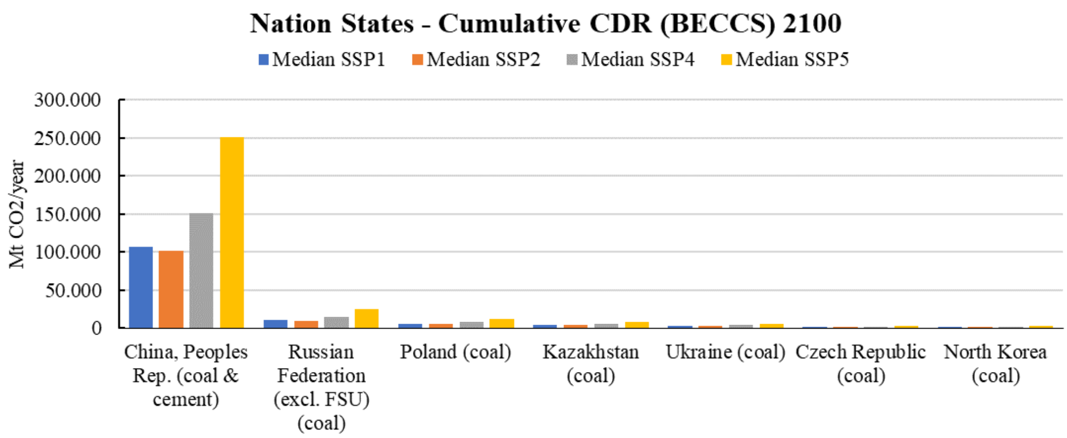


***Figure 15 and 16**: Cumulative CDR by 2050 and 2100 respectively projected for the seven nation states in the Carbon Major database, per SSP. Columns represent the median values for each SSP. Note: for SSP4 and 5, due to model constraints, only one value was available.*

Figure 17 and 18 shows the top IOCs and SOEs, ordered by cumulative emissions (1990-2018) and their CDR projections for 2050 and 2100. This comparison demonstrates that SOEs clearly dominate in regards to the quantity of their historic cumulative emissions.

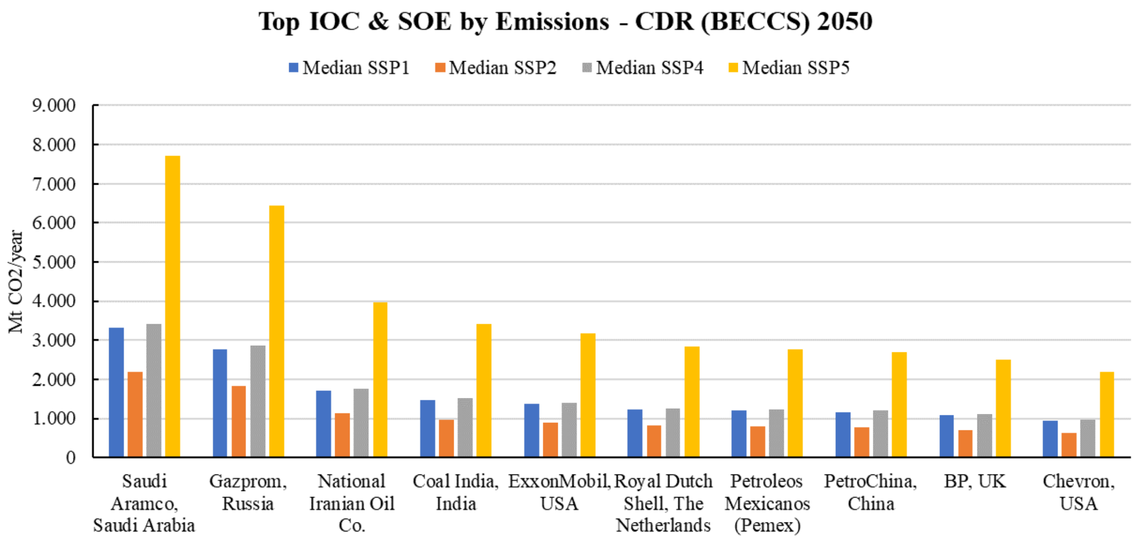


***Figure 17**: top 10 IOCs and SOEs ordered by their total cumulative CO2 emissions (1990-2018) and their CDR projections for 2050.*

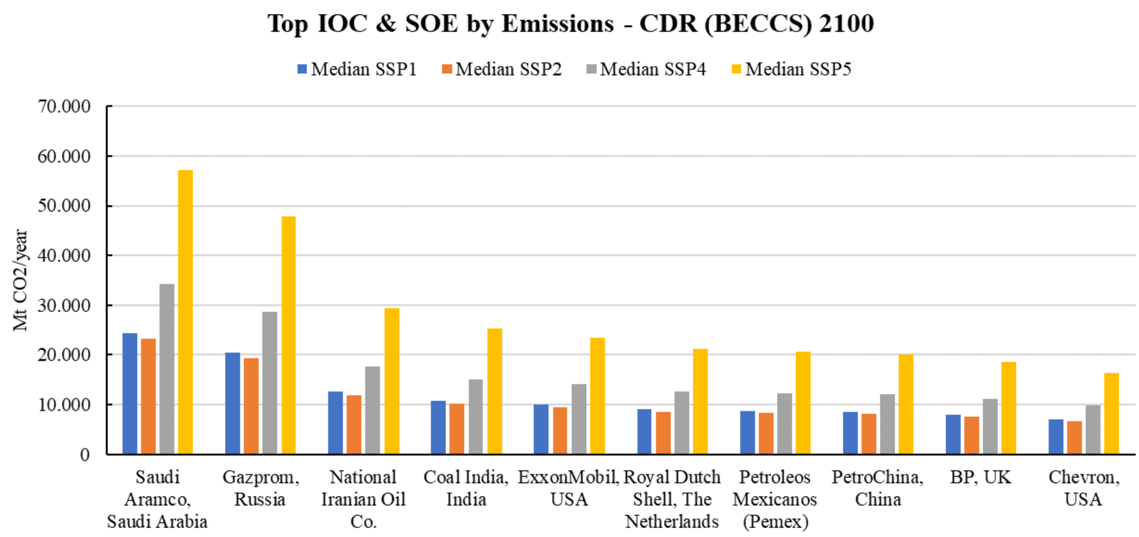


Figure 18*: top 10 IOCs and SOEs ordered by their total cumulative CO2 emissions (1990-2018) and their CDR projections for 2100.*

Chapter 5: Discussion

5.1 Interpreting the results

As a group of entities, the Carbon Major´s share of CO_2 emissions has remained fairly stable over the time period 1990-2018, constituting a very large share (fluctuating between 74%-89%) of the total global CO_2 emissions over the same time period. The fact that their share of global CO_2 emissions has remained consistently high is clearly significant when making the case that these companies should take responsibility for their polluting activities, especially as there is no evidence that they have made significant efforts to reduce their emissions, despite being aware of their damaging effects on the global climate.

When the results are divided into the three types of company (IOC; SOE and nation state) it becomes evident that within each group, there is significant diversity regarding the share of CO_2 emissions contributed by each entity. For IOCs and SOEs, it can be said that the top 5 companies in each group contribute a significantly larger share of CO_2 emissions than the rest of the entities in these respective groups. Whilst in the IOCs, the top 5 companies produce a share of global CO_2 over half as large as that of the rest of the companies (57) in this category. This difference is even more pronounced for the SOEs, where the top five companies produce more emissions than the rest of the SOEs combined. However, it should be noted that the total number of SOEs in this dataset is also significantly smaller than the number of IOCs (32 and 62 respectively). However, the top 2 SOEs: Gazprom and Saudi Aramco together contributed a staggering 8,8% towards global CO_2 emissions over the time frame under analysis.

As respective CDR shares are calculated by invoking the share of cumulative emissions of these entities, the results paint a similar picture regarding the distribution of the CDR burden between the three entity groups. BECCS values are chosen to be visualised, given their dominance in IAMs and the technological know-how and infrastructural capacity of the carbon majors. Differentiating between SSPs and cumulative values by 2050 and 2100 clearly demonstrates the extremely large increases in BECCS required by 2100 compared to 2050, across pathways. Comparisons across pathways demonstrate the stark differences that different socio-economic scenarios have on the timing and magnitude of CDR deployment, with CDR requirement in SSP5 being more than twice as large as those for SSP1 and SSP2.

Thus, the main insights gained from the analysis are that although the Carbon Majors as a whole have contributed a very large share of global CO_2 emissions over time period 1990-2018, there is actually substantial variation within this group and within the separate subgroups. The top five IOCs and SOEs contributed 23,1% of global CO_2 emissions over the time period 1990-2018. Given this insight, the following section will contextualise the results by taking a closer look at the climate pledges and plans of some of the top 5 companies in the IOC and SOE subgroups.

5.1.1 Contextualising the results

As noted previously, whilst scientific concepts such as the carbon budget, net zero and CDR are defined in the scientific literature, their successful implementation and realisation are determined by social, political and economic institutions. In order to illustrate this, feasibility and challenges of large scale CDR deployment will be assessed and compared to the pledges and commitments announced by the Carbon Majors themselves. The suitability of the carbon majors as a target group will also be reevaluated.

In order to begin to contextualise the findings from the data, five of the companies topping the IOC and SOE lists will be assessed in terms of their current climate pledges and targets, specifically attempting to assess their stance and proposed reliance on CDR.

An analysis carried out by Carbon Trackers in 2020 found that a number of the major polluting companies have developed climate policies that allow them to rid themselves of responsibility for total or partial scope 3 emissions, especially those emissions related to use by the end-user. This is extremely significant, as scope 3 emission can constitute up to 95% of the carbon footprint of oil and gas companies (Carbon Tracker, 2020).

The top 5 IOC and SOE companies from my analysis using Heede´s database are: Exxon Mobil (IOC), Royal Dutch Shell The Netherlands (IOC), BP UK, Gazrpom (SOE) and Saudi Aramco (SOE). In the following section, the companies will be briefly described and their net zero target critically assessed. Information is mainly gathered from companies own websites, the Client Earth Greenwashing Files , the The Climate Action 100+ Net-Zero Company Benchmark - which provides an assessment on the progress of the major global corporate GHG emitters regarding their transition to a net zero future and the Transition Pathway Initiative- a tool that assess companies readiness for the transition to a low-carbon economy.

A Greenpeace Briefing report "*Net Expectations-Assessing the role of carbon dioxide removal in companies' climate plans*" (2021), highlights five key points that should be addressed in the climate plans of companies. These include:

1) **How much CDR** specifically will contribute towards achieving the companies climate targets and **how much of this will be achieved by emissions reductions.**

2) A **justification** for why remaining emissions are deemed unavoidable.

3) Which **technological innovations** are being developed to abate the currently unavoidable emissions.

4) **Avoiding double counting** by being transparent about CDR sources that are also included in other companies or countries climate targets and

5) the **specifics of the CDR method relied on**, including details of the location, mechanisms and governance strategy.

These criteria can be used as a benchmark of comparison when analysing the companies climate action plans presented in the following section.

Notably, at the time of writing, *none* of the 5 carbon majors mentioned above are currently part of the UN race to zero campaign or the Science Based Target Initiative (SBTI), a collaboration between global institutions including CDP, the UN Global Impact, the World Resource Institute and the WFF, that develops methodology and criteria for companies to set science-based targets and certifies their pledges (Greenpeace, 2021).
In the Oil and Gas sector, there is a considerable reliance on CDR in companies climate plans, but also a significant vagueness regarding the extent of this reliance and detail of *how* this will be achieved.
According to the Greenpeace Briefing report (2021), companies can either apply CDR within their *own* supply chain, enhancing their ability to absorb carbon by using nature based solutions such as planting more trees on a production site to sequester carbon from the air, or, alternatively, *companies can develop or manage their own CDR projects*, such as investing in nature based solutions or CCS plants. Finally, companies can, in theory, purchase CDR credits on the global carbon market.
A 2021 study by Kenner and Heede, examining the top four IOCs of the carbon major dataset, concluded it to be unlikely that these companies will proactively decarbonise in line with the urgency to do so demanded by climate science, primarily because the executives and directors of the companies will *not* decide to do so. The influence that the personal choices and attitudes of executives and directors of fossil fuel companies has on the company's performance in terms of meeting climate mitigation targets corroborates the finding that there is considerable diversity within the three groups of companies analysed in this paper.

Note: as the sources used to provide benchmark criteria are considered up till 2021 only, there might be some discrepancy with current climate plans published by these companies.

Exxon Mobil

Headquartered in Texas, Exxon Mobil had a reported revenue of $256 billion in 2020 and disclosed scope 3 emissions of 730 million tonnes of carbon dioxide equivalent in 2019 (Client Earth Files). In January 2022, Exxon announced an ambition for net zero GHG emissions by 2050, but limited this to its **operated assets** (Scope 1 and 2 emissions) in its 2022 "Advancing Climate Solutions Progress Report", eager to add a cautionary note explaining that these objectives are forward looking objectives and results are not guaranteed. It expands upon this line of thought in a document titled "Factors affecting future results", which is found on the company's website, where it presents an extensive list of economic, political and social factors that it claims are out of the company's control but can affect the company's financial and operational results. Exxon scores poorly on all of the *Climate Action 100+ Net Zero Company Benchmark* criteria. Exxon claims it supports the Paris Agreement, but simultaneously argues that the agreement *does not* require a decrease in production for targets to be met, claiming that a *decrease* in production would be ineffective, as energy-related emissions are *demand* driven and thus any emissions reduced by Exxon would be simply shifted to another producer, responding to the continuous demand. The company actually claimed that shifting production to another, less efficient company, could result in overall *higher* emissions (Energy and Carbon Summary, 2021).

The company has shared plans about investing in low-carbon and lower emission technologies, with a specific focus on CCS (Client Earth Files) and describes itself as a "leader in carbon capture and storage, with current capacity totalling about 9 million tons per year (Exxon Mobil, 2022). However, this figure actually makes up a woefully small percentage, around 2%, of Exxons total annual emissions and its continued investment in oil and gas render this contribution fairly negligible (Client Earth). Furthermore, a rough comparison with the CDR projections calculated in my analysis reveal that Exxon does not increase its CCS capacity, in 30 years time, it will have stored 270 Mt CO2, which falls drastically short of the total CDR required in SSP1 by 2403,3 Mt and nowhere near the 8671,42Mt required in SSP5.

Exxon's Climate Policy relies heavily on negative emission technologies, especially ones that are currently unproven on a larger scale, such as CCS (Client Earth). In the 2020 Discussion Paper "*Big Oil Reality Check- Assessing Oil and Gas Companies Climate Plans"*, Exxon scores "*grossly insufficient*" in all ten criteria that need to be met to provide the *possibility* of being aligned with the 1.5°C temperature goal. These criteria alone do not guarantee this alignment, but merely represent the *essential preconditions* for achieving this. The criteria cover three broad categories: Ambition, Integrity and Transition Planning which entail subcategories that ensure that targets for oil and gas production are declined by 2030 and *no* new extraction projects are approved, *all* emission scopes are covered, there is not a sole reliance on carbon sequestration and offsetting, lobbying activities that hinder climate action are ceased, explicit dates at which oil and gas extraction ceases are set and the transition of workers into new sectors is supported (Tong and Trout, 2020).

The company has been identified in engaging in greenwashing and misinformation campaigns including making selective claims regarding the trend of its annual emissions over time and setting carbon intensity targets as opposed to committing to absolute emission reduction (Client Earth). Empirical research investigating Exxons internal documents has shown that, although the company has been aware of the negative impacts of climate change for decades, it continued to promote doubt about climate science through its advertisements and editorials (Supran and Oreskes, 2017). The company has also founded and been a member of powerful lobbying groups such as the Global Climate Coalition, the American Petroleum Institute, American Fuel & Petrochemical Manufacturers, the Australian Petroleum Production and Exploration Association, the Canadian Association of Petroleum Producers and Fuels Europe (Client Earth).

Royal Dutch Shell, The Netherlands

Headquartered in the Netherlands, Royal Dutch Shell is a multinational oil and gas company with listed sales of $311.6bn in 2020 (Forbes) and disclosed emissions of 1,377 million tonnes of carbon dioxide equivalent. Emissions projected to be generated between 2018 to 2030 (Shell annual report, 2020) are estimated to make up nearly 1.6% of the global 1.5°C carbon budget (Client Earth). Climate Action 100+ Net Zero Company Benchmark finds that the company meets some of its criteria, but falls short of committing to an ambition to reach net-zero and propose short, medium and long-term targets that achieve this covering *all* scopes of emissions. Similarly to Exxon Mobil, Shell has attempted to shift responsibility in the past, claiming that "*It will only*

move with Society" and stating that its ability to change is limited by the rate of change by society as a whole (Shell Our Climate Targets: FAQs)
In February 2021, Shell reformed its previous Climate Targets. Regarding the carbon intensity of its operations and energy products, Shell intends to reduce this by 6-8% by 2023, 20% by 2030 and 45% by 2035, reaching 100% reductions -net zero- by 2050 (Shell Annual Report, 2020). When laying out its roadmap for reaching net-zero, the company states that it "will seek to have access to an additional 25 million tonnes a year of carbon capture and storage (CCS) capacity by 2035" (Shell, 2021). Shell is currently involved in three CCS projects: Quest in Canada (in operation), Northern Lights in Norway (sanctioned) and Porthos in The Netherlands (planned), which results in a total of around 4.5 million tonnes of capacity. However, an investigation by the watchdog group "Global Witness" revealed that the plant in Canada actually *emits more than it captures,* whilst the plant captured 5 million tons of carbon between 2015-2020, it emitted an additional 7.5 million tonnes of GHG in the same period. Shell's CCS plan only captures 48% of the emissions generated by the plant (Global Witness, 2022). Shell's plans regarding nature-based-solutions for storing carbon are vague, claiming that it will invest $100 million a year into various verified and high-quality projects. Even if Shell managed to ramp up its CCS capacity to reach 25 million tonnes a year by 2035, it too, like Exxon Mobil, falls woefully short of the CDR requirements calculated by the analysis in this paper, which calculates total CDR by 2050 for Shell at 2158,66Mt for SSP1 and 7788,7Mt in SSP5.

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BP, UK

Headquartered in London, BP UK is a multinational, vertically integrated oil and gas company which operates across the oil and gas industry, active in all areas including exploration and production, refining, distribution and marketing, power generation, and trading (Client Earth). BP scores better than Exxon on the "Big Oil Reality Check", scoring "partial alignment" with two of the benchmark criteria: "Decline in oil and gas production by 2030" and "setting absolute targets covering all oil and gas extraction". It scores "insufficient" on the criteria: "End lobbying and ads that obstruct climate solutions" , "stop exploration" and "setting long-term production phase-out-plan aligned with 1.5 degrees" In 2020 BP set new ambitions to become net zero by 2050, supported by five aims. However, BPs statement has been criticised by journalists including Jonathan Watts from the Guardian, who claims that nothing in BPs plans indicates that it will discard its previous plans of increasing oil and gas production over the next decade by 20%. He criticises the statement for being vague regarding how change will be achieved and contradictory because BP continues to reassure its shareholders that their values will not change (Watts, 2021).

BP has a well-known history of significant oil spills, most notably the “Deep Water Horizon” disaster, causing enormous damage to the economy and to the natural ecosystem of the Gulf and the Gulf Coast of the United States (Muralidharan, Dillistone, & Shin, 2011), categorised by the National Commission (2011) as the world´s largest ever accidental release of oil into marine waters.

Research carried out by Greenpeace shed light on the fact that there was a discongruity between BPs investments and their public relation statements, as there investments show an overwhelming share (97%) in oil and gas, versus an insignificant 2.79% and 1.39% being spent on biofuel and solar initiatives respectively (Walker, 2010).

Research into BPs marketing campaign also suggests that the company has continuously engaged in greenwashing activities. Through its branding, including its name” Beyond Petroleum” and the logo of a yellow and green sunflower, the company absolves itself of accountability and promotes the image of environmental stewardship (Barrage, Chyn, & Hastings, 2014). An investigation into BPs attempt at image restoration after the Gulf Coast Oil Spill suggests that this has been achieved through visual decoupling (Muralidharan et al. 2011), a phenomenon where stated (textual) corporate practises are contradicted by actual visual events, especially through the design of websites. Furthermore, in 2018 a complaint was brought against BP by client earth lawyers who claimed that BPs advertisement campaign “*Keep Advancing*” and “*Possibilities Everywhere*” was misleading the public because, in reality, BP was spending more than 96% on oil and gas as opposed to investing in low carbon energy products. Although BP withdrew its campaign before the case could move forward, the case was significant and set a precedent for holding companies accountable for engaging in greenwashing in conjunction with consumer products, based on OECD guidelines (OECD Watch, 2019).

In 2020, BP announced new ambitions regarding its CCS projects and aligned its emissions targets to match those of other countries under the Paris Agreement. It also joined the global CCS Institute and is involved in the Net Zero Teesside Project in the UK, with the aim of decarbonising operations through the deployment of CCS (Rathi, 2020). However, currently the only CCS project mentioned on BP´s website is the Santos' Moomba CCS project in South Australia, with whom BP has entered a non-binding agreement, aiming to capture 1.7 million tonnes of CO2 per year, a fraction of the 1892,6 Mt of CDR required by 2050 in SSP1 and 6828,75Mt required by 2100.

Saudi Aramco

As shown by this analysis, Saudi Aramco is the largest corporate emitter of CO2 globally, having contributed 4,81% of global CO2 between 1990-2018. In 2020, Forbes reported Saudi Aramco´s sales at $329.8 billion and in 2022, the company falls only behind Apple Inc. to win the title of the world's most valuable company. If Saudi Aramco continues its production rates from 2020, its oil and gas reserves are forecast to last until 2077, as its oil and gas reserves are much larger than those of Exxon, Chevron, Shell, BP and Total combined (Client Earth). Although the CO2 embedded in existing fossil fuel reserves would, if used, already push the world past **2°C warming (**Big Oil Reality Check, 2020), Aramco is looking to *continue to grow* its reserves (Client Earth).

Saudi Aramco scores extremely poorly in both the *Climate Action 100+ Net Zero Company Benchmark* (not meeting any of the criteria) and the TPI, where it is shown that Saudi Aramco has not even set GHG reduction targets, disclosed scope 3 emissions or had its operational scope 1 and 2 GHG emission data verified, disclosed any information regarding long-term quantitative targets for GHG reduction, disclosed an internal price of carbon or incorporated climate change risks and opportunities into its scenario planning. After joining the Oil and Gas Initiative in 2020, the company pledged to reduce the carbon *intensity* of its emissions by 13% but notably did *not* include its scope 3 emissions. Emission *intensity* targets are *not* decoupled from economic growth, meaning that if the revenue of a company continues to grow, so will its emissions (even if this might be at a slower pace).

Saudi Aramco has a CCS project at its plant in Hawiyah in Saudi Arabia. However, CCS at this plant is actually used for *Enhanced Oil Recovery* (The challenges of this will be explained in Chapter 6). The amount of CO2/year captured at the plant is estimated at a mere half a million tonnes, a miniscule percentage of Aramco´s annual emissions (Client Earth). Even when taking into account some other of Aramco´s alleged CDR projects such as planting Mangroves or producing blue ammonia, the amount of CO2 Saudi Aramco´s reduces through these processes are minimal and insignificant compared to the vast amount of cumulative CDR required by 2050 according to my calculations, 5851 Mt in SSP1 and 21112,9 Mt in SSP5. Furthermore, Saudi Aramco´s reporting regarding the results of its CDR projects lack transparency and thoroughness (Client Earth)

Gazprom

As far as its share of global cumulative CO2 emissions go, Gazprom falls only shortly behind Saudi Aramco, having contributed a 4,02% share of global CO2 over the time period 1990-2018. Due to the ongoing Russian invasion of Ukraine at the time of writing, data regarding Gazprom's 2022 activities is not available, as both the TPI and the Climate Action 100+ Initiative have paused active engagement with Russian companies for the time being. However, the 2021 assessment shows that Gazprom scored very poorly, not meeting or only partially meeting any of the benchmark criteria. It has not set a net zero GHG target for 2050, nor does its target cover a relevant share of scope 3 emissions. Whilst targets for reducing scope 1 and scope 2 emissions have been set, no explicit pledges have been made that align its capital expenditure plans with the objectives of the Paris Agreement, Furthermore, in 2021, the head of exports at Gazprom, Elena Burmistrova, claimed that natural gas and global goals on climate change were fully compatible and therefore should remain a key resource in energy consumption, highlighting its crucial role for energy security, especially in the European Union, which obtains about a third of its natural gas supplies from Gazprom (Reuters, 2021). An analysis of Gazprom´s stance on climate change by the InfluenceMap provides further evidence that Gazprom is overwhelmingly unsupportive of ambitious climate action and continues to advocate for the long term use of fossil fuels. Its messaging is generally negative and often conveys ambiguity and uncertainty in regards to the findings from climate change science. Its engagement with climate-regulations is contentious, with the company hailing emission *intensity* reduction targets over actual emission reduction targets. The influenceMap assessment recognises that due to Gazprom being headquartered in Russia, obtaining information on climate policy engagement and communication channels is somewhat limited.

Heede and Kenner (2021) corroborate the finding that the top IOCs and SOEs in the Carbon Major database are not presenting net zero ambitions that facilitate a rapid decarbonisation in line with a 1.5 °C pathway, on the basis that enduring disruption as part of the energy transition is an unattractive scenario for directors and executives, who are dependent on the survival of their companies for their substantial personal net worth. The findings from Oreskes and Supran (2017) have already been mentioned earlier on in this paper, but it is relevant again to highlight what the authors say about the communication and strategies employed not only by Exxon, but also other fossil fuel companies. *None of the companies presented in this brief overview actively deny the existence of climate change*, but they all choose sophisticated language that is linked to greenwashing, technological optimism and phrasing fossil fuel as part of the solution as opposed to the problem (Supran, 2021 in *the Harvard Gazette).*This is supported in a study by Li et al., (2022), which conducted a comparative analysis on Exxon Mobil, Chevron, BP and Shell regarding their dedication to the green energy transition, by analysing the wording used in their annual reports, their business strategies, expenditures and investments. The authors concluded that whilst strategies focusing on clean energy and decarbonisation are prominent, these overwhelmingly appear in the form of pledges instead of concrete actions. Crucially, financial analysis of these companies reveals that investment in clean energy remains negligible. Thus, given the lack of alignment between discourse and actions, the claim that companies continue to engage in greenwashing is well grounded (Li et al., 2022).

At the time of writing, an investigation in the british newspaper “The Guardian” revealed that the world´s largest oil and gas companies are planning numerous huge projects, that have been coined “carbon bombs” in the media, which, if they materialise, will crush any hope of reaching the long term 1.5 °C temperature goal (Carrington and Taylor, 2022). Whilst the term carbon bomb has been around for a while, this recent research restricts the use of the word to projects that have the capacity to produce a minimum of 1bn tonnes of CO2 emissions over their lifetime (Carrington and Taylor, 2022). The combination of the war in Ukraine pushing up oil and gas prices and the failure of countries to recover on a “greener trajectory” after the Covid Pandemic has increased the attraction for fossil fuel companies to invest in new projects and exploit high prices. A number of the top Carbon Majors have been identified as having huge short-term expansion plans, with a third of these plans relying

on unconventional and risky sources, such as fracking and ultra-deep offshore drilling. The analysis also shows that three chinese companies - PetroChina, China National Offshore Oil Corporation and Sinopec, that have so far not been under much scrutiny, occupy the top spots when ranked by average annual investment in oil and gas exploration between 2019-2022 (Carrington and Taylor, 2022).
Kühne et al., (2022), highlights the irony of countries enabling companies to go ahead with their carbon bomb projects only months after world leaders came together at the Glasgow climate conference.

5.2 Feasibility of CDR targets - Defining Feasibility

Before one can discuss the feasibility of individual CDR strategies or the likelihood of them being deployed at scale, it is important to discuss what is meant by feasibility in this context. According to Rogelj et al. (2018b), assessing feasibility represents a multidimensional approach, taking into account dimensions such as geophysics, technology, economics, societal acceptance, institutions and politics (and more). This interpretation of feasibility highlights how complex the process of assessing feasibility of a novel mitigation option like CDR is. Currently, the feasibility of future CDR potential remains uncertain, especially in light of the large-scale deployment deemed necessary (Grant et al., 2021). The scale of CDR deployment envisioned in the SSPs is unprecedented (Fajardy et al., 2019; Carton et al., 2020). Whilst a CDR strategy may be deemed as technologically ready, feasibility relies on assessing further factors such as sequestration potential, deployment costs and time lines (Oschlies and Klepper, 2017). This is highlighted by what Corry (2014) has deemed the “contraption fallacy”, which refers to the belief that a technology can work on its own, when in reality, the potential of carbon removal is determined by contextual dynamics and an array of complicating factors (Carton, 2020). This holistic approach to judging feasibility should be kept in mind when discussing some of the challenges of large scale CDR deployment.

5.2.1 Feasibility of Large Scale CDR Deployment

The deployment of CDR on a large scale, that is, CDR of an order of gigatonnes removed per year, as projected by most IAMs, is confronted with major technological and sociological challenges. On the technological side, knowledge about the functionalities of the technologies themselves as well as knowledge regarding the amount of capital needed to finance the required infrastructure is lacking. This is combined with societal concerns over potential unintended consequences of these technologies as well as the potential for them to exacerbate already present inequalities in our global society. Questions regarding timing of deployment and best choice of technologies are delaying action at a time when this cannot be afforded (Buck and Aines, 2021).

Fuss et al., (2018), through analysing the output of a range of published IAMs that deploy scenarios to achieve 1.5°C, present a range of CDR deployment from 1.3 to 29 GtCO2/yr, with most values lying between 5 and 15 GtCO2/yr by 2050 (CDR Primer, 2021). The author herself notes that these model outputs need to be interpreted cautiously, to be interpreted as formal requirements as opposed to clear targets (Fuss et al., 2018).

5.2.2 Feasibility of CDR - BECCS and A/R

Increasingly ambitious temperature targets combined with continued delay of implementation of effective mitigation strategies are putting pressure on the implementation of CDR to be accelerated and rolled out on a larger scale, requiring suitable policy frameworks and governance schemes (Fuss et al., 2020). The main challenges associated with CDR strategies that need to be considered are their biophysical potential for carbon sequestration, their economic costs and their social, economic and environmental impacts linked to their deployment (Fuss et al.,2018).

The biophysical potential for carbon sequestration is dependent on the global storage potential, which, although theoretically extensive globally, could be restricted on a regional level, which would limit the utility of a CDR strategy such a BECCS in particular regions. Additionally, long-term storage would have to be adequately governed, presenting a further challenge. Negative side effects of BECCS include risks to food security and health, loss of biodiversity, forest deforestation and degradation, CO2 leakage and contamination of water and soil through excessive fertiliser use. Wider biogeophysical impacts can include changes in Albedo and GHG emissions (Fuss et al., 2018). For Afforestation and Reforestation, higher food prices due to lower levels of agricultural production, loss of biodiversity due to dominance of monocultures and impacts of land use change such as change in albedo are forecasted. Unlike BECCS, the storage potential is considered less permanent as forests are more prone to saturation, disturbance. Adequate and continuous management of afforested areas is essential (Fuss et al., 2018). For an extensive discussion on the cost, potential and side effects of negative emissions see part two of the series on negative emissions by Fuss et al., (2018).

The next section will briefly touch upon some of the challenges that arise when intending to deploy CDR on a large scale.

5.2.3 Governance challenges- economic incentives

Mace et al., (2018) identify ten key governance challenges that arise when CDR is implemented on a large scale: the speed of scale-up, associated issues regarding ethics and responsibility, incentives for large scale deployment, adequate monitoring once CDR has been initiated, safeguards for sustainable development, accurately measuring and reporting CO2 removals, managing storage issues and potential leakage, anticipating and monitoring biophysical effects of large scale CDR deployment, legal infrastructure and responsibility an lastly, public acceptance and awareness.

An issue identified as critically under researched by Bednar et al., (2021) is the financial viability of large scale CDR deployment. Financing a net-negative carbon economy would require incentivising economic instruments that encourage emitters to repay their carbon debt through "*carbon removal obligations*" (Bednar et al., 2021). Bednar proposes that *temporary* atmospheric Co2 storage should be priced through **interest on carbon debt**, to avoid the risk of carbon debtors defaulting and encouraging more ambitious and near term decarbonisation of major emitters (Bednar et al., 2021). Hastings (2020) provides additional insight on the need for an adequate economic infrastructure to support the large scale deployment of CDR. One such policy measure would be to align the carbon tax and cost of CCS, to create a mechanism for this industry to become economically viable.

5.2.4 Governance Challenges - Separating Reduction and Removal

A major challenge identified in the literature on the deployment of CDR is to ensure that targets for emissions reduction and emissions removal are kept separate on the basis that reduction and removal are fundamentally different processes that have unique requirements, risk and social implications associated with them. They cannot be substituted for one another nor used interchangeably (Lohmann, 2011). Overly optimistic projections of future deployment of CDR could lead to mitigation deterrence, justifying a business as usual approach by some who believe that the ability to offset emissions entitles one to continue with emission producing activities (Carton, 2020). This phenomenon has been exacerbated by a co-evolution of technological promises, modelling, policies and climate change targets, resulting in the potential of these technological promises becoming substantially influenced by the choice of model and choices made by the modeller, as well as the demands of climate policies. Despite no large-scale deployment of CDR existing anywhere yet, it has become an essential component of most climate models, resulting in a potentially destructive cycle of continued promises (of new technology) and delayed action (McLaren and Markusson, 2020).

5.3 Are the Carbon Majors the right target group? - stranded assets

As noted in the introduction, this analysis has focused on the possibilities for sharing the CDR burden and assumed that the reduction of emissions will align with the cost-optimal distribution outlined by the respective pathways. In other words, CDR does not take place in isolation, but is accompanied with a reduction of emissions globally. This is relevant because it suggests that a proportion of fossil fuels will have to be left in the ground. This could be the outcome of new policies such as carbon pricing, cheaper availability of cleaner energy or other lifestyle changes in society. The IEA predicts that global oil demand will start to see slower growth from 2025 (Sheppard, 2020). If companies comply with scientific recommendations to end exploration, cease new extraction and start to invest in low-carbon-energy, they would likely see a decrease in their size and revenue (Kenner and Heede, 2021). This will result in some assets no longer earning an economic return *prior* to the end of their economic life, as a consequence of the energy transition. These assets that essentially turn out to be worth less than expected, have been named "stranded assets" (Carbon Tracker). Examples relevant for the Carbon Majors include fossil fuels left in the ground, exploration assets, production facilities and distribution infrastructure (Carbon Tracker). Thus, stranded assets pose a real threat to the Carbon Majors, as most of them have invested negligible proportion of their capital expenditure into low carbon technologies and are honing homogenous portfolios of primarily fossil fuels (van der Ploeg and Rezai, 2019). A paper by Lu et al., (2022) found that even if the fossil fuel companies diversified their portfolios and invested into negative technologies and converted current assets to be less-carbon intensive, a large amount of expected stranding would be guaranteed. Furthermore, the growing fossil fuel free divestment campaign is exacerbating the threat to survival which the fossil fuel companies are facing, by indirectly impacting companies through tarnishing a company's reputation and image (Ansar et al., 2013). The chances of carbon majors surviving these pressures, as well as the drastic restructuring required of these companies as part of the transition to a net zero economy is uncertain (Bach, 2018). The relevance of this for this paper rests with the premise made that these companies should shoulder the responsibility for a *larger* proportion of the CDR burden. However, this raises the question of whether this is still a viable claim to make if a large proportion of these companies *might no longer exist or be profitable in the decades to come*. Banking on these entities stepping in to remedy the climate crisis with arguably risky technology on a large scale could end up being twice as hazardous as first imagined. It is clear that a Net Zero Emissions scenario will not leave any fossil fuel company unaffected, as a fall in demand and the prohibition of new fossil fuel exploration beyond already approved projects will present a threat to companies earnings (Bouckaert et al., 2021).

5.3.1 Are the Carbon Majors the right target group? - perpetuating a fossil fuel intensive world?

Whilst CDR is often hailed as a crucial technological option to increase the chance of meeting global temperature targets, concerns have been voiced that it is interpreted by some as a way of avoiding continuous emission reduction and subsequently perpetuating a fossil fuel intensive world (Asayama, 2021). A 2019 report by the Centre for International Environmental Law (CIEL) suggests that investment in CCS could increase consumption of coal by 40% and by 923 million additional barrels of oil in the US by 2040 (Muffett et al., 2019). CDR could deter efforts from investing in urgent mitigation measures (McLaren et al., 2019). This is cited as a major reason for why CDR entered the political debate in the first place (McLaren & Markusson, 2020), as outlined in their paper: *"The co-evolution of technological promises, modelling, policies and climate change targets"* (McLaren & Markusson, 2020). The argument that CDR perpetuates a fossil fuel intensive world holds most persuasively for technological CDR options, specifically CCS, which arguably allows the fossil fuel industry to maintain their status quo (Gunderson et al., 2020, Asayama, 2021), supported by the recognition that countries currently promoting the use of CCS are also major producers of fossil fuels (Gaede and Meadowcroft, 2016). An example is Norway, where political support for CCS and REDD+ has been linked to governmental interest in continuing to engage in oil and gas extraction whilst allegedly meeting international climate targets (Røttereng, 2018). Amongst fossil fuel producers, coal companies have been particularly eager to use the promise of CDR technologies in an attempt to clean up the reputation of the industry (Fitzgerald, 2012), also evidenced in many of these companies own reports on climate change and sustainability (see section 6.1). For CDR, the concern is that land-based initiatives such as afforestation could be seen as substitutes for the urgent efforts to cease the use and exploration of fossil fuels, or even justify the continued use of these dirty energy sources (Carton et al., 2020, Asayama, 2021). Furthermore, the sequestration potential of strategies such as afforestation can sounds significant on a global scale, (e.g. Bastin et al., 2019), but smaller scale studies demonstrate that indiscriminate afforestation risks planting trees on land already used for other important purposes or turning valuable grassland biomes, also important players in carbon conservation, into new forests (Allison, 2019). This arguably restricts the extent to which such CDR options can be deployed at scale. Adding fuel to the fire though is the prospect of Enhanced Oil Recovery (EOR) being a, for the fossil fuel companies, positive byproduct of an upscaling of the CCS industry. EOR represents the process of utilising pressurised CO2 to extract *more* hydrocarbon out of existing oil and gas reservoirs, thereby providing *more* oil for the industry whilst leaving a lot of CO2 permanently stored underground (Roberts, 2019). Critics of this approach raise the concern that this seems like a rather perverse way to facilitate large scale carbon sequestration, by essentially subsidising increased production in the industry in which one is trying to *reduce* emission from (Roberts, 2019). Furthermore, the actual net-negative potential of EOR is debated, as dynamic life-cycle analysis suggests that the net-negative potential of EOR projects are time dependent, changing to becoming carbon positive when oil production declines (Núñez-López and Moskal, 2019). Furthermore, currently, most of the CO2 used in EOR does not come from anthropogenic sources, but from underground sources, primarily because there is often not enough CO2 close to oil fields. Using CO2 from natural sources clearly has no environmental benefit (IEA, 2019). When CO2 from anthropogenic sources is utilised, another complication arises from the methodology used to account for the "saved" CO2 emissions, as credit associated with underground storage can only be counted once: either it reduces the emissions from the origins source *or* it reduces the emissions from oil production at the site (IEA, 2019).

However, on the flip side, the argument made earlier in this paper is also relevant here: precisely *because* the technology and skills required for some forms of CCS are so similar to the ones currently employed by the fossil fuel companies for their production processes (Hastings, 2020), they constitute suitable candidates for this role. If the fossil fuel industry manages to scale up the CCS industry, it could be an opportunity for them to begin to shed themselves of their negative reputation as "Big Bad Oil" (Hastings, 2020).

Nevertheless, the premise of relying on the fossil fuel industry to determine at what pace carbon is sequestered underground seems morally questionable, as a large number of these entities are multi-billion dollar, profit oriented companies, whose priority is making revenue as opposed to saving the planet.

5.3.2 Alternative culprits? -The Super rich

A 2020 Oxfam report found that the richest 10% of the global population produced 52% of the cumulative carbon emissions in the 25 years between 1990-2015. The richest 1% were accountable for 15% of cumulative emissions, just over twice as much as the poorest 50% (who were responsible for 7% of cumulative emissions) (Gore, 2020). In order to not exceed the 1.5 temperature targets, global average per capita emissions have been estimated at 2.1 t/year by 2030. The findings from the Oxfam report suggest that the richest 1% currently have a footprint that is 35 times higher than the 2030 target (Gore, 2020). This inequality is further confirmed by a 2020 study by Oswald et al., which finds that, because energy footprints correlate with expenditure, they also are unequally distributed. Energy inequality is especially pervasive in the transport sector, a consequence of intensive use of air travel, often private jets, of the top 10% (Oswald, 2020). Chancel and Piketty (2015), linking consumption with environmental impact, also find that the world's richest citizens are largely to be held responsible. Their environmental impact is exacerbated through their excessive consumption, influential position they occupy in society and the wider impact they therefore have on society through influencing norms and behaviour (Wiedmann et al., 2020). This was confirmed by Nielsen et al., (2021), who identified that, both indirectly and directly, people with high socioeconomic status disproportionately affect GHG emissions, through their consumption and high financial and social resources (Nielsen et al., 2021).

Despite the super-rich playing a dominant role in the domains of politics, social media and business, detailed data regarding their income, lifestyles, resources use and consumption patterns are often lacking (Otto et al., 2019). However, this reflects an, until now, relatively untouched opportunity regarding the reduction of CO2 emissions, through changes in lifestyle in this population segment. Furthermore, the effects of this could be cascading, as these individuals have been found to have an influential effect on citizens in lower social classes (Otto et al., 2019). An example of the influence that the super-rich can have on members of society was demonstrated in a paper by Gössling (2019), who examined the effects of frequent air travel by celebrities on the perception of their followers on social media. Gössling (2019) highlights how celebrities define desirable consumption, and, through living a lifestyle built on frequent air travel, incite their followers to aspire to similar lifestyles, thereby affecting

social norms. Due to limitations regarding data availability, Gössling´s (2019) findings most likely underrepresented the total amount that these celebrities engage in air travel, suggesting that their *actual* impact is even more dramatic.
Current mitigation policies are of a tentative nature in regards to those sectors in which the super-rich are most active: finance, retail and real estate. Environmental taxation will thus only have negligible impacts on their consumption behaviour (Kenner, 2015). More targeted climate policies such as regulation on construction of private property or inheritance taxes would be more effective, but most likely also be met with significant backlash from this segment of the population (Otto et al., 2019). Persuasive efforts are needed to mobilise this powerful fragment of the population to invest their influence and resources into environmental protection, and increase awareness of what will happen if they do not (Otto et al., 2019).

Kenner and Heede (2021) have contributed an insightful paper to this discussion on the personal responsibility of high income individuals, in which they assess the responsibility of the executives and directors of the top four IOCs, by calculating their proportional share of their respective company´s emission, primarily based on the percentage share they have in the company. The study alludes to the dimension of personal responsibility within the Carbon Majors, an interesting area for further research (Kenner and Heede, 2021).

5.4 Alternatives to CDR? Societal Transformation Scenario (STS)

Kuhnhenn et al., (2020) in their publication “Societal Transformation Scenario” emphasise the importance of designing climate mitigation scenarios that incorporate broader societal transformation, such as limiting production and consumption in the Global North as opposed to depending on continued economic growth and relying on technological change. This is particularly interesting in the light of this thesis and the SSPs produced by the IPCC, which emphasise the need for CDR to meet end century warming targets. Kuhnehenn et al., (2020) argue that it is possible to meet these targets *without* relying on overshoot and risky CDR strategies to bring global temperature back

down. In particular, for the global north, the STS focuses on reducing road-based transport, a reduction of personal living space and reducing food waste and meat consumption. Importantly, this is *not* envisaged for the global South, where an increase in consumption is assumed, leading, eventually, to global convergence (Kuhnehenn et al., 2020). Crucially, instead of relying on IAMs (the shortfalls of which will be addressed in the limitation section) the authors employ a more transparent and democratic tool, the "Global Calculator" (http://www.globalcalculator.org/), which does not rely on decision making algorithms but requires the user to choose the inputs. The author does, however, acknowledge that any global emissions model is a simplification of our complex world and therefore is characterised by generalisation and uncertainties (Kuhnehenn, 2018).
Beyond the work by Kuhnhenn et al., (2020), other studies have been carried out examining alternative pathways to reaching the end of century 1.5 °C temperature target. These include Grubler et al., (2018), who highlights the role of social innovation and increased efficiency, transforming the global energy system and making a low-carbon supply side transformation more feasible. Crucially, the study shows that, in this low-demand-energy (LED) scenario, ambitious temperature targets can be met without invoking risky CDR technologies (Grubler et al., 2018). The paper also acknowledges research gaps regarding economic impacts of a LED scenario as well as the impact of a potential rebound effect, the phenomenon where increase in efficiency can result in an increase in consumption, though appropriate policies could dampen this effect. The feasibility of such a LED scenario ultimately depends on institutional and social change that do not promote a continued increase in demand. The challenge of incorporating these socioeconomic changes into a modelling context is acknowledged (Grubler et al., 2018).

Holz et al., (2018) attempt to model the quantity of emissions that will have to be reduced to eliminate or strictly limit the implementation of CDR by using the models C-ROADS and En-ROADS to generate a series of 1.5 °C mitigation scenarios that constrain the scale and type of CDR available. The results show that scenarios where *no* CDR is deployed emission reduction rates are very steep, reaching previously unprecedented levels.

Finally, Van Vuuren et al., (2018) also attempt to reduce the amount of negative emissions needed to meet the 1.5 °C temperature target, though notably they are unable to completely eliminate the use of NETs. The authors combine the SSP2 pathway (middle of the road) with a variety of mitigation measures that alleviate the reliance on negative emissions such as policies like Carbon Taxes, lifestyle changes and demographic changes e.g. (smaller populations).

However, crucially, none of the three additional studies presented here question the continuation of economic growth per se, as is done in the Kuhnhenn (2020) paper.

Chapter 6: Limitations, Future Outlook and Conclusion

6.1 IAMs and Scenario Frameworks

On the basis of continued high GHG emissions, a rapidly diminishing carbon budget and the discount rates utilised, the IPCC claims that conventional climate protection measures, such as using renewable energy or reducing energy consumption by increasing efficiency, are insufficient and thus geoengineering is necessary and a temporary overshoot may have to be tolerated in order to not exceed the 1.5 degree long term warming limit (IPCC; 2018; EEA, 2011 in Kuhnhenn, 2018). However, a key limitation of the SSP scenario framework identified by Kuhnhenn (2018), is the consistent feature of positive growth rates, relying on economic growth till 2100 and use of economic growth as an indicator for quality of life. Kuhnhenn disputes the common argument that decoupling will enable this economic growth to continue whilst simultaneously reducing GHG emissions, stating that the IPCC itself has admitted that this is very difficult to achieve and has only been witnessed in a few isolated cases (Kuhnhenn, 2018). The SSPs, partially due to their (relatively short) time frame of a century, are not able to fully account for the potential of societal change and progress on a large scale, which could render high risk mitigation strategies, such as CDR, unnecessary (Kuhnhenn, 2018). Kuhnhenn (2018) attributes this shortsightedness to the developmental process of the scenario framework, criticising scenario development in a more general sense by stating that the scientists involved are heavily influenced by the research environments of their respective disciplines, frequently characterised by the assumption that negative growth rates are correlated with large negative social consequences. IAMs exacerbate this mindset, as welfare functions employed in models are frequently based on traditional economic theories, maximising economic growth, or material well-being. Thus, models attempt to optimise, meeting emission-reduction targets whilst simultaneously increasing economic activity (and subsequent associated emissions!) to maximise welfare, in the traditional sense. This seems obviously counterproductive, and thus models need to circumvent this contradiction by increasing energy efficiency (thereby reducing relative GHG emissions), using other (cleaner) energy forms or, deploying CDR to remove the CO2 linked to increased production (Kuhnhenn et al., 2020). Due to their design, models will always prioritise least-cost-options or solutions that benefit utility, therefore opting for strategies with the lowest-cost per tonne of CO2 saved or associated economic gains (Kuhnhenn et al., 2020). This is at the expense of arguably more important factors such as environmental and social costs and acceptance (Kuhnhenn et al., 2020). This can be explained by the model design, as supply side measures (such as technological change), are easier to quantify than demand side measures, such as behaviour and lifestyle changes (Larkin et al., 2017). Kuhnhenn et al., (2020) argues that this should not be a reason to *disregard* these messages, warning that a reliance on technological solutions is not without risk (Beck, 2015 in Kuhnhenn et al., 2020) and cannot be viewed in isolation, another key shortfall of the IAMs, which are generally unable to incorporate fully the environmental and social costs (Shue, 2017) associated with a technological solution. Finally, the discount rate used in IAMs is another reason for concern, further increasing the reliance on technological solutions, which are deemed as becoming cheaper over time (Kuhnhenn, 2018), at the expense of overshooting temperature targets in the short-run and risking potentially detrimental climatic effects linked to phenomena such as positive feedback and tipping points.

Carton (2020), adds to the debate by pointing out that IAMs should be acknowledged as *one* possible approach to creating knowledge on climate change, which is political in its nature. Continuing to rely on cost-optimisation models will most likely exacerbate inequality on a local and global scale (Carton, 2020). There should be an increased emphasis on integrating approaches from the social sciences into climate change scenario research in order to improve the understanding of the dynamics of climate policy implementation, better taking into account actors and context (Hewitt et al., 2020).

6.2 Uncertainties- PRIMAP data for global CO2 emissions

Both the data on global CO2 emissions and the Carbon Majors CO2 emissions are prone to uncertainty. The PRIMAP global emissions database acknowledges the difficulty of quantifying the aggregate uncertainty, as the combination of individual datasets with different methodologies for calculating uncertainty complicates the endeavour to produce consistent uncertainty estimates. Datasets vary in the way they estimate emissions and define sectors, as well as in the assumptions they make for missing data points (Gütschow et al., 2016). The authors acknowledge that the creation of the dataset involves decisions that represent further sources of uncertainty including prioritisation of sources, downscaling and extrapolation, the latter being particularly contentious as regional growth rates are used which assume that all countries within a region share *homogenous* growth rates. However, the resulting uncertainties are accepted in order to complete missing data points (Gütschow et al., 2016). **Crucially however, the dataset still manages to provide a more holistic reflection of the historic global emissions of GHGs than could be achieved by using any dataset in isolation (Gütschow et al., 2016).** For a detailed discussion of the limitations of the dataset and techniques employed to attempt to minimise uncertainties, please see the description paper that accompanies the PRIMAP database.

6.3 FAO land use emission data

Compared to other sectors, the AFOLU sector is particularly prone to high uncertainty regarding input data and estimation methodology, with uncertainty for emission estimates from agriculture ranging from 10%-15% (IPCC, 2006 in) and those related to forestry and other land use being even higher, though alternative modelling approaches can somewhat improve this (see Friedlingsten et al., 2011). Overall uncertainty is the product of uncertainty inherent to the activity data and in the emissions coefficients used to arrive at emissions estimates (FAO Analytical Brief, 25).

6.4 Carbon Major dataset

Heede (2014a) himself acknowledges that the project, attributing emissions to carbon producers themselves is unprecedented and involves far greater uncertainties than attributing the consumption of fossil fuels to nations. A number of factors, including poor reporting by the carbon producing entities themselves, missing data and potential double counting, to name just a few, lead Heede (2014a), to assign an estimated uncertainty of +/- 10% for the cumulative sum of the carbon majors, though he acknowledges that this is likely an underestimation in the case of some individual entities, especially as production data becomes less complete the further back in time it is traced. Data gaps are completed through interpolation. Heede identifies the greatest source of uncertainty to emissions from state-owned oil and gas companies, as self-reported emissions are often lacking here. Efforts have been made by Heede (2014a) to avoid double counting by reviewing the available literature. A complete and detailed discussion of all uncertainties of the data set are presented in Annex B (Methodology) of the Carbon Major report (Heede, 2014b). However, in summary, one can say that the main challenge with the projects is the inherent heterogeneity *within* this group of entities regarding not only the quality and consistency of the reporting of their own emissions, but also regarding variability in production processes and subsequent differences in non-energy uses (Heede, 2014b),

6.5 Methodology limitations

Besides the uncertainty inherent in the individual datasets, it should be noted that the analysis conducted in this thesis also comes with limitations. However, as noted at the beginning, the goal of this thesis is *not* to provide accurate quantitative amounts of CDR for individual entities, but rather to draw awareness to the *magnitude* of these amounts and the way these differ significantly between SSPs. Providing an accurate quantitative amount of CDR is limited by the number of models used in this analysis and subsequent small amount of input data, due to the number of models being limited by the requirement of them being consistent with 1.5 pathways. Furthermore, by combining multiple datasets with their own uncertainties, the cumulative uncertainty in the final analysis is likely to be augmented.

6.6 Conclusion/ Future outlook

This thesis has highlighted the magnitude of the share of global cumulative CO2 over the time period 1990-2018, that the Carbon Majors can be held accountable for, based on Heede´s (2014a) research. Combined with the findings of greenwashing, denial and miscommunication in the fossil fuel industry and the fact that by 1990, the science on climate change was confirmed by the publication of the IPCC report, the case for holding the Carbon Major´s responsible for their polluting activities is corroborated. However, appointing responsibility does not automatically translate into action. As we have seen in the discussion, some of the largest polluters amongst the Carbon Majors have incredibly vague, non-committal and non-ambitious climate plans, nowhere near sufficient to ensure global temperature rise does not exceed 1.5°C. The increase in climate litigation cases, as described in section 2.3.3 Climate Change Litigation, demonstrates that there is growing demand to hold fossil fuel companies accountable for the environmental devastation they are causing. This suggests that stricter laws and regulations are needed, treating the fossil fuel industry as one of the root causes of climate change (van Asselt, 2021). This calls for a shift from demand-side focused climate policy towards an emphasis on the supply side, which, up till now, has been neglected in the literature (Lazarus and van Asselt, 2018). Stricter regulation regarding production limits but also CDR quotas could create more clarity here, though, as ever, the question of who would enforce and monitor these activities is hard to answer.

If we are demanding the Carbon Majors and other corporations to take responsibility and actively participate in the fight against climate change, then this inherent lack of oversight regarding climate action in the sector is problematic. Accurate reporting of reductions and removals in the sector is key, but so is a deeper understanding of the governing role that corporations play in the CDR landscape (van Asselt, 2021). CDR should not simply be attributed to companies based on a theoretical similarity with processes and infrastructure requirements (e.g. in the case of BECCS), but other avenues such as consumer preferences, corporate social responsibility, market incentives and leadership opportunities should also be explored. Thus, instead of pointing the finger and shaming companies, another approach could be to see them as part of the solution and and their engagement with CDR as an opportunity, for them to clean up their image and for society as a whole, by actively contributing to mitigating the climate crisis. Adversity can be a catalyst for opportunity, which is something that became visible to an extent during the covid19 pandemic, with companies like Amazon and Zoom experiencing huge profits in their businesses (Shefrin, 2022 in Forbes). Clearer and stronger communication on the benefits for companies investing and engaging with CDR from a financially profitable perspective should be encouraged.

The pandemic showed us that when the world is faced with an acute global emergency, expert minds can come together and find solutions at remarkable speed, as we saw with the rapid development of not one but *numerous* vaccines against Covid19. Whilst we should not pin all our hopes on solving the climate crisis with a myriad of technological solutions, focusing only on the *unlikelihood* of these solutions succeeding could actually increase the chance of this being the case - as investors and researchers will be deterred and disheartened to engage with the topic. Public confidence, support and knowledge about CDR needs to increase in order to mobilise funding and incentivise research and engagement with it. The majority of businesses are profit oriented simply by their nature and need for survival and therefore CDR needs to be presented as an attractive investment in order for adoption to be encouraged. However, one should also not be naive - one of the greatest dangers when assigning a large portion of responsibility for CDR to the Carbon Majors is the risk that, exacerbated by an often fuzzy distinction between reduction and removal targets, CDR will be seen (by some) as an excuse to carry on with business as usual, that is, to keep polluting at current rates or, in some cases, to utilise CDR in combination with even more damaging process such as enhanced oil recovery. Unfortunately, the track record in terms of deceit and deception of many fossil fuel companies present in the Carbon Major database do not make this an unlikely scenario to imagine and recent revelations, touched upon in section 5.1.1, of the carbon bombs belonging to numerous companies in the Carbon Major database only exacerbate this.

Given that global emissions reached the highest level in history in 2021 (IEA, 2022), dashing hopes of a greener path being taken as part of the recovery from the Covid19 pandemic, time to act is vanishing at an ever increased pace. This thesis has shone a light on the track record of lies and deception inherent in the fossil fuel industry, the magnitude of CO2 emissions they are responsible for and the overwhelming lack of action taken so far to remedy any of the damage they have created . However, as these companies are profit oriented businesses, supply will continue as long as demand persists and, as they are entangled in the global economics system through a network of shares and investments. Exemplified by the fact that even through paying into your bank or pension fund, you can indirectly be supporting a fossil fuel company. The increase in climate litigation cases globally is a hopeful indicator that people are beginning to vocally disagree with the status quo. I hope that this thesis will encourage others to do so too.

References

Alcalde, J., et al. (2018). "Estimating geological CO 2 storage security to deliver on climate mitigation." Nature communications 9(1): 1-13.

Allen, M. R., et al. (2009). "Warming caused by cumulative carbon emissions towards the trillionth tonne." Nature 458(7242): 1163-1166.

Allen, M. R., et al. (2009). "The case for mandatory sequestration." Nature Geoscience 2(12): 813-814.

Allen, M., et al. (2020). "The Oxford principles for net zero aligned carbon offsetting." University of Oxford.

Allison, S. (2019). "The trouble with indiscriminate tree-planting in Africa." Mail and Guardian.

American Petroleum Institute. (1980). "Two energy futures: a national choice for the 80s." Laramie: Library of the University of Wyoming. Available at: https://eric.ed.gov/?q=benefits+AND+nuclear+AND+fuel&id=ED196683, accessed April 1st 2022.

American Petroleum Institute (2002). " Classroom energy! Available at: www.classroom-energy.orgwww.classroom-energy.org , accessed April 1st 2022.

Anderson, R. G., et al. (2011). "Biophysical considerations in forestry for climate protection." Frontiers in Ecology and the Environment 9(3): 174-182.

Andonova, L. B., et al. (2017). "National policy and transnational governance of climate change: Substitutes or complements?" International Studies Quarterly 61(2): 253-268.

Andres, R. J., et al. (2012). "A synthesis of carbon dioxide emissions from fossil-fuel combustion." Biogeosciences 9(5): 1845-1871.

Andrew, R. M. (2020). "A comparison of estimates of global carbon dioxide emissions from fossil carbon sources." Earth System Science Data 12(2): 1437-1465.

Ansar, A., et al. (2013). "Stranded assets and the fossil fuel divestment campaign: what does divestment mean for the valuation of fossil fuel assets?".

Armour, J., et al. (2009). "Essential Elements of Corporate Law." The Harvard John M. Olin Discussion Paper Series.

Asayama, S. (2021). "The oxymoron of carbon dioxide removal: Escaping carbon lock-in but yet perpetuating a status quo ante?" Frontiers in Climate 3: 72.

Azar, C., et al. (2013). "Meeting global temperature targets—the role of bioenergy with carbon capture and storage." Environmental Research Letters 8(3): 034004.

Baatz, C. (2013). "Responsibility for the past? Some thoughts on compensating those vulnerable to climate change in developing countries." Ethics, Policy & Environment 16(1): 94-110.

Bach, M. (2019). "The oil and gas sector: from climate laggard to climate leader?" Environmental Politics 28(1): 87-103.

Banerjee, N. (2015). "Exxon's oil industry peers knew about climate dangers in the 1970s, too." Inside Climate News.

Barrage, L., et al. (2014). "Advertising, reputation, and environmental stewardship: Evidence from the BP oil spill." American Economic Journal: Economic Policy, 12(1), 33-61..

Barros, B. and R. Wilk (2021). "The outsized carbon footprints of the super-rich." Sustainability: Science, Practice and Policy 17(1): 316-322.

Barry, C. and R. Kirby (2017). "Scepticism about beneficiary pays: A critique." Journal of Applied Philosophy 34(3): 285-300.

Bauer, N., et al. (2018). "Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison." Climatic Change: 1-16.

Bednar, J., et al. (2021). "Operationalizing the net-negative carbon economy." Nature, 596(7872), 377-383.

Bellamy, R. (2018). "Incentivize negative emissions responsibly." Nature Energy 3(7): 532-534.

Benjamin, L. (2016). "The responsibilities of carbon major companies: Are they (and is the law) doing enough?" Transnational Environmental Law 5(2): 353-378.

Berk, M. M. and M. G. den Elzen (2001). "Options for differentiation of future commitments in climate policy: how to realise timely participation to meet stringent climate goals?" Climate Policy 1(4): 465-480.

Bjørn, A., et al. (2021). "From the Paris Agreement to corporate climate commitments: Evaluation of seven methods for setting "science-based" emission targets." Environmental Research Letters. 16(5), 054019.

Black, R., et al. (2021). "Taking stock: A global assessment of net zero targets." Energy & Climate Intelligence Unit and Oxford Net Zero. Available at: https://eciu.net/analysis/reports/2021/taking-stock-assessment-net-zero-targets. Accessed 6th February 2022.

Bloomberg (2021) "Aramco's new disclosures still exclude vast majority of its emissions." Available at: https://www.bloomberg.com/news/articles/2021-04-06/aramco-s-new-disclosures-still-exclude-vast-majority-of-its-emissions Accessed 7th February 2021.

Bode, S. (2004). "Equal emissions per capita over time–a proposal to combine responsibility and equity of rights for post‐2012 GHG emission entitlement allocation." European Environment 14(5): 300-316.

Boden, T., et al. (2017). "Global, regional, and national fossil-fuel co2 emissions (1751-2014)"(v. 2017), Environmental System Science Data Infrastructure for a Virtual Ecosystem. Carbon Dioxide Information Analysis Centre (CDIAC), Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States).

Boers, N., et al. (2017). "A deforestation-induced tipping point for the South American monsoon system." Scientific reports 7(1): 1-9.

Boon, M. (2019). "A climate of change? The oil industry and decarbonization in historical perspective." Business History Review 93(1): 101-125.

Bouckaert, S., et al. (2021). "Net Zero by 2050: A Roadmap for the Global Energy Sector." IEA.

Bowerman, N. H., et al. (2013). "The role of short-lived climate pollutants in meeting temperature goals." Nature Climate Change 3(12): 1021-1024.

Brack, D. and R. King (2021). "Managing Land‐based CDR: BECCS, Forests and Carbon Sequestration." Global Policy 12: 45-56.

Brown, S., et al. (1996). "Mitigation of carbon emissions to the atmosphere by forest management." The Commonwealth Forestry Review: 80-91.

Buck and Aines (2021). "Foreword. CDR Primer", edited by J Wilcox, B Kolosz, J Freeman. Available at: https://cdrprimer.org/read Accessed 12th February 2022.

Bulkeley, H. and V. Castán Broto (2013). "Government by experiment? Global cities and the governing of climate change." Transactions of the Institute of British Geographers 38(3): 361-375.

Burger, M. and J. Gundlach (2017). "The status of climate change litigation: A global review."

Burkhardt, P. and C. Albanese (2019). "Oil Giant Eni will help protect African forests to offset its carbon footprint". Bloomberg.

Buylova, A., et al. (2021). "Cancel (Out) Emissions? The Envisaged Role of Carbon Dioxide Removal Technologies in Long-Term National Climate Strategies." Frontiers in Climate 3: 63.

C, S. J. a. H. (2021). "Global trends in climate change litigation: 2021 snapshot." London: Grantham Research Institute on Climate Change and the Environment and Centre for Climate Change, Economics and Policy, London School of Economics and Political Science.

Caldecott, B., et al. (2016). "Stranded assets: A climate risk challenge." Washington DC: Inter-American Development Bank.

Campiglio, E. (2012). "Who should pay for climate? The effect of burden-sharing mechanisms on abatement policies and technological transfers". Grantham Research Institute on Climate Change and the Environment.

Caney, S. (2005). "Cosmopolitan justice, responsibility, and global climate change." Leiden journal of international law 18(4): 747-775.

Caney, S. (2009). "Justice and the distribution of greenhouse gas emissions." Journal of global ethics 5(2): 125-146.

Carbon Tracker (2020) "Absolute Impact: Why oil majors' climate ambitions fall short of Paris limits" Available at: https://carbontracker.org/reports/absolute-impact/ Accessed on April 5th 2022.

Carbon Tracker (2020) "Fault Lines: How diverging oil and gas company strategies link to stranded asset risk." Available at: https://carbontracker.org/reports/fault-lines-stranded-asset/ Accessed on 17th March 2022.

Carrington and Taylor (2022). "Revealed: the 'carbon bombs' set to trigger catastrophic climate breakdown" The Guardian. Available at: https://www.theguardian.com/environment/ng-interactive/2022/may/11/fossil-fuel-carbon-bombs-climate-breakdown-oil-gas Accessed on 17th May 2022.

Carton, W., et al. (2020). "Negative emissions and the long history of carbon removal." Wiley Interdisciplinary Reviews: Climate Change 11(6): e671.

Chancel, L. (2021). “Climate change and the global inequality of carbon emissions 1990-2019”. WID.

Client Earth. “The Greenwashing Files- Exxon” Available at: https://www.clientearth.org/projects/the-greenwashing-files/exxonmobil/ Accessed on January 10th 2022.

Client Earth. “The Greenwashing Files- Shell”. Available at: https://www.clientearth.org/projects/the-greenwashing-files/shell/ Accessed on 10th January 2022.

Climate Watch "Historical GHG Emissions." Accessed 12th May 2022.

Climate Action 100+ “Net Zero Company Benchmark.”Available at: https://www.climateaction100.org/net-zero-company-benchmark/ Accessed on January 7th 2022.

Climateactiontracker.org. (2022).” Land use, land-use change and forestry”.Available at: https://climateactiontracker.org/methodology/land-use-and-forestry/ Accessed 27 January 2022.

Coffin, M. (2020). “Absolute Impact: Why Oil Majors’ Climate Ambitions Fall Short of Paris Limits.” Carbon Tracker. Available at: https://carbontracker.org/reports/absolute-impact/ Accessed 28th January 2022.

Collins, M., et al. (2013). “Long-term climate change: projections, commitments and irreversibility.” Climate Change 2013-The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press: 1029-1136.

Cook, J., Supran, G., Lewandowsky, S., Oreskes, N., & Maibach, E., (2019). “America Misled: How the fossil fuel industry deliberately misled Americans about climate change.” Fairfax, VA: George Mason University Centre for Climate Change Communication. Available at: https://www.climatechangecommunication.org/america-misled/ Accessed on 12th February 2022.

Cullity, G. (1995). "Moral free riding." Philosophy & Public Affairs: 3-34.

Cuomo, C. J. (2011). "Climate change, vulnerability, and responsibility." Hypatia 26(4): 690-714.

Davidson, M. D. (2021). "How Fairness Principles in the Climate Debate Relate to Theories of Distributive Justice." Sustainability 13(13): 7302.

Davin, E. L. and N. de Noblet-Ducoudré (2010). "Climatic impact of global-scale deforestation: Radiative versus nonradiative processes." Journal of Climate 23(1): 97-112.

Davis, S. J. and K. Caldeira (2010). "Consumption-based accounting of CO2 emissions." Proceedings of the National Academy of Sciences 107(12): 5687-5692.

de Coninck, H., et al. (2018). “Strengthening and implementing the global response.” Global warming of 1.5° C: Summary for policymakers, IPCC-The Intergovernmental Panel on Climate Change: 313-443.

den Elzen, M. G. and P. L. Lucas (2005). "The FAIR model: A tool to analyse environmental and costs implications of regimes of future commitments." Environmental Modelling & Assessment 10(2): 115-134.

Deng, Z., et al. (2021). "Comparing national greenhouse gas budgets reported in UNFCCC inventories against atmospheric inversions." Earth System Science Data Discussions: 1-59.

Devi, K. S., et al. (2017). "Impacts of cement industry on environment-an overview." Asia Pac. J. Res 1: 156-161.

Domenec, F. (2012). "The “greening” of the annual letters published by Exxon, Chevron and BP between 2003 and 2009." Journal of communication management.

du Pont, Y. R., et al. (2016). "National contributions for decarbonizing the world economy in line with the G7 agreement." Environmental Research Letters 11(5): 054005.

Ekwurzel, B., et al. (2017). "The rise in global atmospheric CO 2, surface temperature, and sea level from emissions traced to major carbon producers." Climatic Change 144(4): 579-590.

Emmerling, J., et al. (2019). "The role of the discount rate for emission pathways and negative emissions." Environmental Research Letters 14(10): 104008.

Enterprises, E. G. o. C. O. t. (2020). "Principles on Climate Obligations of Enterprises."

Erickson, P., et al. (2015). "Assessing carbon lock-in." Environmental Research Letters 10(8): 084023.

Erickson, P., et al. (2020). "The Production Gap Report: 2020 Special Report."

Exxon Mobil (2021) “Updated 2021 Energy and Carbon Summary”. Available at: https://www.google.com/url?q=https://corporate.exxonmobil.com/-/media/Global/Files/energy-and-carbon-summary/Energy-and-Carbon-Summary.pdf&sa=D&source=docs&ust=1654247098626822&usg=AOvVaw3glXwvuyr-kxtD7I9mZnHu Accessed on January 8th 2022.

Exxon Mobil (2022) “Advancing Climate Solutions 2022 Progress Report”. Available at: https://corporate.exxonmobil.com/Climate-solutions/Advancing-climate-solutions-progress-report Accessed on January 8th 2022.

Exxon Mobil (revised February 2022) “ Factor affecting future results”. Available at: https://corporate.exxonmobil.com/-/media/Global/Files/investor-relations/Factors-affecting-future-results.pdf . Accessed on January 8th 2022.

Exxon Mobil (2022) “ExxonMobil planning hydrogen production, carbon capture and storage at Baytown complex”. Available at: https://corporate.exxonmobil.com/News/Newsroom/News-releases/2022/0301_ExxonMobil-planning-hydrogen-production-carbon-capture-and-storage-at-Baytown-complex Accessed on January 8th 2022.

Fajardy, M., et al. (2019). "Negative emissions: priorities for research and policy design." Frontiers in Climate 1: 6.

Fajardy, M. and N. Mac Dowell (2017). "Can BECCS deliver sustainable and resource efficient negative emissions?" Energy & Environmental Science 10(6): 1389-1426.

Fajardy, M. and N. Mac Dowell (2020). "Recognizing the Value of Collaboration in Delivering Carbon Dioxide Removal." One Earth 3(2): 214-225.

Fang, Y., et al. (2014). "Biochar carbon stability in four contrasting soils." European Journal of Soil Science 65(1): 60-71.

Fankhauser, S., et al. (2021). "The meaning of net zero and how to get it right." Nature Climate Change: 1-7.

Financial Times. (2021). Leading “and gas companies worldwide based on revenue as of 2020 (in billion U.S. dollars)”. Statista. Statista Inc.. Accessed: January 02, 2022 https://www.statista.com/statistics/272710/top-10-oil-and-gas-companies-worldwide-based-on-revenue/

Fitzgerald, J. (2012). "The Messy Politics of “Clean Coal” The Shaping of a Contested Term in Appalachia’s Energy Debate." Organisation & Environment 25(4): 437-451.

Forbes. “Shell”. Available at: https://www.forbes.com/companies/royal-dutch-shell/?sh=17f4efd526ed Accessed on 10th January 2022.

Franta, B. (2018). "Early oil industry knowledge of CO2 and global warming." Nature Climate Change 8(12): 1024-1025.

Franta, B. (2021). “Early oil industry disinformation on global warming.” Taylor & Francis.

Fridahl, M. and M. Lehtveer (2018). "Bioenergy with carbon capture and storage (BECCS): Global potential, investment preferences, and deployment barriers." Energy Research & Social Science 42: 155-165.

Friedlingstein P, S. Solomon, G.-K. Plattner, R. Knutti, and M. Raupach. 2011. “Long Term climate implications of twenty-first century options for carbon dioxide emission mitigation.” Nature Climate Change, 1, 4457–4461

Frisch, M. (2013). "Modelling climate policies: A critical look at integrated assessment models." Philosophy & Technology 26(2): 117-137.

Frumhoff, P. C., et al. (2015). "The climate responsibilities of industrial carbon producers." Climatic Change 132(2): 157-171.

Fuentes, R., et al. (2020). "COVID-19 and climate change: a tale of two global problems." Sustainability 12(20): 8560.

Fuss, S., et al. (2020). "Moving toward Net-Zero emissions requires new alliances for carbon dioxide removal." One Earth 3(2): 145-149.

Fuss, S., et al. (2014). "Betting on negative emissions." Nature Climate Change 4(10): 850-853.

Fuss, S., et al. (2016). "Research priorities for negative emissions." Environmental Research Letters 11(11): 115007.

Fuss, S., et al. (2018). "Negative emissions—Part 2: Costs, potentials and side effects." Environmental Research Letters 13(6): 063002.

Futures, T. E. (1980). "A National Choice for the Eighties." Washington DC: American Petroleum Institute.

Fyson, C. L., et al. (2020). "Fair-share carbon dioxide removal increases major emitter responsibility." Nature Climate Change 10(9): 836-841.

Gaede, J. and J. Meadowcroft (2016). “Carbon capture and storage demonstration and low-carbon energy transitions: Explaining limited progress.” The palgrave handbook of the international political economy of energy, Springer: 319-340.

Gambhir, A., et al. (2019). "Energy system changes in 1.5 C, well below 2 C and 2 C scenarios." Energy Strategy Reviews 23: 69-80.

Gardiner, S. M. (2004). "Ethics and global climate change." Ethics 114(3): 555-600.

Gardiner, S. M. (2006). "A Perfect Moral Storm: Climate Change, Intergenerational Ethics and the Problem of Moral Corruption." Environmental Values 15(3): 397-413.

Gasser, T., et al. (2020). "Historical CO 2 emissions from land use and land cover change and their uncertainty." Biogeosciences 17(15): 4075-4101.

Geden, O. and F. Schenuit (2020). "Unconventional mitigation: carbon dioxide removal as a new approach in EU climate policy."

Gifford, L. (2020). “You can’t value what you can’t measure: a critical look at forest carbon accounting." Climatic Change 161(2): 291-306.

Gilfillan, D. and G. Marland (2021). "CDIAC-FF: global and national CO 2 emissions from fossil fuel combustion and cement manufacture: 1751–2017." Earth System Science Data 13(4): 1667-1680.

Global Witness (2022) “Hydrogen project lauded by Shell to boost green credentials emits more carbon than a million cars”. Available at: https://www.globalwitness.org/en/press-releases/shell-plant-emissions-million-cars/ Accessed 12th February 2022.

Goldman, G. (2015). “Peabody Energy, the EPA Clean Power Plan, and corporate consistency on climate change.” The Equation blog of the Union of Concerned Scientists. Available at: http://blog.ucsusa.org/peabody-energy-the-epa-clean-power-plan-and-corporateconsistency-on-climate-change-703. Accessed November 18th 2021.

Gore, T. (2020). "Confronting Carbon Inequality: Putting climate justice at the heart of the COVID-19 recovery."

Gössling, S. (2019). "Celebrities, air travel, and social norms." Annals of Tourism Research 79: 102775.

Gould, K. A. (2007). "The ecological costs of militarization." Peace Review 19(3): 331-334.

Graham, B., et al. (2011). "The national commission on the BP deepwater horizon oil spill and offshore drilling." Deep Water. The Gulf Oil Disaster and the Future of Offshore Drilling. Report to the President.

Grant, N., et al. (2021). "The policy implications of an uncertain carbon dioxide removal potential." Joule 5(10): 2593-2605.

Grasso, M. (2020). "Towards a broader climate ethics: Confronting the oil industry with morally relevant facts." Energy Research & Social Science 62: 101383.

Grasso, M. and K. Vladimirova (2020). "A Moral Analysis of Carbon Majors' Role in Climate Change." Environmental Values 29(2): 175-195.

Greenpeace (2021). “Net Expectations-Assessing the role of carbon dioxide removal in companies' climate plans”. Available at: https://www.greenpeace.org.uk/resources/net-expectations-cdr-briefing/ Accessed online 12th May 2022

Griffin, P. and C. Heede (2017). "The carbon majors database." CDP carbon majors report 2017, 14.

Grubler, A., et al. (2018). "A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies." Nature Energy 3(6): 515-527.

Gunderson, R., et al. (2020). "The fossil fuel industry’s framing of carbon capture and storage: Faith in innovation, value instrumentalization, and status quo maintenance." Journal of cleaner production 252: 119767.

Gütschow, J., et al. (2016). "The PRIMAP-hist national historical emissions time series." Earth System Science Data 8(2): 571-603.

Hagen, K., Eisenack (2016). "Transnational Environmental Agreements with Heterogeneous Actors." Oldenburg Discussion Papers in Economics No. V-387-16.

Hamilton, L. A., et al. (2019). "Plastic & climate: the hidden costs of a plastic planet." Centre for International Environmental Law (CIEL).

Hancock, E. E. (2004). "Red dawn, blue thunder, purple rain: Corporate risk of liability for global climate change and the SEC disclosure dilemma." Geo. Int'l Envtl. L. Rev. 17: 233.

Hare, B., et al. (2018). "Integrated assessment models: What are they and how do they arrive at their conclusions?" Clim. Anal: 1-12.

Hastings, A. F. S. J. and P. Smith (2020). "Achieving Net Zero emissions requires the knowledge and skills of the oil and gas industry." Frontiers in Climate 2: 22.

Heede, R. (2014a). "Carbon Majors: accounting for carbon and methane emissions 1854-2010 Methods'&'Results'Report." Climate Mitigation Services: 104.

Heede, R. (2014b). “Tracing anthropogenic carbon dioxide and methane emissions to fossil fuel and cement producers, 1854–2010.” Climatic change, 122(1), 229-241.

Herrala, R. and R. K. Goel (2016). "Sharing the emission reduction burden in an uneven world." Energy Policy 94: 29-39.

Heyward, C. (2021). "Is the beneficiary pays principle essential in climate justice?" Norsk filosofisk tidsskrift 56(02-03): 125-136.

Hill, B., et al. (2013). "Geologic carbon storage through enhanced oil recovery." Energy Procedia 37: 6808-6830.

Höhne, N., et al. (2014). "Regional GHG reduction targets based on effort sharing: a comparison of studies." Climate Policy 14(1): 122-147.

Holz, C., et al. (2018). "Ratcheting ambition to limit warming to 1.5 C–trade-offs between emission reductions and carbon dioxide removal." Environmental Research Letters 13(6): 064028.

Honegger, M., et al. (2021). "Is carbon dioxide removal ‘mitigation of climate change’?" Review of European, Comparative & International Environmental Law.

Hong, C., et al. (2021). "Global and regional drivers of land-use emissions in 1961–2017." Nature 589(7843): 554-561.

Houghton, R. (1999). "The annual net flux of carbon to the atmosphere from changes in land use 1850–1990." Tellus B 51(2): 298-313.

House, J. I., et al. (2002). "Maximum impacts of future reforestation or deforestation on atmospheric CO2." Global Change Biology 8(11): 1047-1052.

Hsu, A. W.-h. and T. Wang (2013). "Does the market value corporate response to climate change?" Omega 41(2): 195-206.

Huppmann, D., et al. (2018). "A new scenario resource for integrated 1.5 C research." Nature Climate Change 8(12): 1027-1030.

IAMC Models and Documentation. Available at: https://www.iamconsortium.org/resources/models-documentation/ Accessed on 12th February 2022.

IAMC wiki: The common Integrated Assessment Model (IAM) documentation. Available at https://www.iamcdocumentation.eu/index.php/IAMC_wiki Accessed on 12th February 2022.

IEA (2019). "Can CO2-EOR really provide carbon-negative oil?" IEA, Paris. Available online at https://www.iea.org/commentaries/can-co2-eor-really-provide-carbon-negative-oil Accessed on February 15th 2022.

IEA (2022). "Global Energy Review: CO2 Emissions in 2021."IEA, Paris. Available at: https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2.

IEA (2020). "The Oil and Gas Industry in Energy Transitions." IEA, Paris. Available at: https://www.iea.org/reports/the-oil-and-gas-industry-in-energy-transitions

Ikeme, J. (2003). "Equity, environmental justice and sustainability: incomplete approaches in climate change politics." Global Environmental Change 13(3): 195-206.

Institute, A. P. (1982). "energy futures: a national choice for the 80s." American Petroleum Institute.

Jackson, R. B., et al. (2016). "Reaching peak emissions." Nature Climate Change 6(1): 7-10.

Jamieson, D. (2010). "Climate change, responsibility, and justice." Science and engineering ethics 16(3): 431-445.

Jenkins, S., et al. (2020). "Sustainable financing of permanent CO2 disposal through a Carbon Takeback Obligation." arXiv preprint arXiv:2007.08430.

Jewell, J. and A. Cherp (2020). "On the political feasibility of climate change mitigation pathways: Is it too late to keep warming below 1.5 C?" Wiley Interdisciplinary Reviews: Climate Change 11(1): e621.

Jiang, X., et al. (2016). "Controls and dynamics of biochar decomposition and soil microbial abundance, composition, and carbon use efficiency during long-term biochar-amended soil incubations." Biology and Fertility of Soils 52(1): 1-14.

Kassinis, G. and A. Panayiotou (2018). "Visuality as greenwashing: The case of BP and Deepwater Horizon." Organization & Environment 31(1): 25-47.

Keller, D. P., et al. (2014). "Potential climate engineering effectiveness and side effects during a high carbon dioxide-emission scenario." Nature communications 5(1): 1-11.

Keller, D. P., et al. (2018). "The carbon dioxide removal model intercomparison project (CDRMIP): Rationale and experimental protocol for CMIP6." Geoscientific Model Development 11(3): 1133-1160.

Kelly, D. L. and C. D. Kolstad (1999). "Integrated assessment models for climate change control." International yearbook of environmental and resource economics 2000: 171-197.

Kenner, D. (2015). "Inequality of overconsumption: The ecological footprint of the richest." Global Sustainability Institute: 1-18.

Kenner, D. and R. Heede (2021). "White knights, or horsemen of the apocalypse? Prospects for Big Oil to align emissions with a 1.5° C pathway." Energy Research & Social Science: 102049.

Kimuyu, P. (2017). “The Role of the IPCC in the Understanding of Climate Change.” GRIN Verlag.

Klenert, D., et al. (2018). "Making carbon pricing work for citizens." Nature Climate Change 8(8): 669-677.

Klenert, D., et al. (2020). "Five lessons from COVID-19 for advancing climate change mitigation." Environmental and Resource Economics 76(4): 751-778.

Klinsky, S. and H. Dowlatabadi (2009). "Conceptualizations of justice in climate policy." Climate Policy 9(1): 88-108.

Knisely, S. and W. Ferrall (1979). “Controlling the CO2 concentration in the atmosphere, Florham Park, New Jersey, USA.: Exxon Research & Engineering Company.” Available at: https://www.industrydocuments.ucsf.edu/docs/mqwl0228. Accessed 12th February 2022.

Köberle, A. C. (2019). "The value of BECCS in IAMs: a review." Current Sustainable/Renewable Energy Reports 6(4): 107-115.

Kriegler, E., et al. (2018). "Pathways limiting warming to 1.5° C: a tale of turning around in no time?" Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 376(2119): 20160457.

Kriegler, E., et al. (2014). "The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies." Climatic Change 123(3): 353-367.

Kühne, K., et al. (2022). "Carbon Bombs"-Mapping key fossil fuel projects." Energy Policy: 112950.

Kuhnhenn, K. (2018). "Economic growth in mitigation scenarios: a blind spot in climate science." Heinrich Böll Stiftung 25.

Kuhnhenn, K., et al. (2020). "A societal transformation scenario for staying below 1.5° C", Schriften zu Wirtschaft und Soziales.

Lawrence, P. and M. Reder (2019). "Equity and the Paris Agreement: legal and philosophical perspectives." Journal of Environmental Law 31(3): 511-531.

Le Billon, P., et al. (2021). "Fossil fuels, climate change, and the COVID-19 crisis: pathways for a just and green post-pandemic recovery." Climate Policy 21(10): 1347-1356.

Le Quéré, C., et al. (2018). "Global carbon budget 2018." Earth System Science Data 10(4): 2141-2194.

Lee, K., et al. (2021). "Fair distributions of carbon dioxide removal obligations and implications for effective national net-zero targets." Environmental Research Letters 16(9): 094001.

Leimbach, M., et al. (2017). "Future growth patterns of world regions–A GDP scenario approach." Global Environmental Change 42: 215-225.

Leimbach, M. and A. Giannousakis (2019). "Burden sharing of climate change mitigation: global and regional challenges under shared socio-economic pathways." Climatic Change 155(2): 273-291.

Lejeune, Q., et al. (2018). "Historical deforestation locally increased the intensity of hot days in northern mid-latitudes." Nature Climate Change 8(5): 386-390.

Lenzi, D., et al. (2018). "Weigh the ethics of plans to mop up carbon dioxide [Comment]." Nature 561(7723): 303-305.

Li, M., et al. (2022). "The clean energy claims of BP, Chevron, ExxonMobil and Shell: A mismatch between discourse, actions and investments." PloS one 17(2): e0263596.

Liggio, J., et al. (2019). "Measured Canadian oil sands CO 2 emissions are higher than estimates made using internationally recommended methods." Nature communications 10(1): 1-9.

Lim, H. "Ethical perspectives on climate change and implications for global mitigation responses."

“LobbyMap Gazprom”. Available at: https://lobbymap.org/company/Gazprom-aa49c86702c5ffe7cfe50b903292709b Accessed 1st March 2022.

Lohmann, L. (2011). "The endless algebra of climate markets." Capitalism Nature Socialism 22(4): 93-116.

Lu, Y., et al. (2022). "Plant conversions and abatement technologies cannot prevent stranding of power plant assets in 2° C scenarios." Nature communications 13(1): 1-11.

Luderer, G., et al. (2018). "Residual fossil CO 2 emissions in 1.5–2 C pathways." Nature Climate Change 8(7): 626-633.

MacDougall, A. H. (2016). "The transient response to cumulative CO 2 emissions: a review." Current Climate Change Reports 2(1): 39-47.

Mace, M., et al. (2021). "Large‐Scale Carbon Dioxide Removal to Meet the 1.5° C Limit: Key Governance Gaps, Challenges and Priority Responses." Global Policy 12: 67-81.

MacKenzie, I. A., et al. (2009). "Using contests to allocate pollution rights." Energy Policy 37(7): 2798-2806.

Maguire, R. (2012). "Incorporating international environmental legal principles into future climate change instruments." Carbon & Climate Law Review: 101-113.

Manne, A. S. and G. Stephan (2005). "Global climate change and the equity–efficiency puzzle." Energy 30(14): 2525-2536.

Masson-Delmotte, V., et al. (2018). "Global warming of 1.5 C." An IPCC Special Report on the impacts of global warming of 1(5).

Matthews, H. D. and K. Caldeira (2008). "Stabilising climate requires near‐zero emissions." Geophysical research letters 35(4).

Matthews, H. D., et al. (2009). "The proportionality of global warming to cumulative carbon emissions." Nature 459(7248): 829-832.

Matthews, H. D., et al. (2020). "Opportunities and challenges in using remaining carbon budgets to guide climate policy." Nature Geoscience 13(12): 769-779.

Matthews, H. D., et al. (2018). "Focus on cumulative emissions, global carbon budgets and the implications for climate mitigation targets." Environmental Research Letters 13(1): 010201.

McLaren, D. P., et al. (2019). "Beyond “net-zero”: a case for separate targets for emissions reduction and negative emissions." Frontiers in Climate 1: 4.

McLaren, D. and N. Markusson (2020). "The co-evolution of technological promises, modelling, policies and climate change targets." Nature Climate Change 10(5): 392-397.

Meinshausen, M., et al. (2009). "Greenhouse-gas emission targets for limiting global warming to 2 C." Nature 458(7242): 1158-1162.

Meinshausen, M., et al. (2015). "National post-2020 greenhouse gas targets and diversity-aware leadership." Nature Climate Change 5(12): 1098-1106.

Michaelson, C. (2011). "Morally Differentiating Responsibility for Climate Change Mitigation: An Analogy with Tolstoy's" Master and Man"." Business & Professional Ethics Journal: 113-136.

Millar, R., et al. (2016). "The cumulative carbon budget and its implications." Oxford Review of Economic Policy 32(2): 323-342..

Minx, J. C., et al. (2017). "Fast growing research on negative emissions." Environmental Research Letters 12(3): 035007.

Minx, J. C., et al. (2021). "A comprehensive and synthetic dataset for global, regional, and national greenhouse gas emissions by sector 1970–2018 with an extension to 2019." Earth System Science Data 13(11): 5213-5252

Mooney et al. (2021) “Countries´climate pledges built on flawed data, Post investigation finds.” Washington Post. Available at: https://www.washingtonpost.com/climate-environment/interactive/2021/greenhouse-gas-emissions-pledges-data/ Accessed 12th June 2022.

Moreno, A. and P. Capriotti (2009). "Communicating CSR, citizenship and sustainability on the web." Journal of communication management.

Muffett, C. (2019). "Fuel to the Fire: How Geoengineering Threatens to Entrench Fossil Fuels And Accelerate Climate Change." Indigenous Policy Journal 30(1).

Mulvey, K., et al. (2015). "The climate deception dossiers: internal fossil fuel industry memos reveal decades of corporate disinformation."

Muralidharan, S., et al. (2011). "The Gulf Coast oil spill: Extending the theory of image restoration discourse to the realm of social media and beyond petroleum." Public relations review 37(3): 226-232.

Myslinski, D.J. (2011). “35-day mailing—38th Annual Meeting. Memorandum to Education Task Force members of the American Legislative Exchange Council”. Available at: www.commoncause.org/issues/more-democracy-reforms/alec/whistleblower-complaint/ original-complaint/National_ALEC_Exhibit_4_Education_2011_ Annual_Meeting.pdf accessed Accessed October 1st 2021

Nakicenovic, N. (2000). "Global greenhouse gas emissions scenarios: integrated modelling approaches." Technological Forecasting and Social Change 63: 105-109.

Naranjo, M., et al. (2011). "CO2 capture and sequestration in the cement industry." Energy Procedia 4: 2716-2723.

Neumayer, E. (2000). "In defence of historical accountability for greenhouse gas emissions." Ecological economics 33(2): 185-192.

Nielsen, K. S., et al. (2021). "The role of high-socioeconomic-status people in locking in or rapidly reducing energy-driven greenhouse gas emissions." Nature Energy 6(11): 1011-1016.

Nordhaus, W. (2015). "Climate clubs: Overcoming free-riding in international climate policy." American Economic Review 105(4): 1339-1370.

Núñez-López, V., et al. (2019). "Environmental and operational performance of CO2-EOR as a CCUS Technology: A Cranfield Example with Dynamic LCA Considerations." Energies 12(3): 448.

Núñez-López, V. and E. Moskal (2019). "Potential of CO2-EOR for near-term decarbonization." Frontiers in Climate 1: 5.

OECD Watch (2019). “Client Earth vs BP: BP´s misleading fossil fuel advertising campaigns.”Available at: https://www.oecdwatch.org/complaint/clientearth-vs-bp/ Accessed February 15th 2022.

O’Neill, B. C., et al. (2014). "A new scenario framework for climate change research: the concept of shared socioeconomic pathways." Climatic Change 122(3): 387-400.

Olivier, J. and J. Peters (2020). "Trends in global CO_2 and total greenhouse gas emissions." PBL Netherlands Environmental Assessment Agency: The Hague, The Netherlands.

Olszynski, M., et al. (2017). "From smokes to smokestacks: Lessons from tobacco for the future of climate change liability." Geo. Envtl. L. Rev. 30: 1.

Oswald, Y., et al. (2020). "Large inequality in international and intranational energy footprints between income groups and across consumption categories." Nature Energy 5(3): 231-239.

Page, E. A. (2008). "Distributing the burdens of climate change." Environmental Politics 17(4): 556-575.

Panel, E. P., et al. (1965). Restoring the quality of our environment, The White House.

Parfit, D. (1984). Reasons and persons, OUP Oxford.

Peel, J. and H. M. Osofsky (2018). "A right turn in climate change litigation?" Transnational Environmental Law 7(1): 37-67.

Persson, Å. and A. Dzebo (2019). “Exploring global and transnational governance of climate change adaptation”. Springer.

Peters, G. P. and O. Geden (2017). "Catalysing a political shift from low to negative carbon." Nature Climate Change 7(9): 619-621.

Pongratz, J., et al. (2014). "Terminology as a key uncertainty in net land use and land cover change carbon flux estimates." Earth System Dynamics 5(1): 177-195.

Popp, A., et al. (2017). "Land-use futures in the shared socio-economic pathways." Global Environmental Change 42: 331-345.

Powell, A. (2021). “Tracing Big Oil’s PR war to delay action on climate change.” The Harvard Gazette: Available at: https://news.harvard.edu/gazette/story/2021/09/oil-companies-discourage-climate-action-study-says/ Accessed on 13th February 2022.

Pozo, C., et al. (2020). "Equity in allocating carbon dioxide removal quotas." Nature Climate Change: 1-7.

Peters, G. (2021). “Net-zero or zero, or perhaps offsets?” CICERO Center for International Climate Research, Oslo, Norway.

Preston, F. and J. Lehne (2018). "Making Concrete Change Innovation in Low-carbon Cement and Concrete."

Rajamani, L., et al. (2021). "National 'fair shares' in reducing greenhouse gas emissions within the principled framework of international environmental law." Climate Policy 21(8): 983-1004.

Ramankutty, N. and J. A. Foley (1999). "Estimating historical changes in global land cover: Croplands from 1700 to 1992." Global biogeochemical cycles 13(4): 997-1027.

Raupach, M. R., et al. (2007). "Global and regional drivers of accelerating CO2 emissions." Proceedings of the National Academy of Sciences 104(24): 10288-10293.

Rawls, J. (1971). "A theory of justice, Harvard." Press, Cambridge.

Realmonte, G., et al. (2019). "An inter-model assessment of the role of direct air capture in deep mitigation pathways." Nature communications 10(1): 1-12.

Reckien, D., et al. (2018). "How are cities planning to respond to climate change? Assessment of local climate plans from 885 cities in the EU-28." Journal of cleaner production 191: 207-219.

Reisch, N. and S. Kretzmann (2008). "A climate of war: the war in Iraq and global warming." Oil Change International.

Report of the Environmental Pollution Panel, P. s. S. A. C. (1965). Restoring the Quality of Our Environment.

Reuters Staff (2021). "Russia's Gazprom says natural gas fits in with global climate goals." Reuters. Available at https://www.reuters.com/article/us-climate-change-gazprom-gas-idUSKBN29W0ZK Accessed on 11th February 2022.

Revelle, R., et al. (1965). "Restoring the quality of our environment: report of the environmental pollution panel." President's Science Advisory Committee, United States, US Government Printing Office: Washington, DC.

Riahi, K., et al. (2015). "Locked into Copenhagen pledges—implications of short-term emission targets for the cost and feasibility of long-term climate goals." Technological Forecasting and Social Change 90: 8-23.

Riahi, K., et al. (2017). "The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview." Global Environmental Change 42: 153-168.

Rigby, Matt., (2021). “Countries may be under-reporting their greenhouse gas emissions – that’s why accurate monitoring is crucial” The Conversation. Available at: https://theconversation.com/countries-may-be-under-reporting-their-greenhouse-gas-emissions-thats-why-accurate-monitoring-is-crucial-171645. Accessed online 2nd March 2022.

Ringius, L., et al. (2002). "Burden sharing and fairness principles in international climate policy." International Environmental Agreements 2(1): 1-22.

Risse, T. and U. Lehmkuhl (2012). "Governance in areas of limited statehood." The Oxford handbook of governance: 699-715.

Roberts, D. (2019). “Could squeezing more oil out of the ground help fight climate change? The pros and cons of enhanced oil recovery.” Vox. Available at https://www.vox.com/energy-and-environment/2019/10/2/20838646/climate-change-carbon-capture-enhanced-oil-recovery-eor Accessed on February 1st 2022.

Robinson, E. and R. Robbins (1968). "Sources, abundance, and fate of gaseous atmospheric pollutants. Final report and supplement."

Robiou du Pont, Y., et al. (2017). "Equitable mitigation to achieve the Paris Agreement goals."

Rodgers, L. (2018) . “Climate change: The massive CO2 emitter you may not know about”.Available at: https://www.bbc.com/news/science-environment-46455844 Accessed on 1st March 2022.

Rogelj, J., et al. (2015). "Energy system transformations for limiting end-of-century warming to below 1.5 C." Nature Climate Change 5(6): 519-527.

Rogelj, J., et al. (2015). "Zero emission targets as long-term global goals for climate protection." Environmental Research Letters 10(10): 105007.

Rogelj, J., et al. (2016). "Differences between carbon budget estimates unravelled." Nature Climate Change 6(3): 245-252.

Rogelj, J., et al. (2018a). "Scenarios towards limiting global mean temperature increase below 1.5 C." Nature Climate Change 8(4): 325-332.

Rogelj, J., et al. (2018). “Mitigation pathways compatible with 1.5 C in the context of sustainable development. Global warming of 1.5° C”. Intergovernmental Panel on Climate Change (IPCC): 93-174.

Rogelj, J., et al. (2021). "Three ways to improve net-zero emissions targets." Nature 591(7850): 365-368.

Roggero, M., et al. (2019). "Strategic cooperation for transnational adaptation: Lessons from the economics of climate change mitigation." International Environmental Agreements: Politics, Law and Economics 19(4-5): 395-410.

Røttereng, J.-K. S. (2018). "When climate policy meets foreign policy: Pioneering and national interest in Norway's mitigation strategy." Energy Research & Social Science 39: 216-225.

Roy, N. M. (2020). "Climate Change's Free Rider Problem: Why We Must Relinquish Freedom to Become Free." Wm. & Mary Envtl. L. & Pol'y Rev. 45: 821.

Sands, P. (1992). "The United Nations framework convention on climate change." Rev. Eur. Comp. & Int'l Envtl. L. 1: 270.

Schellnhuber, H. J., et al. (2009). "Solving the Climate Dilemma: The Budget Approach (Special Report 2009)." WBGU.

Schleussner, C.-F., et al. (2016). "Science and policy characteristics of the Paris Agreement temperature goal." Nature Climate Change 6(9): 827-835.

Schweizer, V. J., et al. (2020). "Integrated climate-change assessment scenarios and carbon dioxide removal." One Earth 3(2): 166-172.

Seck, S. (2021). "A relational analysis of enterprise obligations and carbon majors for climate justice." Oñati Socio-Legal Series, 11(1), 254-284.

Seto, K. C., et al. (2016). "Carbon lock-in: types, causes, and policy implications." Annual Review of Environment and Resources 41: 425-452.

Shell (2020) "Powering Progress: Annual Reports and Accounts." Available at: https://reports.shell.com/annual-report/2020/servicepages/downloads/files/shell-annual-report-2020.pdf Accessed Feburary 12th 2022.

Shell (2021) "Shell accelerates drive for net-zero emissions with customer-first strategy." Available at: https://www.shell.com/media/news-and-media-releases/2021/shell-accelerates-drive-for-net-zero-emissions-with-customer-first-strategy.html Accessed 12th February 2022.

Shefrin, H. (2022). "The Next Tesla Or Amazon Might Be A CDR Company: Let's Hope!". Forbes [online] Available at:https://www.forbes.com/sites/hershshefrin/2022/02/11/the-next-tesla-or-amazon-might-be-a-cdr-company-lets-hope/?sh=5d7d35083dbc. Accessed 2nd August 2022.

Sheppard, D (2020). “Pandemic crisis offers glimpse into oil industry’s future.” The Guardian. Available at: https://www.ft.com/content/99fc40be-83aa-11ea-b872-8db45d5f6714 Accessed May 12th 2022

Shue, H. (1999). "Global environment and international inequality." International affairs 75(3): 531-545.

Shue, H. (2017). "Responsible for what? Carbon producer CO 2 contributions and the energy transition." Climatic Change 144(4): 591-596.

Sijm, J., et al. (2001). "Differentiation of mitigation commitments: the multi-sector convergence approach." Climate Policy 1(4): 481-497.

Smith, E., et al. (2021). "The cost of CO2 transport and storage in global integrated assessment modelling." International Journal of Greenhouse Gas Control 109: 103367.

Smith, P., et al. (2014). "Agriculture, forestry and other land use (AFOLU)."

Smith, P., et al. (2016). "Biophysical and economic limits to negative CO 2 emissions." Nature Climate Change 6(1): 42-50.

Smith, P. and J. R. Porter (2018). “Bioenergy in the IPCC assessments”. Wiley Online Library.

Solomon, S., et al. (2010). "Persistence of climate changes due to a range of greenhouse gases." Proceedings of the National Academy of Sciences 107(43): 18354-18359.

Sonntag, S., et al. (2016). "Reforestation in a high‐CO2 world—Higher mitigation potential than expected, lower adaptation potential than hoped for." Geophysical research letters 43(12): 6546-6553.

Starr, D. (2016). "Just 90 companies are to blame for most climate change, this carbon accountant says." Science 25.

Stocker, T. (2014). Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change, Cambridge university press.

Strefler, J., et al. (2018). "Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs." Environmental Research Letters 13(4): 044015.

Supran, G. and N. Oreskes (2017). "Assessing ExxonMobil’s climate change communications (1977–2014)." Environmental Research Letters 12(8): 084019.

Sweeney, S. (2020). “There may be no choice but to nationalise oil and gas—and renewables, too.” New Labour Forum, SAGE Publications Sage CA: Los Angeles, CA.

Tavoni, M. and R. Socolow (2013). "Modelling meets science and technology: an introduction to a special issue on negative emissions." Climatic Change 118(1): 1-14.

Taylor, L. L., et al. (2016). "Enhanced weathering strategies for stabilising climate and averting ocean acidification." Nature Climate Change 6(4): 402-406.

“The Global Carbon Project”. Available at: https://www.globalcarbonproject.org/ Accessed 12th June 2022.

“The Global Calculator”. Available at: http://www.globalcalculator.org/ Accessed 16th February 2022.

Timperley, J. (2018). “Q&A: Why cement emissions matter for climate change.” Available at: https://www.carbonbrief.org/qa-why-cement-emissions-matter-for-climate-change/ Accessed 25th March 2022.

Tokarska, K. B., et al. (2019). "Path independence of carbon budgets when meeting a stringent global mean temperature target after an overshoot." Earth's Future 7(12): 1283-1295.

Tong, D. and K. Trout (2020). "Big oil reality check–assessing oil and gas company climate plans." Oil Change International. Retrieved October 1: 2020.

Torvanger, A. and L. Ringius (2002). "Criteria for evaluation of burden-sharing rules in international climate policy." International Environmental Agreements 2(3): 221-235.

Tubiello, Francesco N., et al. "Agriculture, forestry and other land use emissions by sources and removals by sinks." Rome, Italy (2014).

UK, P. F., et al. "2. SM Mitigation pathways compatible with 1.5 C in the context of sustainable development–Supplementary Material."

Union of Concerned Scientists (2017). “How Fossil Fuel Lobbyists Used “Astroturf” Front Groups to Confuse the Public”. Available at: https://www.ucsusa.org/resources/how-fossil-fuel-lobbyists-used-astroturf-front-groups-confuse-public.

Unruh, G. C. (2000). "Understanding carbon lock-in." Energy Policy 28(12): 817-830.

van Asselt, H. (2021). "Governing fossil fuel production in the age of climate disruption: Towards an international law of ‘leaving it in the ground’." Earth System Governance 9: 100118.

van den Berg, N. J., et al. (2020). "Implications of various effort-sharing approaches for national carbon budgets and emission pathways." Climatic Change 162(4): 1805-1822.

Van der Ploeg, F. and A. Rezai (2020). "Stranded assets in the transition to a carbon-free economy." Annual review of resource economics 12: 281-298.

Van Vuuren, D. P., et al. (2017). "Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm." Global Environmental Change 42: 237-250.

Van Vuuren, D. P., et al. (2017). "Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm." Global Environmental Change 42: 237-250.

Van Vuuren, D. P., et al. (2018). "Alternative pathways to the 1.5 C target reduce the need for negative emission technologies." Nature Climate Change 8(5): 391-397.

Watanabe, R. (2008). "Who should pay for climate protection?: Another side of the same coin of burden sharing; back to legal principles."

Watts, J (2020). “BP's statement on reaching net zero by 2050 – what it says and what it means.” The Guardian. Available at: https://www.theguardian.com/environment/ng-interactive/2020/feb/12/bp-statement-on-reaching-net-zero-carbon-emissions-by-2050-what-it-says-and-what-it-means Accessed 15th February 2022.

Walker, H (2010). “Recapping on BP´s long history of greenwashing.” Greenpeace. Available at: https://www.greenpeace.org/usa/recapping-on-bps-long-history-of-greenwashing/ Accessed 12th May 2022.

Weber, C., et al. (2018). "Mitigation scenarios must cater to new users." Nature Climate Change 8(10): 845-848.

Weijers, D., et al. (2010). "Sharing the responsibility of dealing with climate change: Interpreting the principle of common but differentiated responsibilities." Public Policy: why ethics matters: 141-158.

Weischer, L., et al. (2012). "Climate clubs: Can small groups of countries make a big difference in addressing climate change?" Review of European Community & International Environmental Law 21(3): 177-192.

Weiss, K. R. (2015). "Global greenhouse-gas emissions set to fall in 2015." Nature News.

Whitehouse, S., (2020)´. "The fossil-fuel industry's campaign to mislead the American people" The Washington Post. Available at: https://www.washingtonpost.com/opinions/the-fossil-fuel-industrys-campaign-to-mislead-the-american-people/2015/05/29/04a2c448-0574-11e5-8bda-c7b4e9a8f7ac_story.html. Accessed 15th August 2021.

Wiedmann, T., et al. (2020). "Scientists' warning on affluence." Nature communications 11(1): 1-10.

Wilcox, J., Ben Kolosz, and Jeremy Freeman. "CDR Primer." (2021).

Williams, E. (2019). "Attributing blame?—climate accountability and the uneven landscape of impacts, emissions, and finances." Climatic Change: 1-18.

Zhongming, Z., et al. (2021). "Global Climate Litigation Report: 2020 Status Review."

Zhou, P. and M. Wang (2016). "Carbon dioxide emissions allocation: A review." Ecological economics 125: 47-59.

Zickfeld, K., et al. (2009). "Setting cumulative emissions targets to reduce the risk of dangerous climate change." Proceedings of the National Academy of Sciences 106(38): 16129-16134.

Zimmermann, M., et al. (2012). "Rapid degradation of pyrogenic carbon." Global Change Biology 18(11): 3306-3316.