SCIENCE OR SCIENCE-FICTION?

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On the feasibility of CCS and negative emission technologies - a socio-technical review of integrated assessment modelled mitigation scenarios

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Abstract: Most climate change mitigation scenarios rely on carbon capture and storage (CCS) and negative emission technologies (NETs) at a very large scale. This thesis takes a critical look at the use and scale of these technologies in the 1.5 °C and 2 °C mitigation scenarios in the IPCC's special report on Global Warming of 1.5°C (SR15). It provides an overview of the current status of CCS and the various NETs and presents key challenges for these technologies to be deployed at the required scale. This thesis also critically compares the assumptions of the integrated assessment models (IAMs), which are used to develop scenarios, with current knowledge and insights from transition and innovation science. Based on the data and analysis presented, this thesis argues that integrated assessment models miss out on several real-world constraints for the upscaling of technologies. It further argues that CCS and NETs are unlikely to develop and diffuse at the required rate in the real world. By extension, 'only' following the trajectories of the scenarios presented in the IPCC's special report on the 1.5 °C target is unlikely to limit global warming to 2 °C above pre-industrial temperatures, and should be considered a highly risky mitigation strategy. Based on these arguments, the thesis goes on to discuss current weaknesses in mitigation science and suggests potential improvements. It argues mitigation science and strategies are 'limited' by current socio-economical paradigms and are failing at assessing the true range of potential mitigation options. For instance, even though we know economic growth is driving emission growth, none of the scenarios in the SR15 explore the mitigation potential of limiting economic growth. More research exploring the mitigation potential of changes in consumption patterns, lifestyles, and broader socio-economic changes is required. Mitigation science also needs to attend more critically to the realism and real-world feasibility of integrated assessment modelled mitigation scenarios. Finally, based on all the aforementioned factors, this thesis argues that – from a risk management perspective – immediate and radical mitigation cuts is the only 'real' mitigation option for limiting temperatures to 2 °C above pre-industrial temperatures, and that emission reductions at the scale required is unlikely to be brought about by technological change alone. Instead, it is likely to require changes to the broader socio-economical structures and values of society.

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Contents

1. Introduction

“Our house is falling apart. And we are rapidly running out of time. And yet basically nothing is happening.” – Greta Thunberg[1]

If you have wilfully picked a master’s thesis on carbon capture and storage (CCS) and negative emission technologies (NETs) to be your next leisurely reading, you have probably already read countless introductions to articles on the topic of climate change. You may have read about the potential effects – about sea level rise, about droughts and heavy precipitation, about extreme heat and heatwaves, about impacts on biodiversity loss and on species extinction, about warming oceans, increasing ocean acidity, about dying coral reefs, about dying fish stocks, you may have heard of increasing risks to food security and water supply, negative impacts on human health and economic growth, about how a difference of just 0.5 °C could change the number of people “exposed to climate-related risks and susceptible to poverty by up to several hundred million by 2050” (IPCC, 2018b, p. 11), you may have read about how global warming increases the risks from vector-borne diseases, about melting icecaps, about melting permafrost, and about feedback loops (IPCC, 2018b). If you are here – wilfully exposing yourself to thousands of words on integrated assessment models (IAMs), socio-technical transitions, and negative emissions – you have probably already read several introductions referencing historic agreements, watershed moments, about temperature targets, about Paris, and about 1.5 and 2 degrees. Indeed, you may have read this introduction a thousand times and more. About enormous challenges, about fossil fuels, about renewables, and about decarbonization. You know all this, you have heard it all before – you are aware of climate change, you are aware of its effects, and you are aware that – if the goal is mitigation – there is a need for immediate action. You know it, I know it, many people know it, and yet – to borrow the words of a 16-year-old girl from Sweden – basically nothing is happening. Of course, that is not entirely true, *something* is definitely happening. Temperatures are rising, for example. 2018 was the 42nd consecutive year with an above-average global temperature. All of the past five years, 2014 – 2018, are among the five hottest years since records began[2]. Of course, temperatures are not alone in rising, climate gas emissions are rising with them. 2018, the 4th hottest year on record, was also the year with the highest anthropogenic CO2

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[1] https://www.huffpost.com/entry/teen-climate-activist-greta-thunberg-to-eu-lawmakers-i-want-you-to-panic_n_5cb7344ce4b0ffefe3ba6287

[2] See https://www.noaa.gov/news/2018-was-4th-hottest-year-on-record-for-globe and https://www.livescience.com/64700-2018-heat-record.html

emissions in all of human history, just like 2017 was before it (Le Quéré et al., 2018). Methane gas emissions have been growing since 2007, and the growth has accelerated in recent years (Nisbet et al., 2019). In 2018, global oil demand increased by 1.3%, consumption of natural gas increased by an estimated 4.6%, and global coal demand increased by 0.7% (IEA, 2019). Something is happening, but it is not climate change mitigation, it is climate change exacerbation. This lack of mitigation progress, contrasted with the scale of mitigation required, forms the backdrop for the work presented here.

In recent years, carbon capture and storage (CCS) and negative emission technologies (NETs) have become an integral part of most scenarios consistent with a 66 percent chance of limiting global warming to 2 °C or less. As the analysis presented in this thesis will show, most 2 °C scenarios deploy these technologies rapidly and at an enormous scale. In the real world, these are technologies which are both at very early stages of development and are facing a wide range of uncertainties and challenges. Carbon capture and storage, for instance, has had something of a troubled recent past – many proposed projects have failed to materialise, and political support of CCS has often been like electrons in the nucleus of an atom, disappearing and reappearing seemingly at random. Meanwhile, many NETs have never left the lab, and/or only exist at a very small scale with no or few commercial projects. Many of the proposed negative emission solutions also come with severe uncertainties and large challenges. Bioenergy with carbon capture and storage (BECCS), for instance, is the negative emission technology most commonly deployed in scenarios, but BECCS comes with many potential side-effects and caveats – such as the land and water use of bioenergy, and the need for CCS infrastructure. This thesis will take a critical look at the use and scale of CCS and NETs in 1.5 and 2 °C mitigation scenarios – and discuss whether these technologies can develop and diffuse at the required rate – not in a modelled scenario – but in the real world.

The research aims and questions of the thesis are multifaceted. It will assess the scale of these technologies in mitigation scenarios. It aims to provide an overview of the current status of CCS and the various NETs, as well as discuss the biggest challenges for these technologies to be deployed at the required scale. Furthermore, the integrated assessment models (IAMs) behind mitigation scenarios will be presented, and their key weaknesses assessed. Based on the findings, this thesis seeks to address the following key questions:

- Given their many uncertainties, can CCS and NETs realistically mitigate climate gas emissions at the scale they do in current mitigation scenarios?

- What are integrated assessment models (IAMs) missing, and how can mitigation science be improved?
- What do the findings imply for climate change mitigation going forward?

To achieve this, the thesis will present the use of CCS and NETs in the scenarios which form the basis for the Intergovernmental Panel on Climate Change's (IPCC) special report on 'Global Warming of 1.5°C' (SR15). It will present the models which create the scenarios and compare the assumptions of these models with inputs from transition and innovation literature. It will give an overview of the current status of CCS and the various NETs. It will present the key challenges for each technology. It will briefly present the term 'feasibility', and some of the key geophysical uncertainties related to climate change mitigation. In short, by presenting the scale of CCS and NETs in mitigation scenarios, this thesis aims to highlight the true scale of mitigating climate change to 2 °C, to discuss whether CCS and NETs at the imagined scale is feasible, to have a critical discussion about the current state of mitigation science and IAMs – and, finally, begin to discuss what the findings imply for mitigation and mitigation science going forwards.

1.1. Theoretical justification for the thesis

In recent years many scholars have called for critical assessment of the scale and feasibility of NETs in mitigation scenarios (Anderson, 2015a, 2015b; Anderson & Peters, 2016; Boysen et al., 2017; Dooley & Kartha, 2017; Fuss et al., 2014; Fuss et al., 2018; Minx et al., 2018; Nemet et al., 2018; Peters, 2016; P. Smith et al., 2015; van Vuuren et al., 2018; Vaughan & Gough, 2016). Furthermore, there have been several calls for more critical engagement from social scientists in the field of climate change mitigation in general, and with the scale of NETs, the weaknesses of IAMs – and how they miss out on the dynamics of transitions, in particular (Fridahl & Lehtveer, 2018; Geden, 2016; Geels, Berkhout, & van Vuuren, 2016; Loftus, Cohen, Long, & Jenkins, 2015; Minx, Lamb, Callaghan, Bornmann, & Fuss, 2017; Minx et al., 2018; O'Brien, 2018; Peters, 2016; Rogelj, Popp, et al., 2018; Turnheim et al., 2015; Turnheim & Nykvist, 2019; van Sluisveld et al., 2018).

As Minx et al. put it:

> "the modest engagement of social sciences and humanities in NETs research might be seen as a great worry by those who believe that more rapid progress on NETs is needed. If we do not fully comprehend the ethics and social dynamics around NETs, there might be little hope

> to succeed in deploying such technologies at required scales. The fast-growing calls to engage social sciences and humanities at the heart of climate change research might need to be strongly echoed for the issue of NETs" (Minx et al., 2017, p. 17)

Turnheim and Nykvist note "that opening up STPs [sustainability transition pathways] to the evaluation of previously neglected dimensions of change (…) remains crucial, and we suggest that new insights can be gained by more systematically attending to feasibility." (Turnheim & Nykvist, 2019, p. 776). The supplementary material of the SR15 highlights how "governance factors are usually not explicitly accounted for in IAMs" (Forster et al., 2018, p. 14). Glen Peters points out how "very few 2 °C scenarios assume plausible political narratives, questioning the applicability of the scenarios in a political context." (Peters, 2016, p. 648). When assessing current scenario literature, Loftus et al. argue:

> "These studies tend to only superficially address the key technical, economic, infrastructural, and societal factors that may constrain a rapid energy system transition or how such constraints can be plausibly overcome. (…) This point may be lost on lay audiences and the media through which these studies are reported. To be reliable guides for policymaking, these types of scenarios clearly need to be supplemented by more detailed analyses addressing the key constraints on energy system transformation, including technological readiness, economic costs, infrastructure and operational issues, and societal acceptability with respect to each of the relevant technology pathways." (Loftus et al., 2015, p. 109)

This thesis aims to address some of the issues raised above. It will heed the call "to engage social sciences" with the issue of NETs and the "heart of climate change research" (Minx et al., 2017, p. 17). It will take a critical look at the scale of CCS and NETs, and the outputs of IAMs by "systematically attending to feasibility" (Turnheim & Nykvist, 2019, p. 776). It will begin to address some of the "key constraints (…) including technological readiness, economic costs, infrastructure and operational issues, and societal acceptability with respect to each of the relevant technology pathways" (Loftus et al., 2015, p. 109). In short, this thesis aims to take some of the steps on the road to integrating more social science inputs in mitigation science, mitigation literature, and mitigation scenarios. As I believe will become clear for any reader of this thesis – if we wish to have any chance of mitigating climate change to 2 °C or less – it is a road which needs to be walked quickly. The lack of "plausible political narratives" (Peters, 2016, p. 648) in scenarios is glaring. Scaling up CCS and NETs at the speed envisioned in scenarios is an enormous undertaking, and several of the key challenges are currently overlooked in models. The gap between IAMs and real-world dynamics is too wide. If we wish our mitigation scenarios to go from theoretical scenarios, to possible real-world mitigation pathways, that gap must be bridged quickly. This thesis aims to be a small contribution to building that bridge.

By writing this thesis, my wish is to provide a better understanding of the true scale of mitigating climate change. Only by accepting where we are at, can we have an honest and critical discussion of where to go next. Gambling on the rapid diffusion of technologies facing enormous uncertainties might be cost-effective, but, as this thesis makes clear, it may well turn out to be a losing bet. By critically addressing overlooked aspects of the feasibility of CCS and NETs, this thesis aims to make its readers better equipped to decide whether it's a gamble they are willing to take. And, if it is not, give them a basis from which to discuss where we should go from here.

1.2. Brief introduction to key terms and concepts

This section briefly introduces some of the key terms and concepts which will be used and discussed in this thesis.

1.2.1. Key abbreviations

This thesis relies on quite a few abbreviations. The most important of these abbreviations are briefly presented here.

AR5 – The IPCC's 5th assessment report on climate change from 2014

CCS – Carbon capture and storage

DAC – Direct air capture

GtCO2/yr – Gigatons of CO2 per year. One gigaton equals one billion tons, this thesis will generally refer to 'billions of tons', instead of referring to 'gigatons'.

IAMs – Integrated assessment models

IPCC – Intergovernmental Panel on Climate Change

MtCO2/yr - Megatons of CO2 per year. One megaton equals one million tons, this thesis will generally refer to 'millions of tons', instead of referring to 'megaton'.

NETs – Negative emission technologies

NDCs – Nationally determined contributions (in line with the Paris Agreement)

SR15 – The IPCC's special report on 'Global Warming of 1.5°C' from 2018.

1.2.2. IPCC and SR15

This thesis will sometimes refer to the Intergovernmental Panel on Climate Change (IPCC) and often refer to the 'special report on the 1.5 °C target' (SR15). The IPCC is a UN body focused on assessing and presenting the current science on climate change. The IPCC "does not carry out original research," (IPCC, 2010, p. 2) instead it "assesses the findings in scientific publications" (IPCC, 2010, p. 2). The stated goal of the IPCC is to "provide policy-relevant but not policy-prescriptive information on key aspects of climate change, including the physical science basis, impacts of and vulnerability to climate change in human and natural systems, options for adapting to the climate changes that cannot be avoided, and options for mitigation to avoid climate change." (IPCC, 2010, p. 1). The IPCC generally does this by publishing large 'assessment reports' in which they present the current knowledge of climate change science. The Special report on 'Global Warming of 1.5°C' (SR15) from 2018 is one such report.

The SR15 is a report which "assesses current knowledge of the environmental, technical, economic, financial, socio-cultural, and institutional dimensions of a 1.5°C warmer world" (Allen et al., 2018, p. 53). Among other things, it presents what current science says about the difference in climate impacts between 1.5 °C and 2 °C, and about the different drivers of climate change. Most importantly for this thesis, it also presents a series of scenarios assessing different pathways to reaching the 1.5 °C and 2 °C targets. It is these scenarios, the models which create them, and the scenarios' use of carbon capture and storage (CCS) and negative emission technologies (NETs), which will be presented and discussed in this thesis. However, before diving into the analysis and assessments of models, scenarios, and technologies, I will first describe the methods employed in the work presented here.

2. Methods

This section describes and explains the methodical process used in the work on this thesis. In short, this thesis employs two primary methods:

1. An in-depth literature review of scientific literature on negative emissions, negative emission technologies, and integrated assessment models.

2. An in-depth data analysis of the use of CCS and NETs in the 1.5 °C and 2 °C scenarios which form the basis of the IPCC's Special Report on the 1.5 °C target (SR15).

Here I will present how and why these methods have been employed, as well as present a few other methodical choices relevant to the readers of the thesis. This section has been divided into four parts, one discussing the literature review, one discussing the data analysis, one presenting the research strategy employed, and one discussing other relevant information.

2.1.1. Literature review

The literature reviewed for this thesis has, in generalized terms, four main topics: (1) articles about CCS (2) articles about negative emissions and negative emission technologies (NETs) (3) articles about integrated assessment models (IAMs), and (4) theoretical articles on transitions and innovation.

As I have followed the debates on CCS and negative emissions closely over the past few years, literature relevant for all four topics has been obtained over a period stretching far beyond the 'actual' work on this thesis. As such, it is difficult to describe the process in exact terms. That being said, the vast majority of literature presented here stems from searching for the relevant topics in scientific databases such as 'Google Scholar' and 'Web of Science'. Furthermore, the reference lists of both the IPCC's 5th assessment report on climate change (AR5) and the SR15 have served as good starting points for a literature review. As they review the scientific literature on topics relevant for this thesis, they have led me to many valuable sources.

For literature on CCS extensive google scholar searches have been performed, and a multitude of articles reviewed – many more than the few presented in this thesis. Bui et al.'s ~100-page review of the current status of CCS (and of the way forward) has also served as an excellent source for relevant information and has led to me to a wealth of other relevant sources.

For literature on negative emissions technologies, the recent three-part in-depth review of scientific literature on negative emissions technologies – performed by Minx et al. (2018), Fuss et al. (2018), and Nemet et al. (2018) – have been invaluable. Jointly these three reviews aim "to provide a comprehensive and systematic assessment of the academic literature on

NETs" (Minx et al., 2018, p. 2). As such, they have been indispensable both as sources of their own, and as a starting point for finding relevant articles on negative emission technologies. Similarly, the SR15's own overview of literature on the various NETs, found in de Coninck et al. (2018, pp. 342-347), served a similar role as both a source for information and as an overview of other relevant sources. Several searches in scientific databases have also been performed, with searches focusing on both individual technologies and negative emissions in general.

Articles about IAMs stem mainly from searching for integrated assessment models in scientific databases, but also here the SR15 and AR5 have served as good sources for both relevant information and relevant scientific sources. The supplementary material for chapter 2 of the SR15 has also served as an excellent starting point for finding literature on current debates in the field of integrated assessment modelling.

Much of the discussion on transition and innovation theory is based on articles and texts stemming from the actual curriculum of the master program I am currently attending. Over the past two years, I have written several essays and exams where transition theory has been highly relevant, and, as such, have performed several literature reviews of transition theory over the past two years. This thesis relies on much of that literature. However, during the work on this thesis, I have performed new extensive searches in scientific databases for transition and innovation articles which discuss the transition and innovation of CCS and NETs in particular.

2.1.2. Data analysis

Here 'data analysis' refers to the analysis of the actual data contained in the mitigation scenarios which form the basis of chapter 2 of the SR15. This data has been collected from the 'IAMC 1.5 °C Scenario Explorer hosted by IIASA'. A database which contains the "consolidated scenario data supporting the IPCC SR1.5 assessment" (Huppmann, Rogelj, Kriegler, Krey, & Riahi, 2018, p. 1027). This database specifically "ensures the reproducibility and transparency of scenario assessments, but also allows for the reuse of scenario data by other research communities." (Huppmann, Rogelj, et al., 2018, p. 1027). From this database, I have downloaded Excel-sheets containing data on various assumptions in a broad range of scenarios. My focus has been on the 164 scenarios in the database with a greater than 66 percent chance of staying below 2 °C. This includes 90 scenarios considered consistent with the 1.5 °C target (Huppmann, Kriegler, et al., 2018; Rogelj, Shindell, et al., 2018), but excludes 58 scenarios which are considered consistent with 2 °C in the SR15, but which have a less than 66 percent chance of limiting warming to 2 °C. This thesis aims to assess the scale of CCS and NETs in scenarios consistent with the targets in the Paris Agreement. It is debatable whether scenarios with only a 50/50 chance of limiting warming to 2 °C could be considered in line with "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UNFCC, 2015). Thus, this thesis opts to focus on scenarios with at least a 66 percent chance of limiting warming to 2 °C above pre-industrial levels.

I have downloaded and assessed a few different aspects of these scenarios. The main data analysis stems from assessing three aspects of the scenarios, (1) the CO2 emission trajectories of scenarios, (2) the use of CCS in scenarios, (3) the use of the various NETs in scenarios. The next few paragraphs will outline how many scenarios are included/excluded when selecting different variables in the IAMC 1.5 °C Scenario Explorer. For a brief overview of which scenarios are excluded from the analysis of CCS and BECCS, see the appendix of this thesis.

The analysis for the CO2 emission trajectories of scenarios stems from analysing the CO2 emission trajectories of all 164 scenarios consistent with a 66 percent chance of 2 °C.

The data on CCS in SR15 scenarios stem from the 148 scenarios in the database which both are consistent with a 66 percent chance of limiting warming to 2 °C or less and have data on 'CCS (TOTAL)'. Of the 164 scenarios, this excludes 16 scenarios which do not have 'CCS (TOTAL)' included as an option in the scenario database (see Appendix).

The data on BECCS in SR15 scenarios stem from 150 scenarios in the database which are consistent with a 66 percent chance of limiting warming to 2 °C or less and have data on 'Biomass w/CCS (Total)' in the scenario database. Of the 164 scenarios, this excludes 14 scenarios which do not have 'Biomass w/CCS (total)' included as an option in the scenario database (see Appendix).

The data on 'Sequestration through land-based sinks' stem from the 75 scenarios consistent with a 66% chance of limiting warming to 2 °C, which have data on total carbon sequestration from land use. Carbon sequestration through land use refers to how much CO2 is sequestered through land-based sinks, including afforestation, soil carbon enhancement, and biochar. (Huppmann, Kriegler, et al., 2018). Most of the sequestration presented in the section on ‘sequestration through land-based sinks’ will stem from afforestation, but the data does not separate between the different sinks (Forster et al., 2018; Huppmann, Kriegler, et al., 2018; Rogelj, Shindell, et al., 2018).

The data on direct air capture in SR15 scenarios stem from the six scenarios in the database which are consistent with a 66 percent chance of limiting warming to 2°C or less and have data on sequestration through direct air capture.

The data on enhanced weathering in SR15 scenarios stem from the one scenarios in the ‘IAMC 1.5 °C Scenario Explorer hosted by IIASA’ which both is consistent with a 66 percent chance of limiting warming to 2°C or less, and has data on sequestration through enhanced weathering.

The medians of each development have been calculated using the ‘Median’ function in Excel. It is worth noting that in this thesis, ‘median scenario’ does not always refer to the same scenario, but instead refers to the median of the specific year and/or technology it is discussing. As an example, the ‘median’ CCS scenario in 2030 is not necessarily the same scenario as the ‘median’ CCS scenario in 2100. Instead – in this example – median in 2030 refers to the median CCS across all scenarios in 2030, and median in 2100 refers to the median CCS across all scenarios in 2100.

2.1.3. Research Strategy

This thesis aims to offer a critical assessment of the scale of CCS and NETs in 2 °C scenarios, the feasibility of these scenarios – as well as a discussion on how to improve scenarios and IAMs. Since, as will be discussed later in the thesis, assessments of future socio-technological developments are always bound up in some degree of uncertainty – and are likely to necessitate some degree of subjective assessment – one of the key challenges when planning this thesis was how to assess feasibility. Given the lack of a theoretical framework which fit the overarching aims of this thesis, I developed a methodology specifically aimed at exploring the topics of the thesis. The key methodical concept employed is to critically compare the outputs and assumptions of different theoretical fields and data sources. In particular, this thesis offers a critical comparison between the assumptions of integrated assessment models (IAMs) and transition/innovation theory – as well as a critical comparison between the scenario developments for CCS and NETs and the current empirical status and developments of these technologies. This thesis does not claim to hold the ‘true’ answer to the feasibility of these scenarios. Instead, based on the aforementioned comparisons, the thesis attempts to draw some ‘reasonable conclusions’ about feasibility, and the status of climate change mitigation. As such, the research strategy employed in this thesis is much in line with the abductive research approach. In abduction “the case represents a plausible but not logically necessary conclusion – provided that the rule is correct” (Ekstrom & Danermark, 2002, p. 90). In abduction, “the conclusion is a new interpretation of a concrete phenomenon – an interpretation that is plausible, given that we presuppose that the frame of interpretation is plausible” (Ekstrom & Danermark, 2002, p. 90). Furthermore, abduction can be viewed as ‘redescription’ or ‘recontextualization’ (Blaikie, 2009; Ekstrom & Danermark, 2002). Recontextualization is “a central element in scientific practice” (Ekstrom & Danermark, 2002, p. 91). The aim of this thesis is to ‘recontextualise’ climate change mitigation, mitigation science, and the scale of CCS and NETs from the context of scenarios and modelled futures, to the context of real-world technological development, insights from transition/innovation theory, and real-world feasibility. The goal is not to find the ultimate answer to whether CCS and NETs can mitigate as much CO2 as they do in most 2 °C scenarios, but to draw reasonable conclusions about these issues based on the empirical data and current knowledge. In short, much like the abductive research strategy, this thesis aims to present “a new interpretation of a concrete phenomenon” (Ekstrom & Danermark, 2002, p. 90)

2.1.4. Other relevant information

This thesis presents a few calculations of different sorts. Growth rates represent compound annual growth rates, and have been calculated using the following formula in Excel:

> “((End Value/Start Value)^(1/Periods) -1”. So, for example, when calculating the annual average growth rate of CCS sequestration capacity between 2020 and 2030, the formula would be “=(X1/Y1)^(1/10)-1” or, in this example, “=(974/37)^(1/10)-1”.

These calculations have then been checked manually both by calculator and through online average growth rate calculators. Other calculations (such as the amount of average CCS facilities required in 2050/2100) have been done by calculator and checked and confirmed multiple times. The method for each calculation (other than compound annual growth rates) will be presented in footnotes throughout the thesis.

This thesis consistently refers to carbon dioxide (CO2), not carbon (C). This means that numbers from sources and references which refer to Carbon (C) or carbon equivalents (Ceq) have been converted to carbon dioxide (CO2) and carbon dioxide equivalents (CO2eq). This has been done to keep things clearer for the reader. Hopefully, by always referring to the same variable, I can help prevent misunderstandings. Conversions from C to CO2 have been done by multiplying by 3.67, in accordance with this standard "to convert carbon mass to CO2 mass, multiply by 3.67 to account for the mass of the O2." (Ryan et al., 2010, p. 6). This thesis always mentions/highlights when such a conversion has been done. Most conversions have been double checked by checking other sources converting the same numbers. As an example, Smith et al. calculated the land required for removing 3.3 billion tonnes of *carbon* a year through BECCS (P. Smith et al., 2015). In this thesis I convert 3.3 billion tonnes of *carbon* to ~12 billion tonnes of *carbon dioxide (CO2)* (3.3 * 3.67 = 12.111), 12 billion tonnes is the same number as the SR15 uses when referring to Smith et al.'s study (see de Coninck et al. (2018, p. 343)).

Having given an overview of the methods behind the work presented here, the next section will start digging into the meat of the thesis by presenting integrated assessment models and their weaknesses.

3. Scenarios and transition literature – how do they compare?

In this section, I will present some of the current science and recent discussions on mitigation scenarios, and especially on a few key-weaknesses of the scenarios and the models behind them. This section will then move on to presenting insights from transition and innovation literature and compare how these insights relate to the weaknesses of integrated assessment models. As will become clear, many of the weaknesses of scenarios appear to correlate with what transition literature tells us are important drivers and hindrances for large-scale socio-technical transitions. If what the scenarios lack is what current literature is telling us is important – how does that influence the feasibility of the scenarios? How does it influence their assessment of the speed and scale of deployment of CCS and NETs? Are the futures they present still feasible? These are the kind of questions I will begin to explore in the following sub-sections, and which will be elaborated further in the discussion part of this thesis. Now I will first present the known weakness of scenarios, then I will present recent knowledge from transition and innovation literature, before I compare the two.

3.1. Scenarios – what are their weaknesses?

"Prediction is very difficult, especially if it's about the future." – (quote often attributed to Nils Bohr, but its origins are disputed[3]*)*

Predicting the future is difficult. While the scientific method, powerful computers, and complex models have increased our ability for forecasting and prediction, any analysis of future developments is still fraught with uncertainty. Thus, it should come as no surprise that mitigation models and the scenarios they produce come with a series of weaknesses and uncertainties. In this section of the thesis I will take a closer look at some of these uncertainties and weaknesses. There is some uncertainty related to all climate models/scenarios. For instance, the exact 'climate sensitivity,' – i.e. how sensitive the climate/temperature is to CO2 – is still uncertain.

Box 1: 'Equilibrium climate sensitivity'

'Equilibrium climate sensitivity' (ECS) - defined as "global mean warming that would occur if the atmospheric carbon dioxide (CO2) concentration were instantly doubled and the climate were then brought to equilibrium with that new level of CO2." (Cox, Huntingford, & Williamson, 2018, p. 319) – has been described as "one of the most important unknowns in climate change science" (Cox, Huntingford, & Williamson, 2018, p. 319). In the IPCC's Special Report on the 1.5 °C target the 'equilibrium climate sensitivity' is described as 'likely' to be in the 1.5 to 4.5 °C range (Cubasch, 2013; Rogelj, Shindell, et al., 2018). As pointed out in the SR15, there has been research suggesting that both the lower and upper limit of equilibrium climate sensitivity can be revised. In particular, research has suggested that the lower limit "could be revised upwards, which would decrease the chances of limiting warming below 1.5°C in assessed pathways" (Rogelj, Shindell, et al., 2018, p. 103). For now, the IPCC is still using the larger 1.5 to 4.5 °C range and describes any 'major revision' of the ECS as 'premature' (Rogelj, Shindell, et al., 2018). While geophysical uncertainties are not the focus of this thesis, this is an important uncertainty and caveat to keep in mind in any discussion on the feasibility of climate targets.

While climate sensitivity and other uncertainties, such as climate feedbacks, are common unknowns for all assessment of climate change and climate change mitigation, the focus of this section will be on *mitigation* scenarios – scenarios which explore different mitigation measures and pathways towards the 1.5 °C and 2 °C (and other) targets. "Scenario approaches", write Berkhout et al., "have stood at the heart of projections of both climate and socio-economic futures" (Berkhout et al., 2013, p. 879). Scenarios describe potential futures

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[3] See https://quoteinvestigator.com/2013/10/20/no-predict/ for further discussion.

– they are not predictions, but rather a story/description of how the future could unfold under a specific set of circumstances (R. N. Jones, A. Patwardhan, S.J. Cohen, S. Dessai, A. Lammel, R.J. Lempert, M.M.Q. Mirza, and H. von Storch, 2014). Many use these scenarios to discuss mitigation measures, climate change, the feasibility of climate targets, etc. – but this section of the thesis will not focus on the *output* of models/scenarios, instead it will focus on the models/scenarios themselves. To paraphrase the MIT-economist Robert S. Pindyck (Pindyck, 2017), this section will attempt to take a look behind the curtain - to reveal the Wizard of OZ - by highlighting some of the mechanisms, uncertainties and weaknesses in the models which make scenarios.

3.1.1. Integrated Assessment Models

To assess, present, and discuss the weaknesses of mitigation scenarios, we must take a closer look at the models behind them, as most strengths and weaknesses of scenarios stem from the models themselves. Below I present some of the recent academic discussions on Integrated Assessment Models (IAMs) and their weaknesses.

Integrated Assessment, as defined by the IPCC, refers to “a method of analysis that combines results and models from the physical, biological, economic and social sciences and the interactions among these components in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it” (IPCC, 2018a, p. 552)

Integrated assessment models (IAMs), meanwhile, “integrate knowledge from two or more domains into a single framework. They are one of the main tools for undertaking integrated assessments” (IPCC, 2018a, p. 552). There are two main types/classes of integrated assessment models:

1. “One class of IAM used in respect of climate change mitigation may include representations of: multiple sectors of the economy, such as energy, land use and land-use change; interactions between sectors; the economy as a whole; associated GHG emissions and sinks; and reduced representations of the climate system. This class of model is used to assess linkages between economic, social and technological development and the evolution of the climate system” (IPCC, 2018a, p. 552). This is the type of IAM most relevant for this thesis. This class of IAMs – often referred to as process-based IAMs – is the class of IAM used for developing complex mitigation scenarios. Most models used to develop the mitigation scenarios assessed and

discussed in this thesis fall within this class. Unless otherwise stated, when this thesis refers to IAMs, it will generally be discussing this class of IAMs.

2. The second class of IAMs "includes representations of the costs associated with climate change impacts, but includes less detailed representations of economic systems. These can be used to assess impacts and mitigation in a cost-benefit framework and have been used to estimate the social cost of carbon." (IPCC, 2018a, p. 552). This type of IAM is generally used for cost-benefit analysis, and indeed, to calculate 'the social cost of carbon'. This class of IAMs comes with a series of strengths and weakness of their own. While a few paragraphs of this thesis may touch upon this class of IAMs, it will, for the most part, discuss and assess the first class. When this thesis refers to this second 'cost-benefit' class of IAMs, it will make it explicitly clear.

Most long-term mitigation scenarios, both in the IPCC's AR5 and SR15, stem from the first type of IAMs described above – and include multiple sectors and the interactions between them (Clarke et al., 2014; Rogelj, Shindell, et al., 2018). As pointed out in the SR15 "much of the quantitative global scenario literature is derived with such models" and "IAMs lie at the basis of the assessment of mitigation pathways" (Rogelj, Shindell, et al., 2018, p. 100). One of the key strengths of IAMs is that they can combine insights from different fields of research into one framework, enabling them to represent interactions between different systems and structures of society. This allows IAMs to offer a "dynamic description of the coupled energy–economy–land-climate system that cover the largest sources of anthropogenic greenhouse gas (GHG) emissions from different sectors" (Rogelj, Shindell, et al., 2018, p. 100). In short, IAMs take a set of assumptions - be they population growth, economic growth, technological change, etc. – and produce a wide range of outputs, such as emission trajectories, changes in the energy system, the energy mix, etc. (Clarke et al., 2014). The findings of IAMs are used to inform decisions on "energy and climate policy, international negotiations on mitigation targets, and sustainable development strategies" (Wilson et al., 2017, p. 2). The IPCC's SR15 itself is a great example of this, where many different mitigation scenarios created by IAMs are presented as various potential pathways to 1.5 °C and or 2 °C. In general, when people refer to 'IPCC scenarios', they are referring to scenarios which have been assessed by the IPCC, and which were developed by IAMs.

Having presented a simple overview of what IAMs are, and why they are useful, I will now present a few of their weaknesses. The focus will be on weaknesses related to socio-economic, socio-technical, and political factors which could influence the feasibility of mitigation targets, and the speed and scale of CCS and NETs. Weakness and uncertainties related to assessing the geophysical constraints (climate sensitivity, feedback loops, non-CO2 agents, etc.) of mitigation pathways are highly important, and will be briefly discussed later on (section 7. 'Feasibility' – a presentation of the term and related issues), but an in-depth discussion of these fall outside the scope of this thesis[4].

3.1.2. Uncertainties and weaknesses in IAMs

IAMs are 'simplified', 'stylized', and 'idealized' (Clarke et al., 2014; Turnheim & Nykvist, 2019). As Clarke et al. highlight in the IPCC's 5th assessment report (AR5), IAMs are "numerical approaches to represent enormously complex physical and social systems" (Clarke et al., 2014, p. 422). As outlined above, they take in a series of assumptions (population growth, economic growth, technological change, etc.) and produce outputs saying something about changes in the energy system, emission pathways, cost of mitigation, land-use change, and other factors, over the coming decades. (Clarke et al., 2014)

IAMs can give insights into different types of mitigation measures and strategies (van Vuuren et al., 2018). This is usually done by developing so-called *mitigation scenarios*. Mitigation scenarios are usually developed by "finding a cost-optimal combination of technologies" (van Vuuren et al., 2018, p. 391) for emission reductions - given the assumptions you feed into the model. Put another way, you tell the model to reduce emissions to the limits of a set temperature target, say 1.5 °C or 2 °C, feed it with a series of assumptions - population growth, economic growth, immediate/delayed start to mitigation, etc. – and the model produces the most cost-effective technology mix and emission pathway to achieve your target. But, as van Vuuren et al. point out, since IAMs often focus on cost "they normally concentrate on reduction measures for which reasonable estimates of future performance and costs can be made" (van Vuuren et al., 2018, p. 391). Which could lead to some mitigation strategies being overlooked and receiving less attention "as their future performance is more speculative or their introduction would be based on drivers other than cost, such as lifestyle change or more rapid electrification" (van Vuuren et al., 2018, p. 391). Put another way,

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[4] While uncertainties about the geophysical constraints facing mitigation targets will not be discussed at length in this thesis, it is still important to remember that they are there. Since there are uncertainties both in the geophysical and in the socio-technical spheres of climate change mitigation, mitigation scenarios often stem from uncertain assumptions interacting with other uncertain assumptions in uncertain ways. When gambling with the biosphere, it is sometimes good to be reminded that our odds-calculator still has flaws and knowledge gaps. For a discussion on the geophysical uncertainties in IAMs I recommend section 2.1, 2.2, and 2.6 of chapter 2 in the SR15.

since IAMs are ‘numerical approaches’ they struggle to measure, calculate, and assess non-numerical factors. Indeed, as pointed out in the IPCC’s 5th assessment report (AR5), “the models do not structurally represent many social and political forces that can influence the way the world evolves” (Clarke et al., 2014, p. 422). IAMs use “economics as the basis for decision making” (Clarke et al., 2014, p. 422) and therefore “tend towards normative, economics-focused descriptions of the future.” (Clarke et al., 2014, p. 422). However, the economics of IAMs are not the economics of the real-world, as part of their ‘simplified’, ‘stylized’, and ‘idealized’ parts are the assumptions about markets. IAMs tend to assume fully functioning markets “meaning that factors such as non-market transactions, information asymmetries, and market power influencing decisions are not effectively represented.” (Clarke et al., 2014, p. 422). Geels, Berkhout, and van Vuuren (2016) note how, due to their reliance on economic theory, many IAMs “make restrictive assumptions about the behaviour of social actors, for example, that actors have complete information, perfect foresight, rational decision-making, and competitive price-taking behaviour (with no monopolies or strategic behaviour present)” (Geels et al., 2016, p. 578). Meaning, they miss out on behavioural factors other than ‘cost-benefit calculations’ which influence how businesses, consumers and policymakers behave, interact, and influence transitions (Geels et al., 2016). The simplified, idealized economy of IAMs, combined with ‘perfect foresight’, leads to simplified assumptions about governance and policymaking, since the idealized markets lead to outcomes “that would be achieved by a fully informed benevolent social planner” (Staub-Kaminski, Zimmer, Jakob, & Marschinski, 2014, p. 3).

Geels, Berkhout, and van Vuuren (2016) further point out how these simplifications lead to IAMs recommending ‘price-oriented’ mitigation policies, which overlook and downplay three issues related to real-world policymaking:

- “First, policymakers (particularly at national and local levels) are usually constrained by their dependence on other actors (such as firms, electorates and civil society) for skills, financial resources, deployment and legitimacy.” (Geels et al., 2016, p. 578)
- “Second, as IAMs privilege price-based instruments, they restrict consideration of a wider range of policy instruments” (Geels et al., 2016, p. 578)
- “Third, whereas IAMs assume that policymakers are mostly motivated by cost considerations and climate change problems, real-world policymakers in energy, transport and agro-food systems seek to reconcile climate objectives with a range of

> other normative goals and objectives, for example, congestion, safety, health, jobs and competitiveness." (Geels et al., 2016, p. 578)

Similarly, "perfect foresight" leads IAMs to overlook "irreducible real-world uncertainty" that could lead "a social planner to choose costly 'hedging' strategies", which again may lead IAMs to underestimate abatement cost (Staub-Kaminski et al., 2014, p. 22). Meaning, that by assuming policy-makers will only make 'perfect' decisions IAMs risk underestimating the 'true' cost of emission mitigation. Moreover, IAMs are also criticised for focusing too much on one scale/level of transitions – typically the global scale - thus missing out on interactions between the different scales (global, national, local, etc.) (Geels et al., 2016; Turnheim et al., 2015). This will be outlined further in the coming sub-section of this thesis (section 3.2 Characteristics of transitions)

The simplified, numerical approach outlined above often makes it difficult to see how some of the outputs of IAMs relate to the less 'idealized' approaches of the real world. As Berkhout et al. pointed out in 2013 "finding a 'fit' between the life-world of decision-makers and the outputs of scenario-based assessments remains a major challenge." (Berkhout et al., 2013, p. 880). This sentiment is echoed by O'Brien, when she writes "often the social complexity of transformation processes is downplayed or ignored in favour of technical solutions and behavioural approaches" (O'Brien, 2018, p. 153), and is again repeated by Turnheim and Nykvist when they point out "modelling approaches reduce decision-making to a 'bird's-eye' view on macro-economic interventions and hence risk overlooking other constraints at play." (Turnheim & Nykvist, 2019, p. 776). Thus, when it comes to assessing the feasibility of transformation pathways and specific temperature goals, these models are somewhat limited, because they can overlook both 'non-numerical' constraints and mitigation strategies which cannot be easily calculated and quantified. As the IPCC writes in AR5 "beyond cases where physical laws might be violated to achieve a particular scenario (…), these integrated models cannot determine feasibility in an absolute sense." (Clarke et al., 2014, p. 424).

Another key uncertainty when using IAMs to model socio-economic and socio-technical mitigation factors are the input assumptions themselves. We do not know for certain how the economy will grow in coming decades, we do not know for certain how much the global population will grow, and we do not know the 'real' discount rate. This third input – the discount rate – could potentially have quite a significant impact on the mitigation strategies of scenarios made with IAMs. As noted in the SR15 “assumptions about the social discount rate” affect the “choice and timing of investments in individual measures” (Rogelj, Shindell, et al., 2018, p. 150). For example, in a study assessing the role for direct air capture (DAC) in greenhouse gas emission mitigation, Chen and Tavoni (Chen & Tavoni, 2013) found that since the model used (a model called ‘WITCH’) “assumes perfect foresight” policymakers in the model ‘know’ the most cost-optimal way to reduce emissions. This means that when you both introduce a discount rate and negative emissions “the result is more emissions in the near term and fewer in the long run.” (Chen & Tavoni, 2013, p. 65). When Chen & Tavoni set the discount rate to zero, they “observe significantly lower deployment of DAC.” (Chen & Tavoni, 2013, p. 65) Leading the authors to conclude that negative emission technologies “are affected by the way the future is discounted into present terms; lowering the social rate of time preference would reduce the scope of DAC since it would counteract the tendency to shift policy costs onto future generations.” (Chen & Tavoni, 2013, p. 70). Put another way, the output of the model is significantly changed by the discount rate. With a high discount rate a high reliance on future negative emissions is more cost-effective, while a low discount rate counteracts “the tendency to shift policy costs onto future generations” (Chen & Tavoni, 2013, p. 70), i.e. leading to more stringent immediate emission reductions. Now, this would not be a problem if we knew the ‘right’ discount rate, but this is not the case. According to the supplementary material of chapter 2 in the SR15, “in a survey of modelling teams contributing scenarios to the database for this assessment, discount rate assumptions varied between 2%/year and 8%/year depending on whether social welfare considerations or the representation of market actor behaviour is given larger weight” (Forster et al., 2018, p. 14). Based on the findings of Chen and Tavoni, there is a very real chance that our assumptions about the discount rate is one of the key factors shaping the pathways of current mitigation scenarios. For instance, a recent comment in nature communications argues that negative emission technologies (NETs) “enter IPCC scenarios for the wrong (discounting), not for the right reason (hedging uncertainties)” (Bednar, Obersteiner, & Wagner, 2019, p. 1). Currently, "the impact of the choice of discount rate on mitigation pathways is underexplored in the literature" (Forster et al., 2018, p. 14).

Box 2: The discount rate in 'simple' cost-benefit IAMs

While the use of the discount rate in in the second 'class' of IAMs is not directly relevant for this thesis, a quick exploration of it opens questions which are. As noted earlier, this type of IAM is generally used for cost-benefit analysis and calculating the social cost of carbon (SCC). The 'Social cost of carbon (SCC)' is defined as "the net present value of aggregate climate damages (…) from one more tonne of carbon in the form of carbon dioxide (CO2), conditional on a global emissions trajectory over time." (IPCC, 2018a, p 558). As MIT-economist, Robert S. Pindyck, points out, "there is no consensus among economists as to the "correct" discount rate to use in estimating the SCC, but different rates will yield wildly different estimates of the SCC and the optimal amount of abatement that any IAM generates" (Pindyck, 2017, pp. 100-101) The difference in discount rate input is one of the key reasons why Nordhaus (2008) and Stern (2007) come to such differing conclusions about the social cost of carbon and optimal climate change abatement (Pindyck, 2013, 2017). However, in spite of this uncertainty, calculations of the social cost of carbon is already being used to inform policy choices (Rogelj, Shindell, et al., 2018). While this thesis focuses on the first class of IAMs, the use of scenarios and models full of uncertainties to inform current policy is one of the topics I will discuss in the discussion section of this thesis. The discount rate's influence on the SCC is one example of such and uncertainty. (See this New York Times article from 2007 for a summary of the Stern vs. Nordhaus debate: https://www.nytimes.com/2007/02/21/business/21leonhardt.html)

One way IAMs try to both introduce different societal factors and reduce input uncertainties is through the 'Shared Socio-Economic Pathways' (SSPs) (Allen et al., 2018; Rogelj, Shindell, et al., 2018). The SSPs are "reference pathways describing plausible alternative trends in the evolution of society and ecosystems over a century timescale, in the absence of climate change or climate policies." (O'Neill et al., 2013, pp. 387-388). In short, the Shared Socio-Economic Pathways are five different baseline pathways, or 'storylines', about how society can develop over the coming century. They are reference scenarios which can provide input and comparison to mitigation scenarios, as the SSPs themselves "assume no climate change or climate impacts, and no new climate policies" (O'Neill et al., 2013, p. 389). The SSPs, simply put, allows modellers to model climate mitigation policies/scenarios in five different futures. These futures are described narratively and comes with a series of quantified measures (population growth, economic growth, etc.) (O'Neill et al., 2013). As such, the SSPs "describe plausible alternative trends in the evolution of society and natural systems over the 21st century" (O'Neill et al., 2013, p. 389). For example, based on different assumptions about everything from education to migration, “population projections vary between 8.5 and 10.0 billion people by 2050 and between 6.9 and 12.6 billion people by 2100 across the SSPs” (Rogelj, Shindell, et al., 2018, p. 109). While the SSPs alleviate some of the input uncertainties for IAMs – and gives modellers a way to model some potential societal choices – it is important to note that “detailed qualitative storylines are still considered to be oversimplifications of reality, devising stylised representations of political, institutional and social change.” (van Sluisveld et al., 2018, p. 2). Thus, while the SSPs may contribute to reduce some of the uncertainties and weaknesses in IAMs, they do not alleviate the problems outlined earlier in this section.

To summarize, this section has presented some of the key weaknesses of integrated assessment models. It has shown that they are idealized models focused on numerical approaches, but which miss out on solutions and constraints which cannot be reasonably estimated numerically. It has also presented how IAM outputs generally “tend towards normative, economics-focused descriptions” (Clarke et al., 2014, p. 422), while missing out on many social and political factors. This section has also addressed how uncertain inputs, such as the discount rate, can influence the output of the models. When it comes to mitigation scenarios, the outputs of IAMs are – to some extent – assessments of idealized systems interacting in uncertain ways based on uncertain inputs. In a paper discussing ‘Some Contributions of Integrated Assessment Models of Global Climate Change’, John Weyant[5], a former lead author and review editor for IPCC assessment reports, concluded:

> “Given the challenges involved in producing IAM results and the many uncertainties underlying those results, I believe it is best to view these models as providing a good place to start in terms of basic principles and rough numbers to use in developing short-term (say through the next 5 to 10 years) policies and research priorities, but a poor place to finish in the design of specific longer-term global policies.” (Weyant, 2017, p. 129)

3.2. Characteristics of transitions

Are the weaknesses and uncertainties of IAMs and mitigation scenarios relevant for large-scale transitions? Could these uncertainties affect their assessment of the speed and scale of the CCS and NETs build-outs? Do the weaknesses affect IAMs’ assessments of feasibility? To try and answer these questions, this section of the thesis will present knowledge from transition and innovation literature. Once relevant knowledge from these fields has been presented, the next section of the thesis will compare the knowledge from transition studies

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[5] https://emf.stanford.edu/people/john-weyant

with the uncertainties of mitigation scenarios. These findings will later be used to discuss what the discrepancies between the fields could mean for the scenarios' feasibility in the real world, and potential implications for mitigation science.

"Socio-technical transitions" refers to complex "processes of structural change in major societal subsystems. They involve a shift in the dominant 'rules of the game', a transformation of established technologies and societal practices, movement from one dynamic equilibrium to another"(Meadowcroft, 2009, p. 324). Much like climate change and IAMs, socio-technical transitions are complex beasts in and of themselves. Giving a complete overview of our current knowledge on socio-technical transitions falls somewhat outside the scope of this thesis. Instead, this section will focus on a few specific aspects of large-scale transitions, namely, what *drives* them, what are potential *roadblocks,* and how *fast* can they go? Transition theory is important for the analysis of this thesis, for, as Meadowcroft and Rosenbloom point out, "the transition approach has developed important insights with respect to the large-scale societal transformations needed to respond to climate change." (Rosenbloom & Meadowcroft, 2014, p. 671). The type of transition needed to respond to the challenge of climate change is often referred to as "sustainability transitions". Sustainability transitions have been described as "processes of fundamental social change in response to societal challenges" (Avelino, Grin, Pel, & Jhagroe, 2016, p. 557). To Smith et al. the key to these transition "lies in the recognition of agency in social choices about technological futures." (A. Smith, Stirling, & Berkhout, 2005, p. 1508). While Frank Geels notes, transitions towards sustainability are "about interactions between technology, policy/power/politics, economics/business/markets, and culture/discourse/public opinion" (Geels, 2011, p. 25). Moreover, Geels notes, sustainability transitions have some characteristics which differ from most historical transitions (Geels, 2011). First, "sustainability transitions are goal-oriented (…) in the sense of addressing persistent environmental problems, whereas many historical transitions were 'emergent'." (Geels, 2011, p. 25). Second, transitions towards sustainability do not necessarily offer 'user benefits' and are therefore unlikely to occur "without changes in economic frame condition" (Geels, 2011, p. 25). Third, the transport, energy, and agri-food sectors which need to transform in a sustainability transition are characterized by large companies. These companies "possess 'complementary assets' such as specialized manufacturing capability, experience with largescale test trials, access to distribution channels, service networks, and complementary technologies." (Geels, 2011, p. 25). These assets give incumbent firms an advantage over smaller companies developing new innovative solutions, which, potentially, can contribute to systemic inertia and slowing down the transition.

Turnheim et al. (2015) point out that sustainability transitions "present a number of challenges" (Turnheim et al., 2015, p. 240) before they present five reasons for this:

> "(1) the multiple scales, geographies and temporalities of transformational processes, (2) uncertainties associated with radical innovation and the limits of prediction, (3) the interplay between the inertia of existing socio-technical systems and the emergence of novelty, (4) the problem of shaping innovation in relation to multiple social objectives and public goods, and (5) contested perspectives about the governance of complex processes of social, economic and technical change." (Turnheim et al., 2015, p. 240).

While IAMs generally solve the problem of multiple scales by simplifying and looking at very broad specific scales (like the global scale) (Geels et al., 2016; Turnheim et al., 2015), transition theory highlights how transitions are "enacted by a wide range of actors such as firms, consumers, national policymakers, local authorities, researchers, social movements and wider publics." (Geels et al., 2016, p. 577). Moreover, actors from different levels, with differing interests and beliefs about solutions and goals, often find themselves 'struggling' against each other. Indeed, to Geels, sustainability transitions require "changes in policies, which entails politics and power struggles." (Geels, 2011, p. 25). These struggles can come in many forms, including "business struggles between incumbents and new entrants (…), discursive struggles in public debates (…), and political struggles over goals, policy frameworks and the setting of specific instruments." (Geels et al., 2016, p. 577). These factors are all reflected in the multi-level perspective (MLP), one of the most commonly employed analytical frameworks for analysing socio-technical transitions. While the MLP will not be employed as an analytical tool in this thesis, its insights are still of value for the assessment presented here. As such, the key concepts of the MLP are outlined below.

The MLP views transitions as non-linear processes which results from interactions and developments on and between three different analytical levels - the niche level, the socio-technical regime level, and an exogenous socio-technical landscape (Geels 2011).

- The regime level refers to the structure which provides "the stability of an existing socio-technical system," and to the "semi-coherent set of rules that orient and coordinate the activities of the social groups that reproduce the various elements of socio-technical systems (Geels, 2011, p. 27). The socio-technical regime "contains ‘policy’ as one dimension” along with “technology, user practices, science, cultural meaning, infrastructure and industry” (Geels, Tyfield, & Urry, 2014, p. 23). In short, the regime is the dominant practices and actors within a given system. In the energy sector, incumbent fossil fuel companies would be an example of actors at the regime level.

- At the niche level, we find the actors who “work on radical innovations that deviate from existing regimes” (Geels, 2011, p. 27). Niche-actors develop new ideas and technologies with the “hope that their promising novelties are eventually used in the regime or even replace it” (Geels, 2011, p. 27). “Niches are crucial for transitions,” Geels writes, “because they provide the seeds for systemic change.” (Geels, 2011, p. 27). In the personal transportation sector, the electric car is an example of an innovation that came from the niche level, and now (arguably) has been taken up and adopted by the regime.
- The socio-technical landscape is the “wider context, which influences niche and regime dynamics” (Geels, 2011, p. 28) but “also includes demographical trends, political ideologies, societal values, and macro-economic patterns” (Geels, 2011, p. 28). It is important to note that “this varied set of factors can be combined within a single ‘landscape’ category, because they form an external context that actors at the niche and regime levels cannot influence in the short run” (Geels, 2011, p. 28). Put another way, ‘socio-technical landscape’ refer to the exogenous social factors which cannot be directly influenced by niche and regime actors in the short-term. Globalized free-market capitalism and climate change are both examples of factors we could find in the socio-technical landscape.

As mentioned above, the MLP sees transitions as resulting from the interplay of these three different levels. As Geels explains:

> “The core logic is that niche-innovations build up internal momentum (…) changes at the landscape level create pressures on the regime; and destabilization of the regime creates windows of opportunity for the diffusion of niche-innovations. The alignment of these processes enables the breakthrough of ‘green’ innovations in mainstream markets where they struggle with the existing regime on multiple dimensions.” (Geels et al., 2014, p. 23).

‘Changes create pressure’, ‘destabilizations of the regime creates windows of opportunity’, innovations ‘struggle with the existing regimes’ (Geels et al., 2014, p. 23). What these phrases – and indeed the MLP itself – highlights, is that transitions are not ‘simple’ events which can be easily guided, steered, and controlled. Indeed, as Geels points out, “the MLP does away with simple causality in transitions. There is no single ‘cause’ or driver.” (Geels, 2011, p. 29). Instead, the interactions between different actors, different levels and scales, differing goals and perspectives, and the subsequent struggles, often lead to transitions being ‘messy’, nonlinear, unpredictable, and difficult to control (Geels et al., 2016; O’Brien, 2018; Turnheim et al., 2015). The MLP is a good heuristic device for describing some of the dynamics of socio-technical transitions, and especially for visualizing some of the necessary conditions for innovation, change, and transitions to occur. But, as mentioned, socio-technical transitions are complex beasts, and no framework can give a good description of all the factors and interactions at play. To ensure a broader understanding of socio-technical transitions, and how their dynamics may influence the feasibility of CCS, NETs and the goals of the Paris Agreement, I will take a more detailed look at some aspects of transitions below.

While actors in IAMs are equipped with perfect foresight, guiding idealized systems which respond to their rational decisions, real-world socio-technical systems come with a series of challenges and characteristics which could complicate transitions even for the flawlessly cerebral actors of IAMs. For instance, socio-technical systems often come with some form of inertia, path-dependence, and/or ‘lock-in’ (Sovacool, 2016; Turnheim et al., 2015). This inertia stems from many different factors - some social, some technical, some political, some economic. These factors include sunk investments, existing infrastructure, existing shared beliefs and discourses, existing regulatory practices, lobbying from incumbent actors, and established power relations. (Geels, 2011; Geels et al., 2014; Turnheim et al., 2015). Moreover, “consumer lifestyles and preferences may have become adjusted to existing technical systems,” (Geels, 2011, p. 25) meaning transitions need to overcome social resistance to change, and/or help facilitate lifestyle changes in order make the transition possible. Clearly, there is a wide range of factors which can help and hinder transitions. As shown above, everything from established beliefs and discourses within the field of economy, to the very physical realities of existing infrastructure, can be important hindrances and/or facilitators in socio-technical transitions. Given these factors’ complexity and interconnectedness, it should be quite clear that large-scale transitions are not only about a ‘simple’ switch in technologies and technology mixes. No wonder then that “no historical precedent of socio-technical transition can be found that has not involved fundamental re-configurations of not only technologies, but also markets, practices, norms and values concomitantly” (Turnheim & Nykvist, 2019, p. 777). This is especially true of normative transitions, like the sustainability transition necessary to prevent climate change (Turnheim & Nykvist, 2019). Put together, these factors can make it very difficult for actors and policymakers to change existing socio-technical systems – regardless of intentions and level of rationality. Moreover, as alluded to in the previous section of this thesis, policymakers often have to balance the goals of the sustainability transition with a wide range of other objectives. This includes securing good economic development, job creation, health, safety and security, and all the other issues decision makers have to contend with (Geels et al., 2016; Meadowcroft, 2011; Turnheim et al., 2015). As Turnheim et al. puts it "optimising on a single objective like inflation, growth or employment is a good deal more straightforward analytically and in governance than balancing across many objectives." (Turnheim et al., 2015, p. 242). Taken together, the aforementioned factors – transitions as struggles, 'lock-in', the complexity of transitions, and the diversity of policy issues – highlight how difficult it is for real-world policy makers to achieve outcomes similar to those of the "fully informed benevolent social planner" (Staub-Kaminski et al., 2014, p. 3) in IAMs.

Given the dynamics of transitions outlined above, it should come as no surprise that many scholars argue that sustainability transitions both (1) need to be politically driven, and (2) take time. Both these points have been matters of debate and focus among transition scholars, and thus deserve a closer look. "The decarbonization challenge", writes Rosenbloom and Meadowcroft, "will be politically driven" (Rosenbloom & Meadowcroft, 2014, p. 676), before they note "the scale of existing societal dependence on fossil fuels, their convenience and continued availability mean that sustained policy pressure will be required to encourage a decisive shift away from a GHG emitting development trajectory." (Rosenbloom & Meadowcroft, 2014, p. 676). Meadowcroft has earlier pointed out that politics "requires explicit attention from those interested in understanding sustainability transitions" (Meadowcroft, 2011, p. 73), and that "politics is the constant companion of socio-technical transitions, serving alternatively (and often simultaneously) as context, arena, obstacle, enabler, arbiter, and manager" (Meadowcroft, 2011, p. 71). While all socio-technical transitions involve politics to some extent, sustainability transitions are arguably even more political (Meadowcroft, 2011). This is due to their normative nature, and because "the operation of social institutions does not spontaneously generate a sustainable development trajectory" (Meadowcroft, 2011, p. 71). Kern and Rogge, meanwhile, 'contend' that 'firm political commitment' is at " the heart of the pace of low carbon energy transitions" (Kern & Rogge, 2016, p. 16). As alluded to earlier in this section, many solutions required for sustainability transitions “do not offer obvious user benefits (because sustainability is a collective good), and often score lower on price/performance dimensions than established technologies.” (Geels, 2011, p. 25). Fossil fuels with CCS contra fossil fuels without CCS is a good example of this, where CCS adds cost, but with no (immediate) user benefits. Changes to “economic frame conditions (e.g., taxes, subsidies, regulatory frameworks)” (Geels, 2011, p. 25) are therefore most likely necessary to drive the transition. These types of changes will have to be driven politically (Geels, 2011; Kern & Rogge, 2016; Meadowcroft, 2011). The above citations, from some of the foremost scholars in the transition field, make it abundantly clear that politics – and the formulation of policy – is key in socio-technical transitions. However, in the real world, politics and policy-making are not simple and straightforward. There are many different actors with many differing opinions, goals and priorities (Geels, Sovacool, Schwanen, & Sorrell, 2017). Moreover, actors are not only guided by the outputs of cost-benefit analysis, “but also by entrenched beliefs, conflicting values, competing interests, unequal resources, and complex social relations” (Geels et al., 2017, p. 463). Indeed, many actors even disagree that a transition is needed (as examples, Trump, Bolsonaro, many Australian politicians). Others contest various aspects of the sustainability transition for different reasons. Some examples are ‘Not In My Back Yard’ (NIMBY) battles against on-shore wind and underground carbon storage, opposition to nuclear, and opposition to phasing out fossil fuel industries in fossil fuel exporting countries (Geels et al., 2017; Lipponen et al., 2017). It is clear then, that politicians and policymakers do not always have the option, will, nor power to always make the most ‘rational’ choice required for the smoothest, cheapest, and fastest transition. Instead, “substantial policy changes involve political struggles and public debate” (Geels et al., 2017, p. 464).

The focus on politics in sustainability transitions has been an important part of the discussions on how fast the current decarbonization transition can go. Historically, socio-technical transitions – with energy transitions as a prime example – have taken a long time (Grubler, 2012; Smil, 2016; Sovacool, 2016), from “many decades” to “ even above a century” (Grubler, 2012, p. 11). This has led some scholars to argue that the transition to decarbonize society, the economy and the energy system will similarly take a long time (Grubler, Wilson, & Nemet, 2016; Smil, 2016). Smil, for example, notes:

> “We now have a truly global energy supply system relying overwhelmingly (~85% in 2015) on fossil fuels. Replacing it by new arrangements based on (mostly liquid) biofuels and intermittent (mostly wind and solar) electricity generation is—even after ignoring all

> environmental and social problems associated with the requisite up-scaling of biofuel production, and all technical challenges associated with mass-scale reliance of generating electricity with low capacity factors—a task that will necessarily occupy us for generations to come." (Smil, 2016, p. 196)

Other scholars, however, argue that given the decarbonization transition is normative, and thus needs to be guided, controlled, and steered – and, given we now have improved knowledge on how transitions happen, the current transition could be 'sped up' and go much faster than historical transitions (Bromley, 2016; Kern & Rogge, 2016; Sovacool, 2016). Sovacool and Geels summarize the arguments of the two sides expertly, their arguments are outlined in the following sentences. One side views transitions as slow due to "various techno-economic rationales". (Sovacool & Geels, 2016, p. 233). These rationales include, the long time it takes to build infrastructure and related systems, the time it takes for new systems and technologies to become competitive and cost-effective, and the time it takes to displace established systems and technologies - due to sunk costs and a wish to reap the profits of existing assets and investments (Sovacool & Geels, 2016). The other side, on the other hand, argues the coming transition will/can be faster than historical transitions. The reason for this is that "political will and a societal sense of urgency" (Sovacool & Geels, 2016, p. 233) could lead to the introduction of policies which "change markets and selection environments (e.g. carbon tax, cap-and-trade, feed-in-tariffs, renewables obligations, contracts-for-difference) or even phase-out technologies before they are written off" (Sovacool & Geels, 2016, p. 233). In other words, the scholars on this side of the argument argue that in the case of this specific socio-technical transition "politics may trump economics" (Sovacool & Geels, 2016, p. 233). It is not for this thesis to be the arbiter of the debate on the potential speed of the current transitions, that, instead, must be left for future historians. What this debate highlights, however, is that global socio-technical transitions are incredibly complex and demanding. Moreover, it makes it very clear that attempts to speed up the transition must be – at least partially – politically driven. As Grubler et al. put it, the current sustainability transition "require changes that are systemic, large scale (need to be implemented globally) and often have little immediate adoption benefits besides significant reductions in social and environmental externalities." (Grubler et al., 2016, p. 24). Creating the economic environment for selecting sustainable technologies and phasing out polluting ones, therefore, require some form of policy. And the creation of policy – like it or not – requires politics (Meadowcroft, 2011). Unfortunately, "real (as opposed to a rhetorical) politics of sustainability implies hard choices: picking priorities (and setting aside other projects); making decisions that are almost guaranteed to be suboptimal and assuming current costs to hedge uncertain future risks; and cutting through distributional entanglements." (Meadowcroft, 2011, p. 72). Theories on decision and policy-making speak of 'muddling through' and 'disjointed incrementalism' – and see decision and policy making/implementation as a back-and-forth process full of experimentation and learning by doing. (Enderud, 1976; Geels et al., 2017). In Lindblom's 'muddling through' model problems are rarely 'solved', and decisions are more an 'escape' from problems than a process working towards a set normative goal (Enderud, 1976). Other theories, like the 'garbage can' model and the' multiple streams' approach, also view decision and policy-making as processes far removed from the rationality of IAMs. Other political theories, like theories of policy networks "see policymaking as a deeply political process involving negotiations, compromises, and the building of coalitions with stakeholders" (Geels et al., 2017, p. 475), similar ideas are reflected in the Advocacy Coalition Framework (Sabatier & Weible, 2007). Put another way, in these models and theories, decision-making processes are not logical step-by-step processes in which a policymaker sees a problem, prescribes a policy, implements a policy, and thus fixes the problem. No, much like socio-technical transitions themselves, policy and decision making are messy back and forth processes, full of struggles and compromise, where a solution's ability to please current stakeholders is often more important than its level of optimization/rationality (Geels et al., 2017). As Geels et al. excellently puts it "politics is the ''art of the possible'' rather than the ''calculation of the optimal.'' This suggests that more expensive transitions may be preferable if stakeholder support makes their implementation more feasible." (Geels et al., 2017, p. 475).

What this section has shown, is that socio-technical transitions are messy, non-linear, events – difficult to steer, rife with conflict and disagreement – and about much more than a simple change in technology mixes. Thus, the feasibility and speed of our current transition is highly dependent on the struggles and hard choices of real-world politics. And the world of real-world politics is much like transitions themselves - difficult to steer, rife with conflict and disagreement – and about much more than a simple change in policy. To paraphrase the statesman Donald Trump's words on health care[6], nobody knew transitions could be so complicated.

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[6] Trump's comment was "nobody knew health care could be so complicated". See: https://edition.cnn.com/2017/02/27/politics/trump-health-care-complicated/index.html

3.3. IAMs and real-world transitions– brief summary of how they compare

The previous sections outline some of the key weaknesses of IAMs, as well as some of the key characteristics of real-world transitions. This section of the thesis will take a brief, comparative look at the discrepancies between IAMs and real-world transitions. While some discrepancies between IAMs and real-world transitions may already have been noticed by attentive readers, this section aims to make these discrepancies clearer. The following paragraphs simply aim to highlight and summarize the key takeaways from the two previous sections. A deeper discussion of what these discrepancies could mean for the feasibility of scenarios, CCS, and NETs, will come in the discussion part of this thesis.

IAMs have idealized markets, idealized actors, and idealized decision-making processes, which "make restrictive assumptions about the behaviour of social actors, for example, that actors have complete information, perfect foresight, rational decision-making, and competitive price-taking behaviour" (Geels et al., 2016, p. 578). Transition theory, meanwhile, speaks of how policies and transitions need to overcome social resistance to change, how new technologies and actors 'struggle' against existing incumbent regimes, and how transitions are difficult to steer and control. While IAMs focus on "finding a cost-optimal combination of technologies" (van Vuuren et al., 2018, p. 391), actors in transition theory are not only guided by the outputs of cost-benefit analysis, "but also by entrenched beliefs, conflicting values, competing interests, unequal resources, and complex social relations" (Geels et al., 2017, p. 463). While new technologies in IAMs 'simply' arrive, both on time and when they would be most optimally implemented, transition literature speaks of how socio-technical transitions require "fundamental re-configurations of not only technologies, but also markets, practices, norms and values concomitantly" (Turnheim & Nykvist, 2019, p. 777). While IAMs simply introduce bioenergy with CCS (BECCS) (and/or other solutions) at enormous scales, policy makers have to balance between sustainability transitions and other goals – and, as we shall see later, in the case of BECCS even have to balance between different sustainability considerations. While IAMs "do not structurally represent many social and political forces that can influence the way the world evolves" (Clarke et al., 2014, p. 422), transition scholars focus on how sustainability transitions need to be politically driven, and how politics “requires explicit attention from those interested in understanding sustainability transitions” (Meadowcroft, 2011, p. 73).

In short, while IAMs mostly focus on simple changes of technology mixes, transition literature points out that no such thing exists. While IAMs do not contain opposition, struggle, and disagreement, “substantial policy changes involve political struggles and public debate” (Geels et al., 2017, p. 464). While IAMs are idealized numerical models, the real world is a collection of messy processes interacting in messy, unpredictable ways. However, while IAMs “normally concentrate on reduction measures for which reasonable estimates of future performance and costs can be made” (van Vuuren et al., 2018, p. 391), real-world policymakers potentially also have less ‘numerical’ measures at their disposal. Put another way, while real-world actors may not be as rational and cerebrally immaculate as their IAM counterparts, they may still have the benefit of better imagination. All these discrepancies are good to keep in the back of our minds when we delve into the use of CCS and NETs in scenarios.

4. Introduction to CCS and negative emission technologies

This section will give a brief introduction and overview of both carbon capture and storage and various negative emission technologies. This section will not go into the main challenges and uncertainties each technology is facing – as these will be explored further in a later section of the thesis (section ‘6. Key challenges for the different technologies’). First, carbon capture and storage will be introduced, then I will move on to negative emission technologies.

4.1.Carbon Capture and Storage

Carbon capture and storage technologies are technologies which capture CO2 from a CO2-emitting source. The source can be an oilrig, a power-plant – be it a coal, gas, or biomass plant - CO2-emitting industries, etc. Once the CO2 has been captured, it is transported to suitable storage points, where the carbon is stored away for the foreseeable future (Bui et al., 2018). There are different techniques for both storing and capturing the CO2, and new ways are being discussed and developed (Coley, 2011). The captured CO2 can be injected and stored underground. For instance, it can be stored in old oil/gas fields, in old coal seams, or in saline aquifers (Coley, 2011). Captured CO2 has also been used for enhanced oil recovery, wherein CO2 is injected into an oil well to help recover more the oil (Coley, 2011).

In 2018 there were 18 large-scale[7] CCS facilities in commercial operation (GCCSI, 2018). According to the Global CCS Institute (GCSSI) the current annual capture capacity is approximately 37 million tonnes CO2 (MtCO2) per year (GCCSI, 2017, 2019). However, while their database lists 18 large-scale CCS facilities as being currently in operation[8], the added up cumulative capture capacity of these facilities (as listed in the database) amounts to 31.7 – 33.3 million tonnes of CO2[9] per year. A different paper – Gaurina-Međimurec and Mavar (2019) – operates with a CCS capturing capacity of "approximately 30 Mt/y" (Gaurina-Međimurec & Mavar, 2019, p. 6). Giving an exact estimate of the current capture capacity of large-scale CCS is thus difficult, but safe to say, it appears to be in the ballpark of 30-40 million tonnes of CO2 per year. For the sake of simplicity, I will give the GCCSI the benefit of the doubt, and use the 37 MtCO2/yr number listed in a report from 2019 (GCCSI, 2019). As we shall see, many scenarios operate with total capturing capacities of 1 billion tonnes of CO2 per year or more. Thus, while a discrepancy of 6-7 million tonnes sounds like a lot, it will not really affect the reliability of the assessment presented in this thesis.

4.2.Negative Emission Technologies

This part will introduce various negative emission technologies. Here I will briefly introduce how they are meant to work and their current status. Many of these solutions are at very early stages of development A further discussion on uncertainties and challenges each technology is faced with will follow later in the thesis (section '6. Key challenges for the different technologies')

4.3.Bioenergy with CCS

Like most NETs described in this section, bioenergy with CCS (BECCS) is exactly what it sounds like. Namely, energy provided through biomass, with carbon capturing technologies capturing CO2 emissions from the energy production, before storing the captured CO2 in geological formations (Bui et al., 2018; Fuss et al., 2018; P. Smith & Friedmann, 2017). If the

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[7] According to the co2re-database (a CCS database operated by the GCSSI) 'large scale' CCS refers to facilities involving the "capture, transport, and storage of CO2 annually at a scale of at least 800,000 tonnes of CO2 annually for a coal–based power plant, or at least 400,000 tonnes of CO2 annually for other emissions–intensive industrial facilities (including natural gas–based power generation)." (Source: https://co2re.co/FacilityData)

[8] Data collected from https://co2re.co/FacilityData?fbclid=IwAR2QFlVMj1lsxyIg0q7poJH_H-g2YxFKsAtuqE0-fAkYbJpoATAwVZtU-vYon on the 2nd of March 2019.

[9] Data collected from https://co2re.co/FacilityData?fbclid=IwAR2QFlVMj1lsxyIg0q7poJH_H-g2YxFKsAtuqE0-fAkYbJpoATAwVZtU-vYon on the 2nd of March 2019

biomass used as feedstock for the bioenergy can be grown and provided with low or no emissions, the biomass will sequester more CO2 than its production releases. By capturing and storing the CO2 released when converting the biomass to energy, the system sequesters more CO2 overall than it emits, thus generating negative emissions (Bui et al., 2018; Fuss et al., 2018). The key premise and assumption is that the biomass will bind and sequester more CO2 over its lifetime than what is emitted through its production and conversion to bioenergy (Bui et al., 2018; Fuss et al., 2018). The actual capture and storage is done through ‘normal’ CCS, as outlined in the previous section.

Today, there is one large-scale BECCS facility, Illinois Industrial in Decatur, Illinois, USA (Bui et al., 2018; Nemet et al., 2018). Illinois Industrial has a sequestration capacity of approximately one million tons of CO2 per year (Bui et al., 2018; GCCSI, 2018; Nemet et al., 2018). Apart from Illinois Industrial there are five other smaller scale BECCS projects operating worldwide (Bui et al., 2018). None of these five projects remove more than 300.000 tons of CO2 per year (Nemet et al., 2018), and together they sequester approximately 850.000 tons CO2 per year (Bui et al., 2018). In terms of future projects, Nemet et al. notes “only one project in planning exceeds 1Mt CO2 yr” (Nemet et al., 2018, p. 4). These numbers may appear a bit abstract for now, but will be put in perspective later in the thesis (in section 5.3 ‘The use of NETs in Scenarios’ and section 6.2 ‘Key Challenges for BECCS’).

4.4. Afforestation

Afforestation, quite simply put, means planting more trees. In much of the scientific literature on the topic, afforestation refers to planting trees on land where there have not been trees for a long time, while reforestation refers to planting trees on areas which were deforested in more recent years (Fuss et al., 2018; P. Smith & Friedmann, 2017). However, as noted by Fuss et al. “the distinction between afforestation and reforestation is often not clean in the literature” (Fuss et al., 2018, p. 14). Their paper therefore “categorize them jointly” (Fuss et al., 2018, p. 14). This thesis will follow the same practice and will not distinguish between afforestation and reforestation.

Trees sequester CO2, thus, planting more of them can contribute to removing CO2 from the atmosphere, providing negative emissions (Fuss et al., 2018). While afforestation may not be much of a ‘technology’, it is one of the few NETs proven at scale (Nemet et al., 2018). However, while it is true that afforestation is a ‘technology’ which is ready for deployment, it’s worth noting that currently the global forest cover is decreasing not increasing. (UNEP, 2019).

4.5. Direct Air Capture

Unsurprisingly, direct air capture (DAC) refers to capturing CO2 from ambient air, and then transporting and storing it in the same way as ‘conventional’ CCS. The CO2 can be separated from the air both through physical and chemical processes (P. Smith & Friedmann, 2017). Today, some small scale DAC projects exist, for instance, a project in Switzerland which captures about 900 tonnes of CO2 per year and supplies the CO2 to a greenhouse (Bui et al., 2018; Nemet et al., 2018). There is also a small DAC facility connected to a thermal power plant in Reykjavik, Iceland (Nemet et al., 2018), but overall DAC is at a very early stage of development (Bui et al., 2018; Nemet et al., 2018)

4.6. Soil carbon sequestration

Soil carbon sequestration refers to changing land management and agricultural practices to increase the carbon content of soil (Fuss et al., 2018; P. Smith & Friedmann, 2017). By managing land in such a way that it increases CO2 input to the soil, or reduces CO2 losses from the soil, soil carbon sequestration can remove CO2 from the atmosphere. (Fuss et al., 2018; P. Smith & Friedmann, 2017). Examples of such practices are, “less invasive tillage with residue management, organic amendment, improved rotations/deeper rooting cultivars, optimized stocking density, fire management, optimized nutrient management and restoration of degraded lands” (P. Smith, 2016, p. 1316). As soil carbon sequestration relies as much on changing practices as on technology it is difficult to present its ‘current status,’ however, this also means it is a negative emissions solution which is “immediately deployable” (Fuss et al., 2018, p. 28).

4.7. Biochar

Biochar as a negative emissions solution refers to producing biochar through the pyrolysis of biomass and adding the produced biochar to soil. Since charcoal and other biochar is “resistant to decomposition and can stabilize organic matter” (P. Smith & Friedmann, 2017, p. 62), adding biochar to the soil can increase the CO2 storage potential of soil, much like other soil carbon sequestration techniques can (Fuss et al., 2018; P. Smith & Friedmann, 2017).

4.8. Enhanced weathering

Enhanced weathering is a negative emission solution focused on enhancing the natural weathering rocks. Weathering, in this case, refers to “the natural process of rock decomposition via chemical and physical processes.” (Fuss et al., 2018, p. 20). The weathering of rocks can bind CO2 from the atmosphere, and enhanced weathering, simply put, are solutions aimed at speeding up this process to provide negative emissions (P. Smith & Friedmann, 2017; Strefler, Amann, Bauer, Kriegler, & Hartmann, 2018). Today, enhanced weathering remains a largely theoretical solution (Fuss et al., 2018)

4.9. Ocean alkalinisation

Increasing the alkalinity of the ocean enhances the amount of carbon it can store (P. Smith & Friedmann, 2017). This could theoretically be done in different ways (releasing calcium ions in the ocean, electrolysis of sea water, weathering of minerals) (P. Smith & Friedmann, 2017). However, ocean alkalinisation has received little attention, and costs and potential side-effects are poorly understood (Fuss et al., 2018).

4.10. Ocean Fertilization

Not surprisingly, ocean fertilization refers to fertilizing the oceans to create algal bloom, which again leads to sequestration of carbon (Fuss et al., 2018). This could be achieved by adding nutrients such as iron, nitrogen, or phosphorus to the oceans (de Coninck et al., 2018). There have been experiments with ocean fertilization, but like most other NETs it remains at a very early stage of development, and comes with a wide range of uncertainties (Fuss et al., 2018; Nemet et al., 2018).

Having briefly presented the various technologies, I will now move on to presenting the data on CCS and NETs in SR15 scenarios.

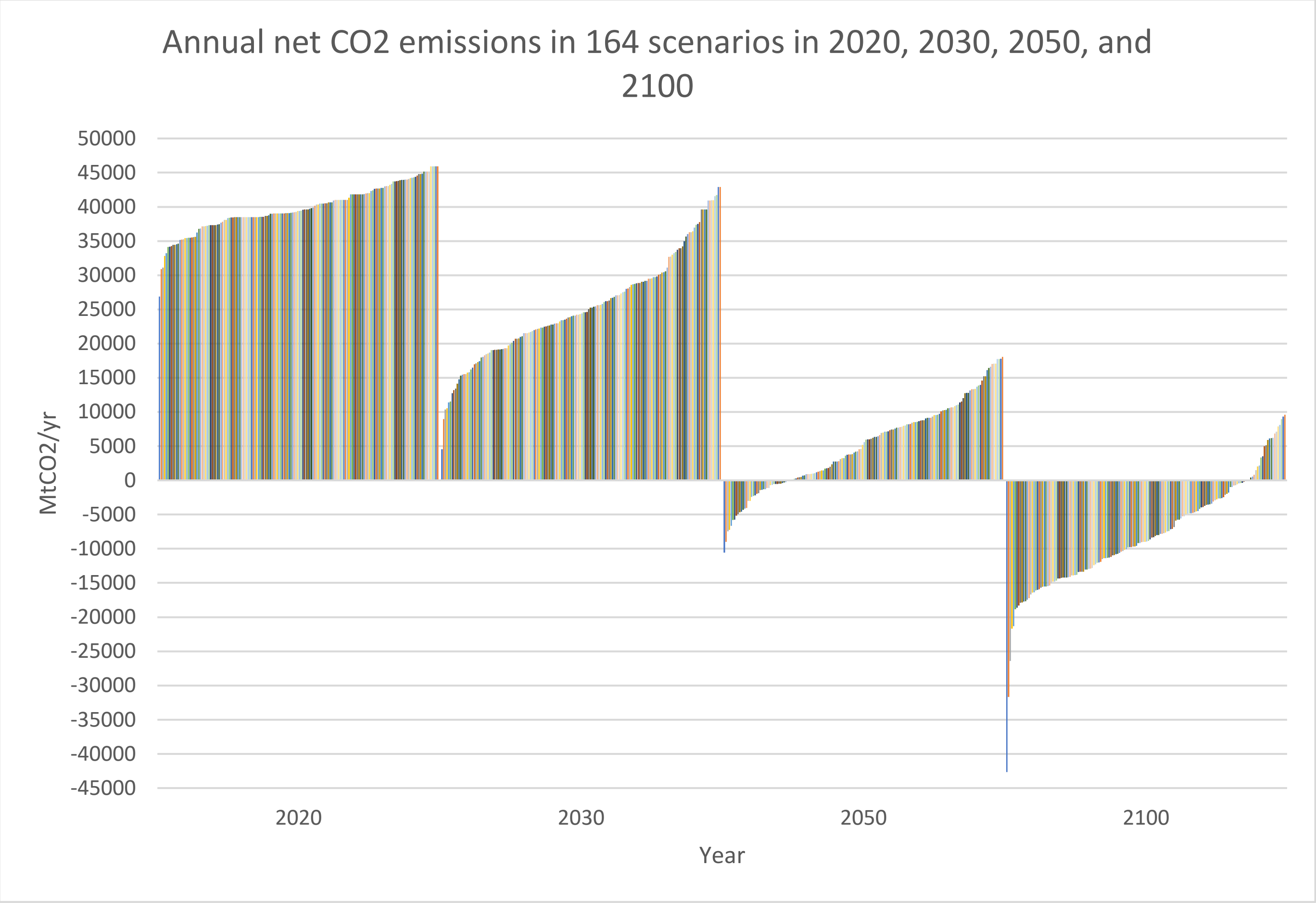
5. Data of the scenarios

This section will present data from the mitigation scenarios in the IPCC’s Special Report on the 1.5 °C target (SR15), focusing on the use of negative emission technologies (NETs) and carbon capture and storage (CCS). It will present how their use varies across scenarios, but also the speed and scale of the build-out of these technologies envisioned in most scenarios. For the data from SR15, this section relies both on the Special Report itself, as well as the ‘IAMC 1.5 °C Scenario Explorer hosted by IIASA’. As outlined in the methods section of this thesis, this database contains the "consolidated scenario data supporting the IPCC SR1.5 assessment" (Huppmann, Rogelj, et al., 2018, p. 1027), which specifically "ensures the reproducibility and transparency of scenario assessments, but also allows for the reuse of scenario data by other research communities." (Huppmann, Rogelj, et al., 2018, p. 1027). The data presented in this section relies on the 164 scenarios in the database with a greater than 66 percent chance of staying below 2 °C. This includes 90 scenarios considered consistent with the 1.5 °C target (Huppmann, Kriegler, et al., 2018; Rogelj, Shindell, et al., 2018). Only 9 of the scenarios consistent with the 1.5 °C target achieve this with a 50–66% chance of remaining below the 1.5 °C target for the entire 21st century. The remaining 81 scenarios considered consistent with the 1.5 °C target has greater than 50% chance of temperatures first temporarily overshooting the target, before being brought back to temperature levels consistent with the 1.5 °C temperature target through negative emissions (Huppmann, Kriegler, et al., 2018; Rogelj, Shindell, et al., 2018). The following paragraphs may appear a bit intimidating and difficult to read, but it is a necessary step to understand the scale of CCS and NETs (mostly BECCS) in most scenarios.

5.1.Overview of emission trajectories in SR15 scenarios

Before looking at the use of the specific technologies, it is worth taking a quick look at how total CO2 emission trajectories vary and develop between the 164 scenarios consistent with a 66% of staying below 2 °C. Currently, CO2 emissions are approximately 42 billion tonnes per year (IPCC, 2018b). Between 2008 and 2017, fossil emissions have grown by an average of approximately 1.5% per year (Le Quéré et al., 2018). Fossil emission in 2018 have been estimated to be more than 2% higher than in 2017 (Le Quéré et al., 2018). In short, emissions are high and still rising. As we shall see, this is not entirely in line with the trajectory in most SR15 scenarios.

Figure 1*: The following graph shows the net CO2 emissions in each of the 164 scenarios in 2020, 2030, 2050, and 2100. Net emissions are measured in millions of tonnes of CO2 per year. The scenarios are sorted from the lowest to the highest net emissions in each of the years, and the colour and position of each scenario may change between the years. As such, this graph should be read as an overview of how emissions develop across the full range of scenarios between the years. It cannot be used to track developments in individual scenarios. Data source: (Huppmann, Kriegler, et al., 2018).*



In the median scenario, of the 164 scenarios consistent with a 66% chance of limiting warming to 2 °C or less, annual emissions have sunk to 24.3 billion tonnes of CO2 in 2030. That's a decrease of about 42% from current levels – and the equivalent of reducing annual global emissions by 1.77 GtCO2/yr per year[10] of the coming decade. However, CO2 emissions vary greatly across scenarios in 2030. They range from 4.5 – 42.9 GtCO2/yr, i.e. from status quo in 2030 to a 90% decrease by the same year. 127 of 164 scenarios have emissions below 30 GtCO2/yr in 2030 (Huppmann, Kriegler, et al., 2018).

By 2050, all 164 scenarios have more than halved annual emissions compared to the current level. The emissions range from -10.5 – 18 GtCO2/yr. 38 of the 164 scenarios have net-negative emissions by mid-century. The median across all 164 scenarios is 5.4 GtCO2/yr

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[10] Yes, you read that right, and /yr per year is not a typo, as annual emissions (/yr) must decrease by 1.77 every year (per year).

emitted in 2050, while the median for the 90 scenarios consistent with 1.5 °C has dropped below one billion tonnes, to 0.91 GtCO2/yr.

Before looking at emissions in 2100, it is worth noting that already by 2060 more than half the scenarios (84) have net-negative emissions, and the median scenario has -0.1 GtCO2/yr, thus removing 100 million tonnes of CO2 from the atmosphere per year (Huppmann, Kriegler, et al., 2018).

Finally, in 2100, emissions range from -42.6 – 9.5 GtCO2/yr. Put another way, in 2100 annual emissions range from one-fourth of current emissions, to scenarios where we remove the same amount of CO2 from the atmosphere as we currently emit. By the end of the century, the median has dropped to -8.9 GtCO2/yr, and 141 of 164 scenarios have net-negative emissions (Huppmann, Kriegler, et al., 2018).

It is important to remember that most scenarios employ some sort of NETs to reduce emission even before their total reach net-negative emissions. This should become clear in section 5.3, which presents the use of NETs (mainly BECCS) in scenarios. But first, the following section will present the use of CCS in scenarios.

5.2. CCS in SR15 scenarios

The following data stems from the 148 scenarios consistent with a 66% chance of staying within 2 °C with data on ‘Total CCS’ in the IAMC 1.5 °C scenario database. Across these 148 scenarios, the annual CCS capacity ranges from 0 – 7.6 billion tonnes CO2 captured per year (GtCO2/yr) in 2030 (Huppmann, Kriegler, et al., 2018). From 0 – 28.3 GtCO2/yr in 2050, and from 0 – 41.3 GtCO2/yr in 2100 (Huppmann, Kriegler, et al., 2018). This means the annual CCS capacity in 2100 ranges from less than today to more than 1000 times our current capacity of approximately 0.037 billion tonnes per year (GCCSI, 2017, 2019; Huppmann, Kriegler, et al., 2018). While looking at the full range highlights that there still are different pathways to 1.5 °C and 2 °C, it does not paint a very clear picture – nor does it tell us much about the full extent of the use of CCS in scenarios, other than that the use varies. It is, therefore, necessary to break down the numbers further. It is important, however, to keep the following advice in mind when reading the coming sections of this thesis:

> “*Don’t interpret the scenario ensemble as a statistical sample or in terms of likelihood/agreement in the literature.* A number of scenarios show that limiting global warming to 1.5 °C can be achieved without the deployment of BECCS, while the majority of scenarios use it. This information by itself does not imply that reaching ambitious climate

> goals is less likely without BECCS — instead, it shows that pathways with and without BECCS exist for implementing the goals of the Paris Agreement, highlighting that different societal preferences and strategies can result in vastly different outcomes.” (Huppmann, Rogelj, et al., 2018, p. 1029)

What the above citation highlights is that just because, as will become clear, most scenarios deploy CCS ‘this information by itself does not imply that reaching ambitious climate goals is ‘less likely’ without CCS. With this important caveat in mind, let us break down the use of CCS in scenarios a bit further.

As alluded to earlier, reading the following paragraphs may require a bit of concentration. To make this section more readable, a summary will round off each sub-section. These summaries will also try to make the size of these numbers clearer by putting them in perspective and pointing out what they would mean in the real world.

5.2.1. CCS in scenarios in 2030

Annual capacity in 2030 (GtCO2/yr)	Number of scenarios
0	3
Less than 0.100	4
0.100 – 0.499	41
0.500 - 0.999	28
1 – 1.9999	30
2 – 2.9999	24
3 – 4.6	16
More than 5	2
0.9746	Median

In 2030 the median CCS sequestration capacity across the 148 scenarios is just shy of one billion tonnes of CO2 a year (0.9746 GtCO2/yr). There are three scenarios with zero CCS in 2030. Of the 148 scenarios, seven scenarios require less than 100 million tonnes of CO2 sequestered per year through CCS in 2030, 69 scenarios require between 100 million and 1 billion, and 72 scenarios require more than 1 billion tonnes captured and stored through CCS (Huppmann, Kriegler, et al., 2018).

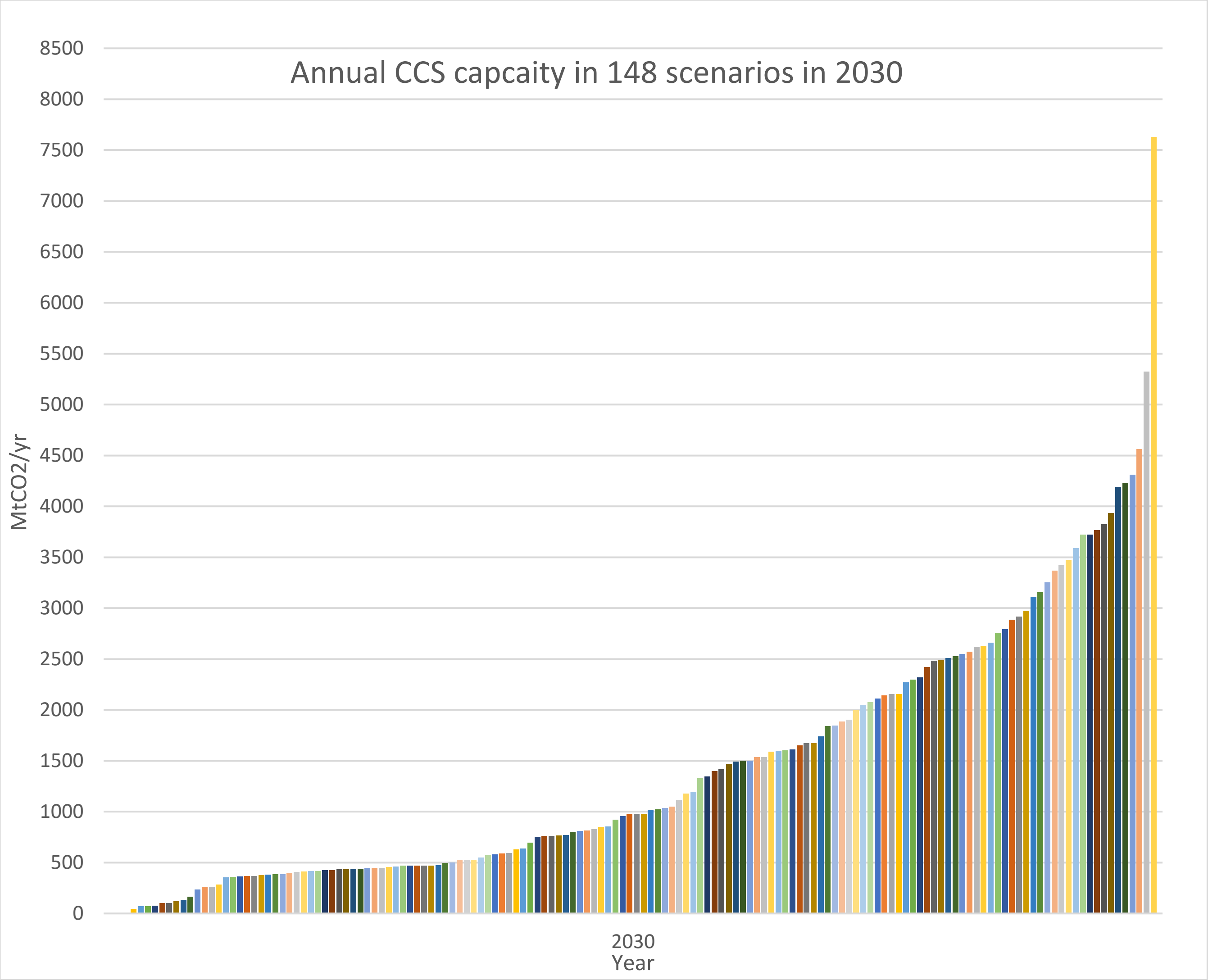
Given the SR15’s focus on the different climate impacts between 1.5 °C and 2 °C of global warming (IPCC, 2018b), it’s worth taking a look at the difference in CCS deployment between scenarios consistent with the 1.5 °C and 2 °C targets. Of the 148 scenarios, 85 scenarios are consistent with a more than 50% chance of limiting warming to 1.5 °C (including scenarios which first overshot the target), the remaining 63 are consistent with a

66% chance of limiting global warming to 2 °C above pre-industrial temperatures. (Huppmann, Kriegler, et al., 2018).

In SR15 scenarios consistent with a 50% chance or more of staying within 1.5 °C (including scenarios overshooting the target) the CCS use in 2030 ranges from 0 to 7.6 billion tonnes per year (GtCO2/yr), with a median of 1.1 GtCO2/yr. (Huppmann, Kriegler, et al., 2018).

In SR15 scenarios consistent with a 66% chance of limiting global warming to 2 °C the CCS use in 2030 ranges from 0 to 4.56 GtCO2/yr, with a median of 0.77 GtCO2/yr (772 MtCO2/yr) (Huppmann, Kriegler, et al., 2018).

Figure 2: *The following graph shows the CCS sequestration capacity in all 148 scenarios in 2030. Sequestration capacity is measured in millions of tonnes of CO2 per year. Similar graphs are presented for 2050 and 2100. Please note that the scenarios are sorted from the lowest to the highest sequestration capacity in each of the years, and the colour and position of each scenario may change between the graphs. As such, these graphs should be read as an overview of the sequestration capacity across the scenarios in each of the years. They cannot be used to track developments in individual scenarios. Data source: (Huppmann, Kriegler, et al., 2018).*



To summarize, 145 of the 148 scenarios use CCS as a mitigation measure in 2030. The median scenario has a CCS capacity just shy of one billion tonnes of CO2 a year (0.97 GtCO2/yr) in 2030. This equals an increase in CCS capacity by a factor of approximately 26 between 2019 and 2030[11] (GCCSI, 2017, 2019; Huppmann, Kriegler, et al., 2018). Only 6 scenarios have less than double our current CCS capacity in 2030. In the vast majority, 128 of 148 scenarios, the CCS capacity is at least ten times higher in 2030 than it is today (GCCSI, 2017, 2019; Huppmann, Kriegler, et al., 2018).

Let us put these numbers in perspective. Today there are 18 large-scale CCS facilities. The CO2RE database lists 25 additional large-scale facilities in various stages of development. The cumulative annual capture capacity of all 43 facilities adds up to 70-80 million tonnes per year[12]. This includes several projects (16) in early development, these facilities list estimated operation dates ranging from '2020-2021', via '2020s', to as late as '2028'[13]. Thus, if no new facilities were planned, and all currently planned CCS projects were to start operating on time with planned capacity, the global annual capturing capacity in 2028 would still be more than ten times short of the 2030 capacity in the median scenario. The same 2028 capacity would be less than half of the 2030 capacity in 137 of 148 scenarios. To put these numbers in even further perspective, the average capture capacity of the 43 current and planned large-scale CCS facilities in the CO2RE database is 1.69 - 1.94 MtCO2/yr. Thus, the capacity in the median 2030 scenario (974 million tonnes CO2 per year), is the equivalent of ~502 average CCS facilities[14]. That is more than ten times the facilities currently planned or operating, and the equivalent of opening 0.93 extra facilities every week between 2020 and 2030[15]. Since, as the IEA notes, "large-scale CCS projects can take as long as a decade to commission" (IEA, 2016, p. 71) the annual capture capacity in 2030 is likely to be decided over the next few years. Safe to say, to be on the path to follow the 2030 trajectory of the vast majority of SR15 scenarios, CCS would need an urgent and significant push.

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[11] Own calculation: 974 MtCO2/yr / 37 MtCO2/yr = 26.32.

[12] Data collected from https://co2re.co/FacilityData?fbclid=IwAR2QFlVMj1lsxyIg0q7poJH_H-g2YxFKsAtuqE0-fAkYbJpoATAwVZtU-vYon on the 4th of March 2019

[13] Data collected from https://co2re.co/FacilityData?fbclid=IwAR2QFlVMj1lsxyIg0q7poJH_H-g2YxFKsAtuqE0-fAkYbJpoATAwVZtU-vYon on the 4th of March 2019

[14] Own calculation: 974 MtCO2/yr / 1.94 MtCO2/yr = 502.06

[15] Own calculation: 974 MtCO2/yr - 37 MtCO2/yr = 937 MtCO2/yr. 937 MtCO2/yr/ 1.94 MtCO2/yr = 482.98 facilities. 52 weeks * 10 years = 520 weeks. 492.98 facilities / 520 weeks = 0.9288 facilities/week

5.2.2. CCS in scenarios in 2050

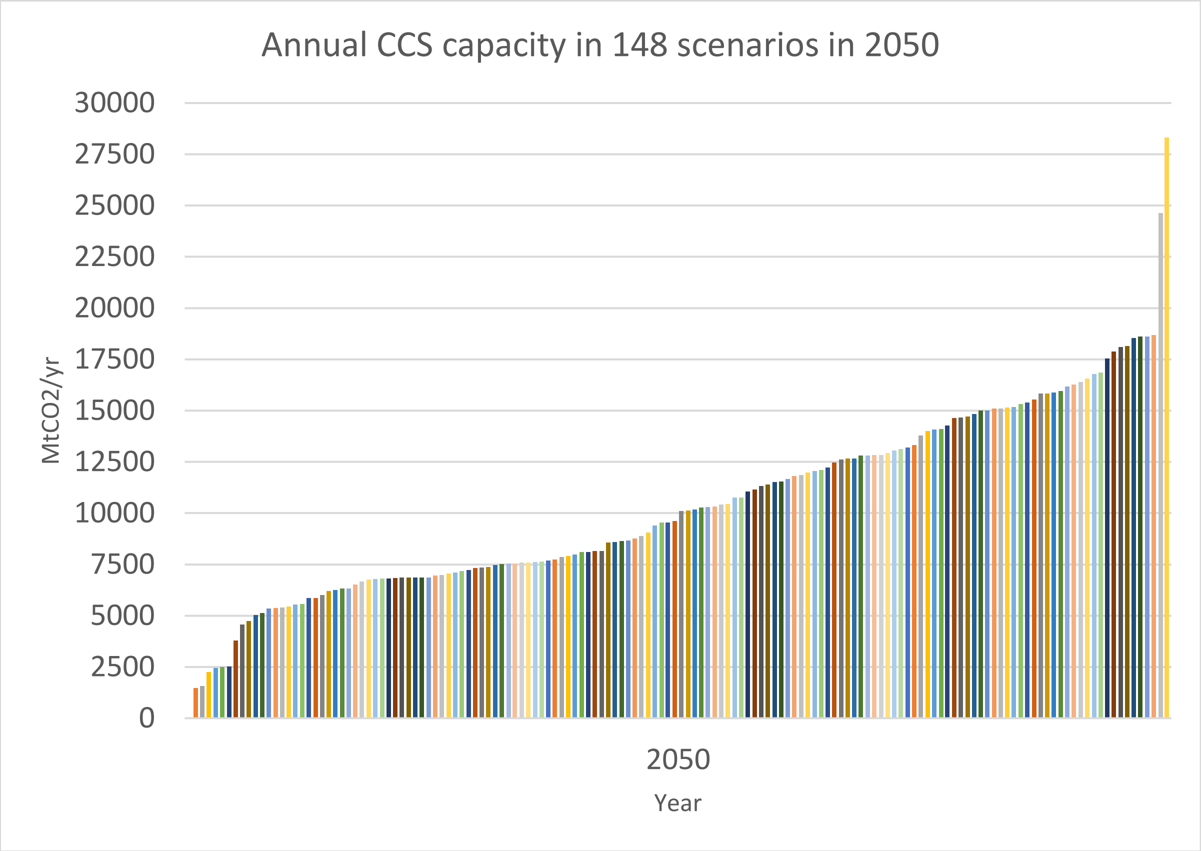
Annual capacity in 2050 (GtCO2/yr)	**Number of scenarios**
0	1
0.001 – 1.399	0
1.400 – 1.999	2
2 – 4.999	7
5 – 9.9999	64
10 – 14.9999	47
15 – 19.999	25
More than 20	2
9.862	Median

In 2050 the median capacity is just below ten billion tonnes of CO2 sequestered through CCS per year (9.862 GtCO2/yr), about ten times higher than it was in 2030. There is only one scenario with zero CCS in 2050. No other scenario has less than 1.4 billion tonnes sequestered per year by mid-century (Huppmann, Kriegler, et al., 2018).

In SR15 scenarios consistent with a 50% chance or more of staying within 1.5 °C (including scenarios overshooting the target) the CCS use in 2050 ranges from 0 to 28.3 GtCO2/yr, with a median of 10.766 GtCO2/yr. (Huppmann, Kriegler, et al., 2018).

In SR15 scenarios consistent with a 66% chance of limiting global warming to 2 °C the CCS use in 2050 ranges from 2.4 to 24.6 GtCO2/yr, with a median of 7.91 GtCO2/yr (Huppmann, Kriegler, et al., 2018).

Figure 3: *The following graph shows the CCS sequestration capacity in all 148 scenarios in 2050. Sequestration capacity is measured in millions of tonnes of CO2 per year. Similar graphs are presented for 2030 and 2100. Please note that the scenarios are sorted from the lowest to the highest sequestration capacity in each of the years, and the colour and position of each scenario may change between the graphs. As such, these graphs should be read as an overview of the sequestration capacity across the scenarios in each of the years. They cannot be used to track developments in individual scenarios. Data source: (Huppmann, Kriegler, et al., 2018).*



To summarize, 147 of the 148 scenarios use CCS as a mitigation measure in 2050. The median scenario has a CCS capacity of 9.862 GtCO2/yr in 2050, equalling an increase in CCS capacity by a factor of approximately 266.54 between 2019 and 2050[16] (GCCSI, 2017, 2019; Huppmann, Kriegler, et al., 2018). Only one scenario has an annual capacity of less than 1.4 billion tonnes in 2050 (Huppmann, Kriegler, et al., 2018). To go from current capacity to the 2050 median is the equivalent of building 5064 average CCS facilities between today and 2050[17], or 3.25 average facilities every week between 2020 and mid-century[18]. Only 7 of the 148 scenarios has a CCS capacity of less than 100 times our current capacity in 2050 (GCCSI, 2017, 2019; Huppmann, Kriegler, et al., 2018). To put the median number of 9.862 GtCO2/yr in perspective, consider this from Mac Dowell et al.:

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[16] Own calculation: 9862 MtCO2/yr / 37 MtCO2/yr = 266.54

[17] Own calculation: 9862 MtCO2/yr – 37 MtCO2/yr = 9825 MtCO2/yr.
9825 MtCO2/yr / 1.94 MtCO2/yr = 5064.43.

[18] Own calculation: 52 weeks * 30 years = 1560 weeks. 5064.43 facilities / 1560 weeks = 3.246 facilities/week

> “in 2050 the CCS industry will need to be larger by a factor of 2–4 in volume terms than the current global oil industry. In other words, we have 35 years to deploy an industry that is substantially larger than one which has been developed over approximately the last century, resulting in the sequestration of 8–10 GtCO2 per annum by 2050” (Mac Dowell, Fennell, Shah, & Maitland, 2017, p. 244)

5.2.3. CCS in scenarios in 2100

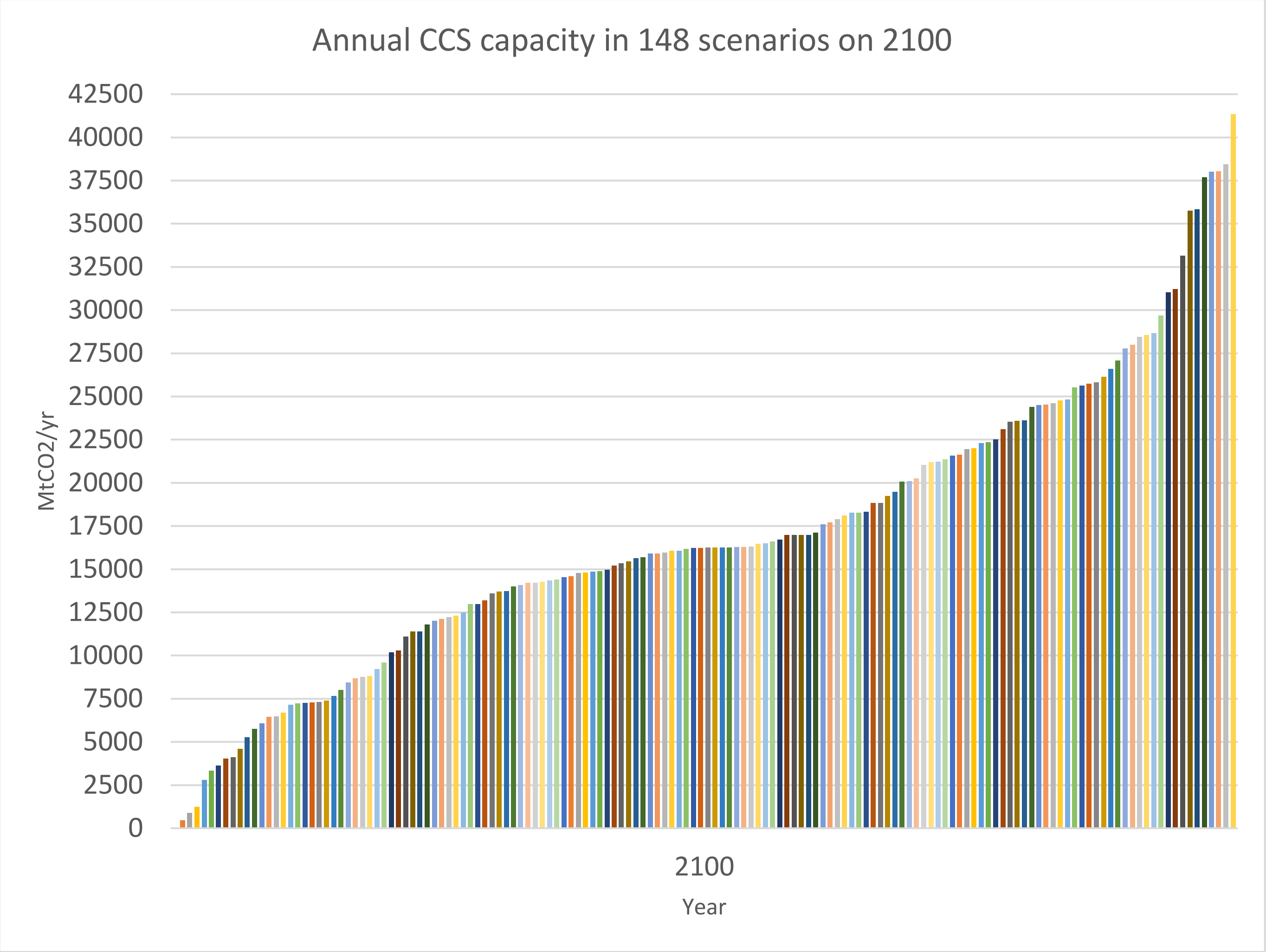
Annual capacity in 2100 (GtCO2/yr)	Number of scenarios
0	1
0.01 – 1.999	3
2 – 4.999	6
5 – 9.999	20
10 – 14.9999	31
15 – 19.9999	40
20 – 24.999	24
25 – 29.999	13
30 – 39.999	9
More than 40	1
16.228	Median

Finally, at the turn of the century, the median CCS carbon sequestration capacity is just above 16 billion tonnes per year (16.228 GtCO2/yr). Just like in 2050, Grubler et al.’s ‘Low Energy Demand’ scenario (Grubler et al., 2018) is the only one without any CCS (Huppmann, Kriegler, et al., 2018). A few scenarios have started scaling down CCS by 2100, meaning we have two other scenarios with a capacity of less than one billion tonnes in 2100 (compared to no other scenarios in 2050). However, only ten scenarios have an annual capacity of less than 5 billion tonnes in 2100 (Huppmann, Kriegler, et al., 2018).

In SR15 scenarios consistent with a 50% chance or more of staying within 1.5 °C (including scenarios overshooting the target) the CCS use in 2100 ranges from 0 to 38 GtCO2/yr, with a median of 16.251 GtCO2/yr. (Huppmann, Kriegler, et al., 2018).

In SR15 scenarios consistent with a 66% chance of limiting global warming to 2 °C the CCS use in 2100 ranges from 0.447 to 41.3 GtCO2/yr, with a median of 15.895 GtCO2/yr (Huppmann, Kriegler, et al., 2018).

Figure 4: *The following graph shows the CCS sequestration capacity in all 148 scenarios in 2100. Sequestration capacity is measured in millions of tonnes of CO2 per year. Similar graphs are presented for 2030 and 2050. Please note that the scenarios are sorted from the lowest to the highest sequestration capacity in each of the years, and the colour and position of each scenario may change between the graphs. As such, these graphs should be read as an overview of the sequestration capacity across the scenarios in each of the years. They cannot be used to track developments in individual scenarios. Data source: (Huppmann, Kriegler, et al., 2018).*



To summarize, 147 of the 148 scenarios use CCS as a mitigation measure in 2100. The median scenario has a CCS capacity of 16.228 GtCO2/yr in 2100, equalling an increase in CCS capacity by a factor of approximately 439 between 2018 and 2100[19] (GCCSI, 2017, 2019; Huppmann, Kriegler, et al., 2018). Five scenarios have an annual CCS capacity more than 1000 times higher in 2100 than our current capacity. To go from current capacity to the 2100 median is the equivalent of building 8346 average CCS facilities between today and

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[19] Own calculation: 16228.72 MtCO2/yr / 37 MtCO2/yr = 438.61

2100[20], or two average facilities every week between 2020 and 2100[21] (GCCSI, 2017, 2019; Huppmann, Kriegler, et al., 2018).

This section has offered an overview of the use of CCS in SR15 mitigation scenarios. It has shown how most scenarios rely on CCS at a very large scale. The coming sections will present the use of negative emission technologies in the same scenarios.

5.3. The use of NETs in Scenarios

Before looking at the actual data of the use of NETs – or 'carbon dioxide removal' (CDR) – in SR15 scenarios, it might be good to take short break from numbers and look at what the special report itself has to say on the issue. As the SR15 notes in chapter 2, "all analysed pathways limiting warming to 1.5°C with no or limited overshoot use CDR [carbon dioxide removal]" (Rogelj, Shindell, et al., 2018, p. 96), before it points out how "some pathways rely more on bioenergy with carbon capture and storage (BECCS), while others rely more on afforestation, which are the two CDR methods most often included in integrated pathways" (Rogelj, Shindell, et al., 2018, p. 96). The SR15 further highlights the two ways NETs can be used in mitigation scenarios, namely (1) to help bring down emissions faster, and (2) to ensure net negative emission (Rogelj, Shindell, et al., 2018).

The following sections will focus mostly on BECCS, as it is by far the most common negative emission technology employed in scenarios, but a brief overview of the use of other NETs in scenarios will also be provided. Importantly, however, the SR15 notes "as additional CDR [carbon dioxide removal] measures are being built into IAMs, the prevalence of BECCS is expected to be further reduced." (Rogelj et al., 2018, p. 122.) Meaning, as direct air capture and other NETs and CDR measures get baked into the models behind these scenarios, we can expect the reliance of BECCS to fall in future and upcoming scenarios. Put another way, don't be surprised if the IPCC 6th Assessment Report – expected in 2022 – has more scenarios with direct air capture and other measures, and that – all else equal – total BECCS may be lower in many of the AR6 scenarios. With that in mind, let us take a look at the use of BECCS in SR15 scenarios.

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[20] Own calculation: 16228.72 MtCO2/yr – 37 MtCO2/yr = 16191.72 MtCO2/yr
16191.72 MtCO2/yr / 1.94 MtCO2/yr = 8346.247 facilities

[21] Own calculation: 52 weeks * 80 years = 4160 weeks. 8346.25 facilities / 4160 weeks = 2.00 facilities/week

5.3.1. BECCS in SR15 scenarios

As previously mentioned, the following data stems from the 150 scenarios in the IAMC 1.5 °C scenario database (Huppmann, Kriegler, et al., 2018) consistent with a 66% chance of limiting global warming to 2 °C and with data on 'total CCS w/biomass'.

5.3.2. BECCS in scenarios in 2030

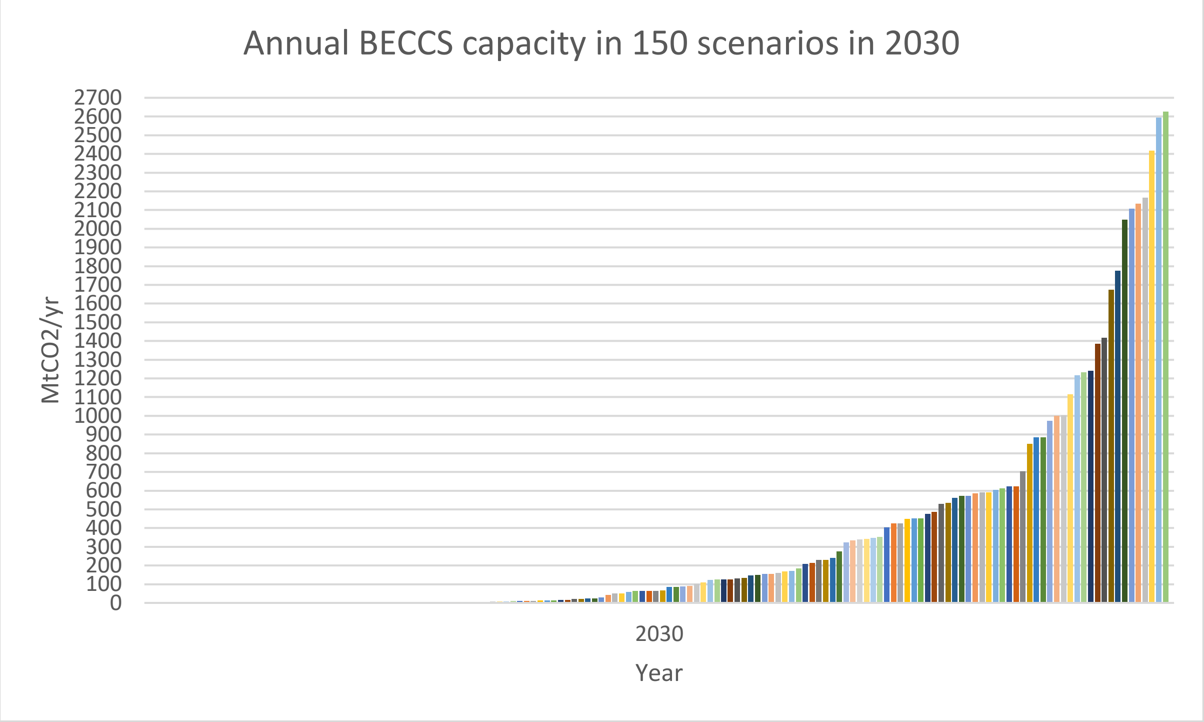
Annual capacity in 2030 (GtCO2/yr)	Number of scenarios
0 – 0.001 (Less than 1 million tonnes/yr)	27
0.001 – 0.01 (1 million to 10 million/yr)	30
0.01 – 0.099	24
0.1 – 0.49	35
0.5 – 0.99	17
1 – 1.99	10
2 – 2.7	7
0.065	Median

The use of BECCS in 2030 ranges from 0 – 2.6 GtCO2 sequestered per year. The median amount of CO2 sequestered through biomass with CCS per year in 2030 is 65 million tonnes. 81 scenarios have a BECCS capacity lower than 100 million tonnes per year. 52 scenarios sequester between 100 million and 1 billion tonnes per annum, and 17 scenarios sequester more than 1 GtCO2/yr (Huppmann, Kriegler, et al., 2018).

In SR15 scenarios consistent with a 50% chance or more of staying within 1.5 °C (including scenarios overshooting the target) the BECCS use in 2030 ranges from 0 – 2.59 GtCO2/yr, with a median of 100 million tonnes a year (0.09999 GtCO2/yr). (Huppmann, Kriegler, et al., 2018).

In SR15 scenarios consistent with a 66% chance of limiting global warming to 2 °C the BECCS use in 2030 ranges from 0 – 2.6 GtCO2/yr, with a median of 41 million tonnes captured a year (0.041 GtCO2/yr) (Huppmann, Kriegler, et al., 2018).

__Figure 5:__ The following graph shows the BECCS sequestration capacity in all 150 scenarios in 2030. Sequestration capacity is measured in millions of tonnes of CO2 per year. Similar graphs are presented for 2050 and 2100. Please note that the scenarios are sorted from the lowest to the highest sequestration capacity in each of the years, and the colour and position of each scenario may change between the graphs. As such, these graphs should be read as an overview of the sequestration capacity across the scenarios in each of the years. They cannot be used to track developments in individual scenarios. Data source: (Huppmann, Kriegler, et al., 2018).



To summarize, BECCS use in 2030 varies greatly, but the median capacity is 65 million tonnes of CO2 sequestered through BECCS per year. To put that number in perspective, Illinois Industrial in Decatur, Illinois, USA is the first and only large scale BECSS facility currently in operation (Nemet et al., 2018). It removes approximately 1 million tonnes of CO2 a year (GCCSI, 2018; Nemet et al., 2018). Thus, the maths are pretty simple, reaching the median BECCS capacity in 2030 equals building approximately 64 more Illinois Industrial plants between today and 2030. If we include current smaller scale BECCS capacity in the calculation, that number changes to approximately 63 more Illinois Industrial plants. As far as new large-scale BECCS projects go, “only one project in planning exceeds 1Mt CO2 yr” (Nemet et al., 2018, p. 4).

5.3.3. BECCS in scenarios in 2050

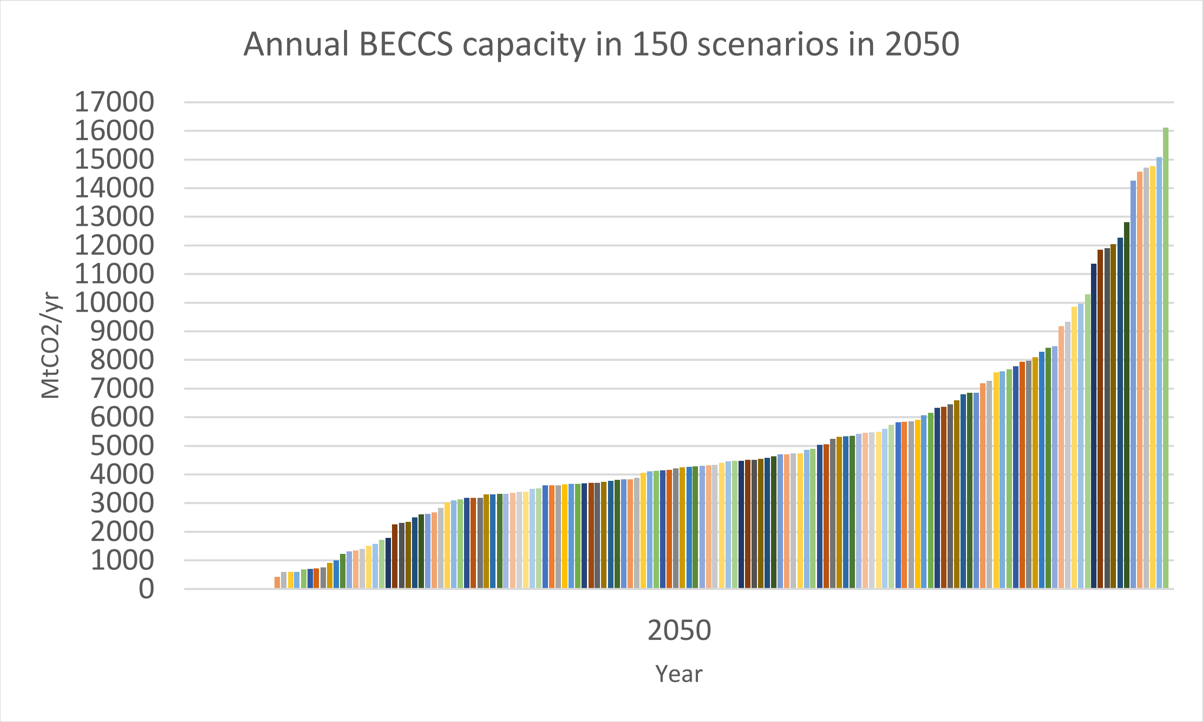
Annual capacity in 2050 (GtCO2/yr)	Number of scenarios
0	8
More than 0, but less than 1 million tonnes/yr	5
0.4 – 0.99	10
1 – 2.99	16
3 – 3.99	30
4 – 4.99	27
5 – 5.99	16
6 – 6.99	9
7 – 9.99	16
10 – 16.1	13
4.229	Median

In 2050, the use of BECCS in the 150 scenarios ranges from 0 – 16.1 GtCO2/yr. The median is 4.2 billion tonnes of CO2 sequestered through BECCS per year. 23 scenarios have a capacity of less than one billion tonnes, 73 sequester between one and 5 billion tonnes, 41 between five and ten, and, 13 scenarios have us sequestering more than ten billion tonnes through BECCS in 2050 (Huppmann, Kriegler, et al., 2018).

In SR15 scenarios consistent with a 50% chance or more of staying within 1.5 °C (including scenarios overshooting the target) the BECCS use in 2050 ranges from 0 – 16.1 GtCO2/yr, with a median of 4.7 billion tonnes a year (Huppmann, Kriegler, et al., 2018).

In SR15 scenarios consistent with a 66% chance of limiting global warming to 2 °C the BECCS use in 2050 ranges from 0 – 7.7 GtCO2/yr, with a median of 3.6 billion tonnes captured a year (Huppmann, Kriegler, et al., 2018).

__Figure 6:__ The following graph shows the BECCS sequestration capacity in all 150 scenarios in 2050. Sequestration capacity is measured in millions of tonnes of CO2 per year. Similar graphs are presented for 2030 and 2100. Please note that the scenarios are sorted from the lowest to the highest sequestration capacity in each of the years, and the colour and position of each scenario may change between the graphs. As such, these graphs should be read as an overview of the sequestration capacity across the scenarios in each of the years. They cannot be used to track developments in individual scenarios. Data source: (Huppmann, Kriegler, et al., 2018).



To summarize, while the median in 2030 was ‘only’ 65 million tonnes sequestered through BECCS per year, by 2050 it has risen to 4.2 billion tonnes per year. The median scenario in 2050 thus requires an increase in BECCS capturing capacity equalling 4199 Decatur-scale facilities over the next 31 years. That equals opening 139.96 facilities per year, or 2.69 facilities per week between 2020 and 2050[22]. Or, as Nemet et al. put it:

> “Scaling up 1Mt of a specific NET in 2020 to 1Gt in 2050, average deployment growth rates of 26% must be sustained for 30 years. Such a scale of growth had been observed for other technologies before, in particular solar PV, but is nonetheless extremely challenging.” (Nemet et al., 2018, p. 4).

Of course, only 23 scenarios capture 1 GtCO2/yr or less in 2050, and 119 of 150 scenarios capture more than 2 GtCO2/yr. Moreover, as we shall see in coming sections of this thesis, BECCS comes with certain challenges which might make growth rates equalling solar PV ‘extremely challenging’ indeed.

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[22] 4199/30 =139.96. 4199/1560= 2.69

5.3.4. BECCS in scenarios in 2100

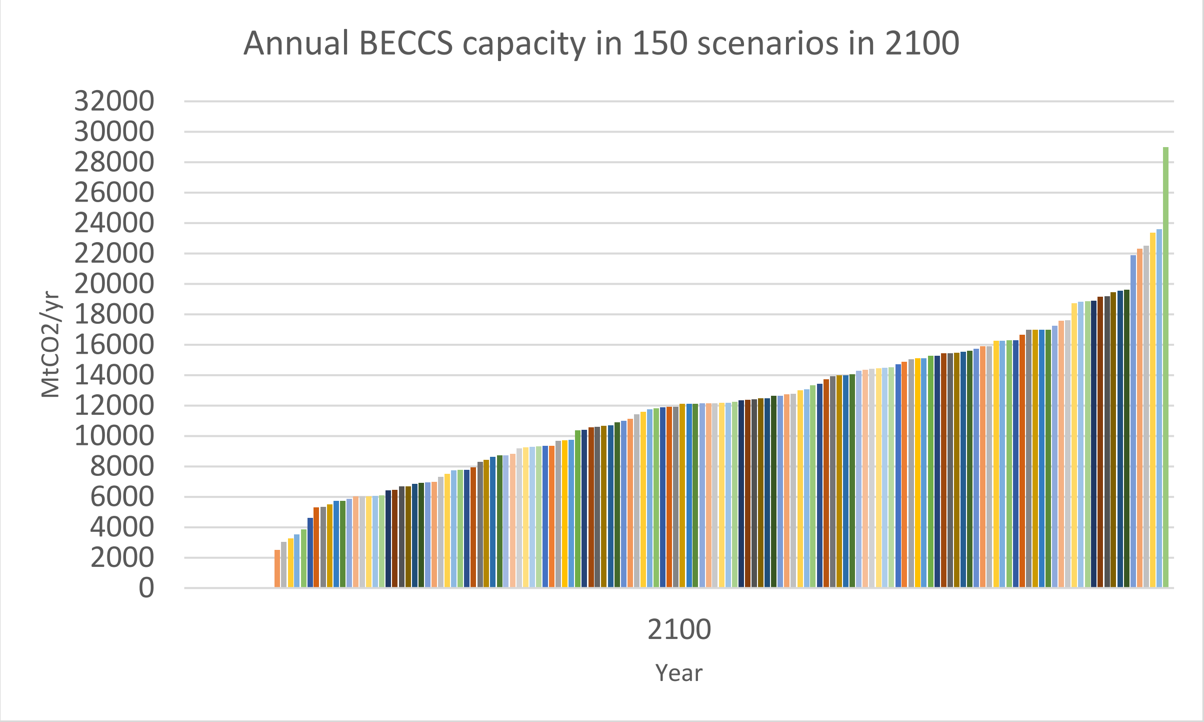
Annual capacity in 2100 (GtCO2/yr)	Number of scenarios
0	8
More than 0, but less than 1 million tonnes/yr	5
2.5 – 4.99	6
5 – 6.99	19
7 – 9.99	21
10 – 11.99	16
12 – 13.99	26
14 – 15.99	22
16 – 19.99	21
20 – 29	6
12	Median

At the end of the century, BECCS sequestration ranges from 0 – 28.9 GtCO2/yr. The median scenario sequesters 12 billion tonnes CO2 through BECCS in 2100. Only 13 scenarios have a capturing capacity below one billion tonnes in 2100, and only an additional six scenarios sequester less than five billion tonnes. 40 scenarios sequester between five and ten billion tonnes, 85 scenarios capture between 10 and 20, and six scenarios sequester more than 20 billion tonnes CO2 per year with BECCS in 2100 (Huppmann, Kriegler, et al., 2018).

In SR15 scenarios consistent with a 50% chance or more of staying within 1.5 °C (including scenarios overshooting the target) the BECCS use in 2100 ranges from 0 – 28.9 GtCO2/yr, with a median of 12.77 billion tonnes a year (Huppmann, Kriegler, et al., 2018).

In SR15 scenarios consistent with a 66% chance of limiting global warming to 2 °C the BECCS use in 2100 ranges from 0 – 23.6 GtCO2/yr, with a median of 9.67 billion tonnes sequestered a year (Huppmann, Kriegler, et al., 2018).

Figure 7: *The following graph shows the BECCS sequestration capacity in all 150 scenarios in 2100. Sequestration capacity is measured in millions of tonnes of CO2 per year. Similar graphs are presented for 2030 and 2050. Please note that the scenarios are sorted from the lowest to the highest sequestration capacity in each of the years, and the colour and position of each scenario may change between the graphs. As such, these graphs should be read as an overview of the sequestration capacity across the scenarios in each of the years. They cannot be used to track developments in individual scenarios. Data source: (Huppmann, Kriegler, et al., 2018).*



To summarize, by 2100 most scenarios rely heavily on BECCS, with only 13 of 150 scenarios sequestering less than one billion tonnes of CO2 per year. The median of 12 GtCO2/yr equals building 11999 Decatur-scale facilities between today and 2100. That equals opening 149.98 facilities per year, or 2.88 facilities every single week between 2020 and the end of the century[23]. As mentioned, of those 11999 facilities, there is “only one project in planning” (Nemet et al., 2018, p. 4). These numbers will be put into further perspective in section 6.2 of this thesis, which presents the key challenges and uncertainties for BECCS.

5.4. Brief summary of other NETs in scenarios

This section will introduce the use of NETs other than BECCS in scenarios. Since BECCS is by far the most common NET in scenarios, these sections will be shorter, and only briefly introduce the use of each of the technologies in SR15 scenarios.

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[23] 11999/80 = 149.98. 11999/4160 = 2.88

5.4.1. Sequestration through land-based sinks (mostly afforestation)

The following numbers stem from the 75 scenarios - consistent with a 66% chance of limiting warming to 2 °C - which have data on total carbon sequestration from land use in the IAMC 1.5 °C scenario explorer. These numbers show how much CO2 is sequestered through land-based sinks, including afforestation, soil carbon enhancement, and biochar. (Huppmann, Kriegler, et al., 2018). Most of the sequestration envisioned in the following numbers stems from afforestation/reforestation.

Annual sequestration in 2030 (GtCO2/yr)	**Number of scenarios**
Scenarios which release CO2, don't sequester	8
0	5
0.1 – 0.99	24
1 – 1.99	20
2 – 2.99	10
3 – 3.99	7
4+	1
1	Median

The CO2 emitted/sequestered through land-based sinks varies greatly across the 75 scenarios in 2030, from emitting 2.79 billion tonnes CO2/yr to sequestering 4.55 billion tonnes CO2/yr. The median annual sequestration capacity in 2030 in just above 1 billion tonnes CO2/yr (1.007 GtCO2/yr) 8 scenarios have land-based sinks emit more than they sequester in 2030, 5 scenarios neither sequester nor emit. 24 scenarios sequester between 100 million and 1 billion tonnes CO2/yr in 2030, while 38 scenarios sequester between 1 and 4.5 billion tonnes CO2/yr.

Annual sequestration in 2050 (GtCO2/yr)	**Number of scenarios**
Scenarios which release CO2, don't sequester	8
0	0
0.1 – 0.99	3
1 – 1.99	10
2 – 2.99	11
3 – 3.99	8
4 – 4.99	4
5 – 5.99	12
6 – 6.99	9
7 – 7.99	4
8 – 8.99	4
10 +	2
3.7	Median

In 2050 the CO2 emitted/sequestered through land-based sinks ranges from emitting 5.49 billion tonnes CO2/yr to sequestering 10.52 billion tonnes CO2/yr. The median scenario sequesters 3.74 billion tonnes CO2 through land-based sinks in 2050.

Annual sequestration in 2100 (GtCO2/yr)	**Number of scenarios**
Scenarios which release CO2, don't sequester	8
0.01 – 0.09	2
0.1 – 0.99	4
1 – 1.99	4
2 – 2.99	10
3 – 3.99	9
4 – 4.99	16
5 – 5.99	12
6 – 6.99	3
7 – 7.50	7
4.166	Median

In 2100 the CO2 emitted/sequestered through land-based sinks ranges from emitting 5.24 billion tonnes CO2/yr to sequestering 7.45 billion tonnes CO2/yr. The median scenario sequesters 4.166 billion tonnes CO2 through land-based sinks in 2100.

5.4.2. Direct air capture in SR15 scenarios

Six scenarios with a 66% chance of limiting warming to 2 °C include direct air capture (DAC) as a sequestration method. Three scenarios deploy DAC in 2030. In these three scenarios DAC captures 5.8, 10.8, and 433.73 million tonnes CO2/yr. A fourth scenario deploys DAC in 2035, and by 2050 these four scenarios have DAC sequester between 0.19 million tonnes and 1.66 billion tonnes CO2/yr. By 2100 six scenarios deploy DAC, capturing between 1.2 and 38.2 billion tonnes CO2 per year. No large-scale DAC facility exists today.

5.4.3. Enhanced weathering

Enhanced weathering is used in one SR15 scenario consistent with a 66% chance of limiting warming to 2 °C. In this scenario it first appears in 2035[24], sequestering 62.86 million tonnes by this year. In 2050 it sequesters 1.19 billion tonnes CO2/yr, while in 2100 the same scenario sequesters 2.48 billion tonnes CO2/yr through enhanced weathering.

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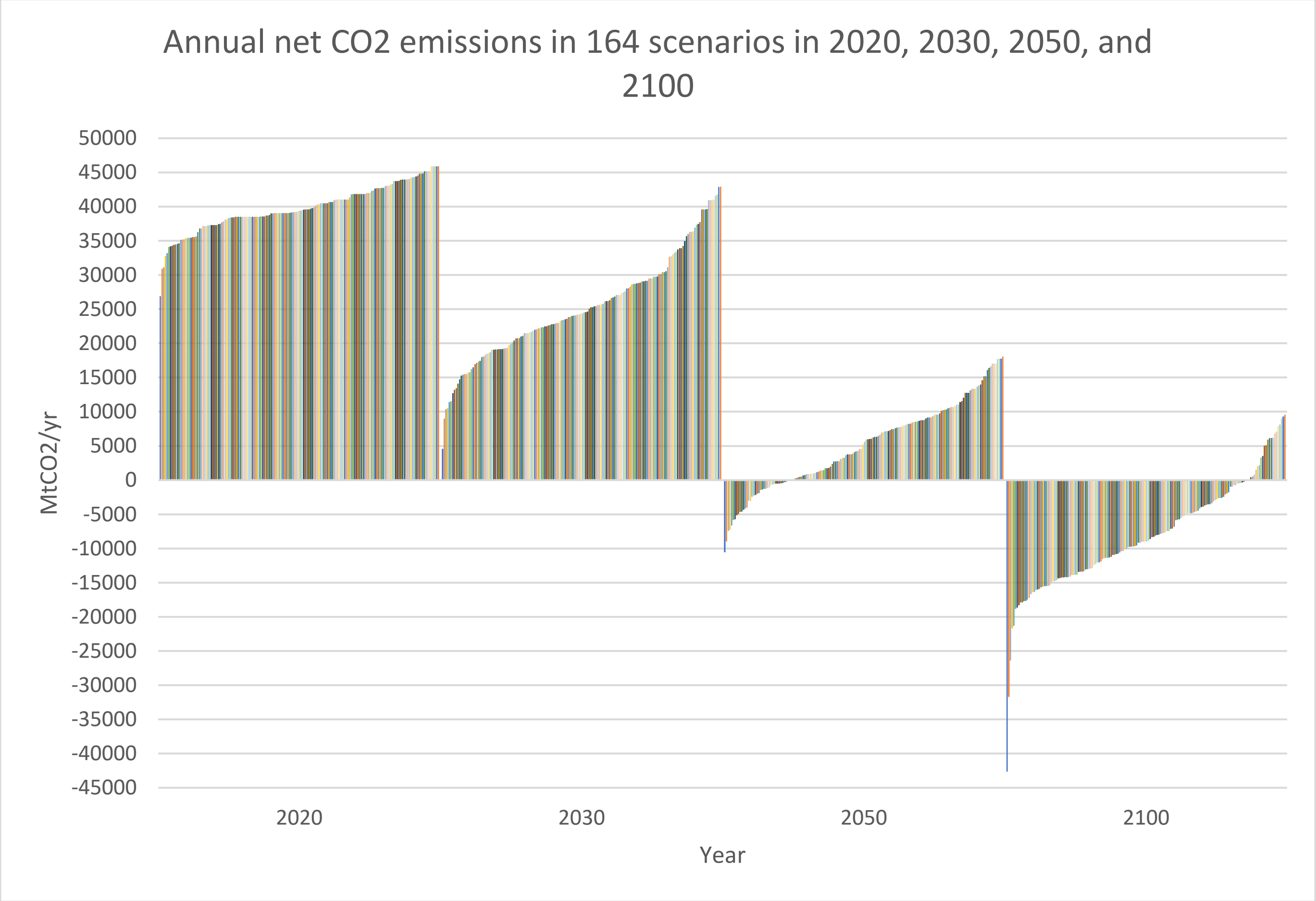
[24] The scenario only has data for every fifth year, so this means deployment could start as early as 2031.

5.5. Brief summary of section ‘5. Data of the scenarios’

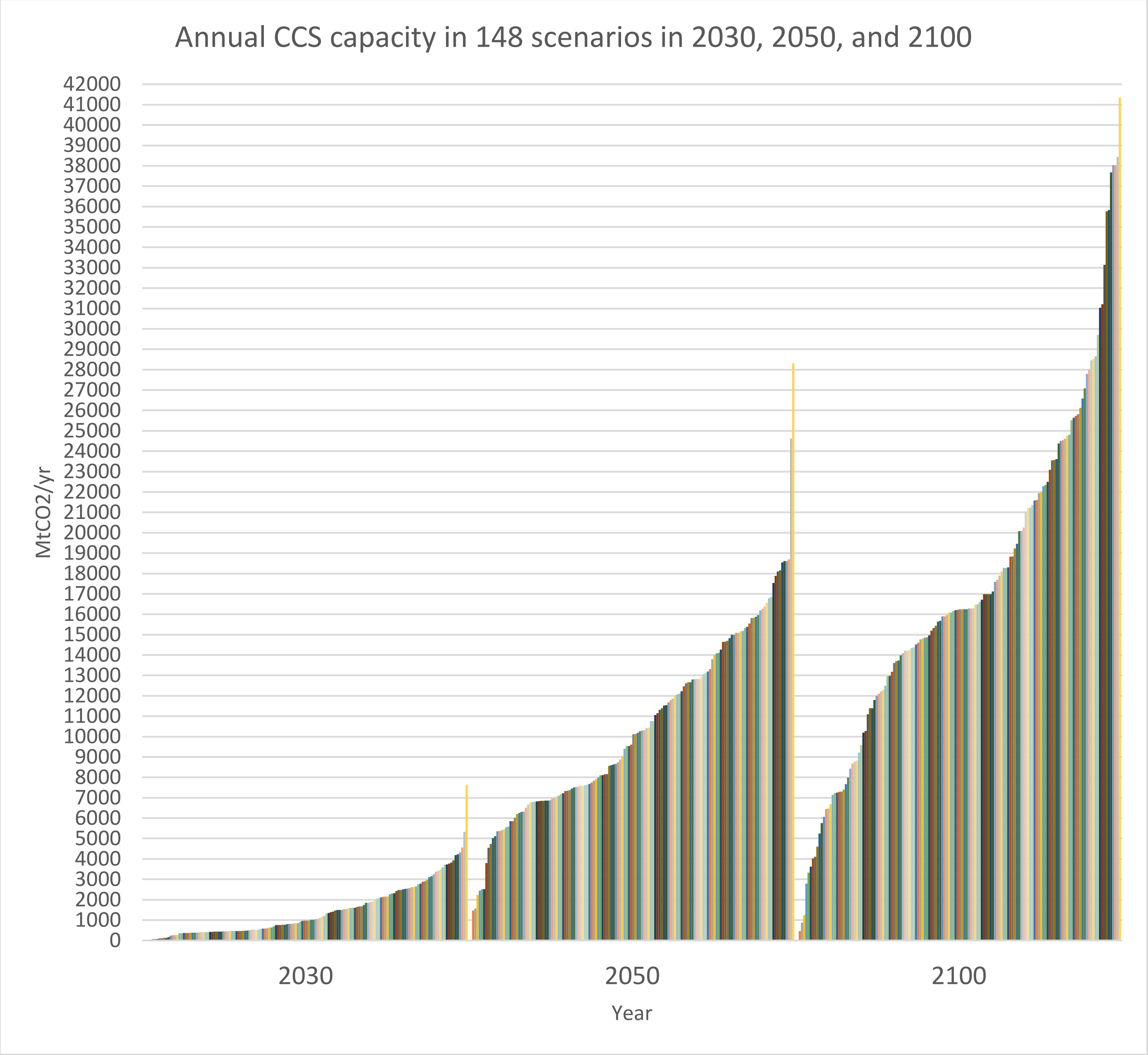
If you are still here, I congratulate you on getting through the hardest part of this thesis. Almost five thousand words of megatons and gigatons is no leisurely Sunday read. For that reason, this sub-section will briefly summarize some of the key points presented in the sections above.

Figure 8*: The following graph shows the net CO2 emissions in each of the 164 scenarios in 2020, 2030, 2050, and 2100. Net emissions are measured in millions of tonnes of CO2 per year. The scenarios are sorted from the lowest to the highest net emissions in each of the years, and the colour and position of each scenario may change between the years. As such, this graph should be read as an overview of how emissions develop across the full range of scenarios between the years. It cannot be used to track developments in individual scenarios. Data source: (Huppmann, Kriegler, et al., 2018).*



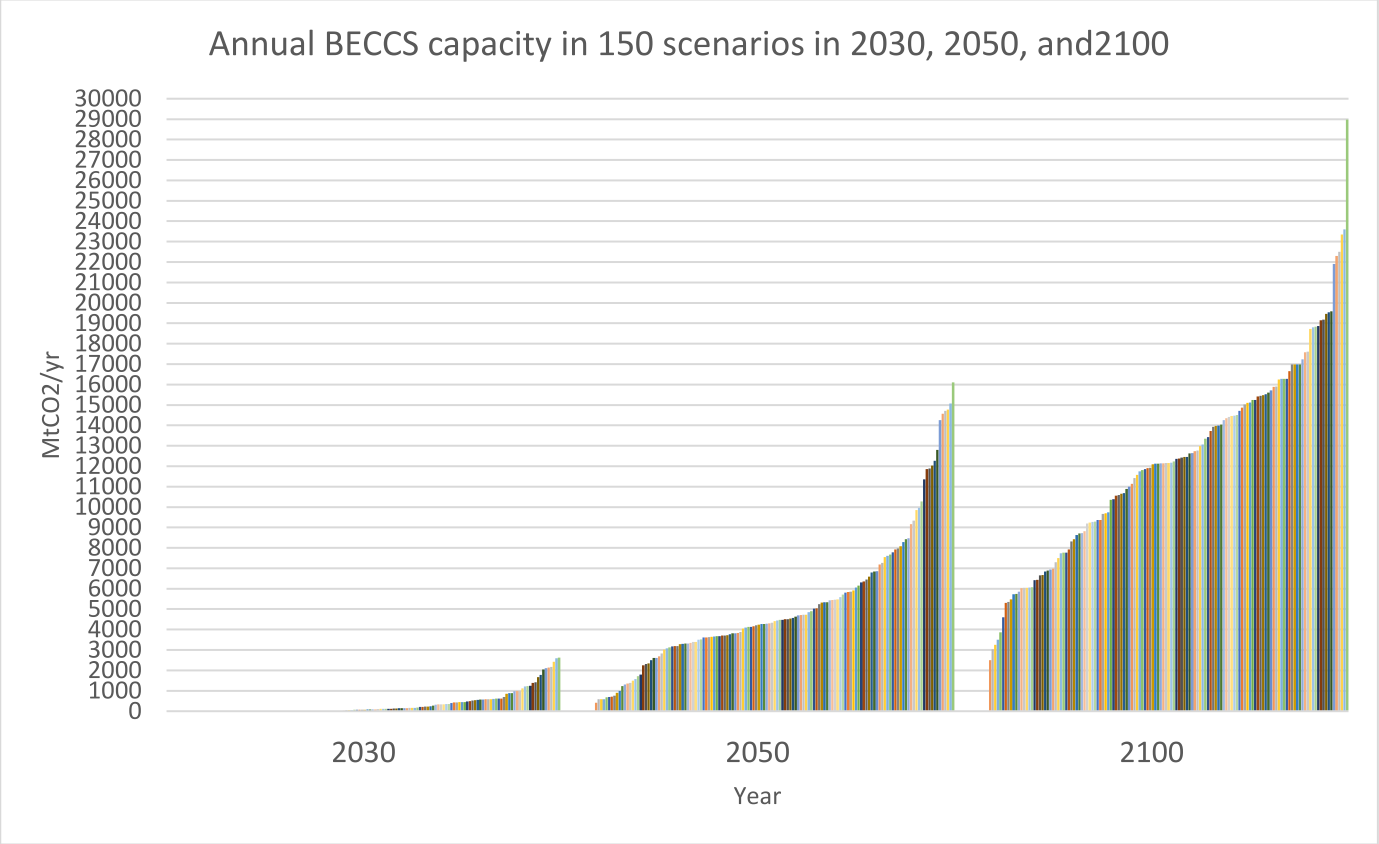
This section has shown that in most scenarios, emissions fall very rapidly. By 2030, CO2 emissions have dropped with 42 percent from current levels in the median scenario. By 2050, emission have dropped by approximately 87 percent in median scenarios. By 2060 the median scenario has net-negative emissions, and by 2100 the median net-emissions of CO2 are -8.9 billon tonnes per year.

Figure 9: *The following graph shows the CCS sequestration capacity in all 148 scenarios in 2030, 2050, and 2100. Sequestration capacity is measured in millions of tonnes of CO2 per year. The scenarios are sorted from the lowest to the highest sequestration capacity in each of the years, and the colour and position of each scenario may change between the years. As such, this graph should be read as an overview of how CCS capacity develops across the full range of scenarios between the years. It cannot be used to track developments in individual scenarios. Data source: (Huppmann, Kriegler, et al., 2018).*



This section has also shown how most scenarios rely on CCS at a very large scale. In 2030, the median CCS sequestration capacity is just shy of one billion tons of CO2 sequestered per year. By 2050, CCS sequester more than 1.4 billion tonnes of CO2 per year in 147 of 148 scenarios, and the median scenario sequester 9.86 billion tonnes per year. By 2100, only 10 of 148 scenarios sequester less than five billion tonnes of CO2 through CCS, and the median has risen to 16.2 billion tonnes of CO2 captured and stored every year using CCS.

Figure 10: *The following graph shows the BECCS sequestration capacity in all 150 scenarios in 2030, 2050, and 2100. Sequestration capacity is measured in millions of tonnes of CO2 per year. The scenarios are sorted from the lowest to the highest sequestration capacity in each of the years, and the colour and position of each scenario may change between the years. As such, this graph should read as an overview of how BECCS capacity develops across the full range of scenarios between the years. It cannot be used to track developments in individual scenarios. Data source: (Huppmann, Kriegler, et al., 2018).*



Most scenarios rely on BECCS to provide the required negative emissions. Compared to CCS BECCS is used more sparingly in 2030, with a median capacity of 65 million tonnes of CO2 sequestered per year. By 2050, however, the scale of BECCS has increased to a median of 4.2 billion tonnes sequestered per year, and only 23 of 150 scenarios have BECCS sequester less than one billion tons of CO2 per year. Finally, by the end of the century, BECCS sequester 12 billion tonnes of CO2 per year in the median scenario, and only 13 scenarios have BECCS sequester less than 2.5 billion tonnes per year in 2100.

While numbers presented here show the scale of CCS and NETs in mitigation scenarios, they still only tell half the story of the true challenge of following the trajectories of these pathways. The following section will attempt to highlight the other half of the story. It will do this by putting the scale of CCS and NETs into a ‘real-world’ perspective, namely, by assessing and presenting the key challenges for CCS and the various NETs.

6. Key challenges for the different technologies

This section will offer an overview of some of the key challenges and uncertainties CCS and the various NETs are faced with. The goal of this section is to highlight difficulties and uncertainties which may make the build out envisioned in scenarios challenging. Given the speed and scale of the build-out of CCS and NETs in most scenarios, uncertainties and challenges these technologies are facing today can have a serious impact on the feasibility of many of these scenarios – especially with regards to the scale of these solutions envisioned already in 2030 and 2050.

6.1. Key Challenges for CCS

For CCS the speed and scale of the envisioned build-out may prove quite the challenge in and of itself – no matter how small or great the other challenges the technology is facing may be. In particular, reaching anything near the envisioned scale in 2030 is an enormous and urgent task. As mentioned, today there are 18 large-scale facilities in operation, capturing somewhere between 31 and 37 million tonnes of CO2 per year. The median capture capacity in scenarios in 2030 is 974 million tonnes of CO2 sequestered through CCS every year, requiring approximately 502 average CCS facilities. To get from 37 million tonnes and 18 facilities in 2020, to 974 million tonnes and 502 facilities in 2030, equals an annual growth rate of 39% sustained over ten years. To put that in perspective, the cumulative installed capacity of solar PV had an annual average growth of 38% between 1998 and 2015 (Creutzig et al., 2017). As mentioned, however, there are currently only 25 new large-scale CCS projects in various stages of development. If they all come online in a timely fashion, and with the maximum expected annual capacity, the total capacity of all 43 currently planned and operating facilities will be 80 million tonnes in 2028. That equals an annual growth rate of 8% between 2018 and 2028, much, much lower than the 39% required for the median scenario. Large-scale CCS projects are, in general, projects which require a lot of time to develop – up to a decade in some cases (IEA, 2017; Lipponen et al., 2017) – as such, there is a real risk that the feasibility of many of the scenarios in SR15 will be decided over the next 2 – 5 years. Despite this – and despite CCS featuring in 147 of 148 scenarios – “CCS is largely absent from the Nationally Determined Contributions and lowly ranked in investment priorities” (de Coninck et al., 2018, p. 343). When analysing the content in the Intended Nationally Determined Contributions (INDCs) in line with the Paris Agreement, Spencer et al. noted that CCS “appear unlikely to be developed under the INDCs at the scale and speed required for a 2°C scenario” (Spencer et al., 2015, p. 9). In short, disregarding any other challenges CCS may be facing, the speed and scale of the CCS development in SR15 scenarios is an enormous challenge in and of itself.

The scale and speed required is not the only challenge CCS is faced with, however. In fact, CCS has followed a somewhat troubled path in recent years. Last year Bui et al. published an in-depth paper on the current status of CCS, assessing CCS from nothing less than "the global to molecular scales" (Bui et al., 2018, p. 1). When it comes to recent attempts to commercialize CCS, they found that:

- Despite a "number of flagship government backed programmes" aimed at demonstrating commercial viability of CCS "progress has been minimal." (Bui et al., 2018, p. 72)
- "The European Union's ambition for up to 12 CCS projects in operation by 2015 (…) has failed to deliver a single CCS project." (Bui et al., 2018, p. 72)
- While some projects in the USA have been successful, another project has "encountered a number of problems with delivery delays, major technical issues and being significantly over-budget." (Bui et al., 2018, p. 72)
- "In the United Kingdom two competitive CCS procurement programmes for power generation have been run by the UK Government since 2007 with both having being [sic] abandoned without success." (Bui et al., 2018, p. 72)

They further note that "the physical and commercial risks" associated with CCS projects have "so far outweighed the potential rewards on offer, as evidenced by the abandonment of many tens of promising CCS projects around the world." (Bui et al., 2018, p. 72).

Among the other key challenges/uncertainties CCS is facing, we find cost, political support, public opinion challenges, and challenges linked to transportation (Bui et al., 2018; IEA, 2016; Lipponen et al., 2017). Challenges linked to cost and political support seem to have been particularly pressing/important for hindering further development over the past decades. As the International Energy Agency (IEA) points out in a report on the past 20 years of CCS, "CCS deployment has been hampered by fluctuating policy and financial support" (IEA, 2016, p. 10). The challenges related to political support of CCS are strongly linked to both cost and public opinion challenges. For instance, in both Germany and the Netherlands public opinion turned against CCS due to worries about the safety of onshore CO2 storage, this, in turn, led to reduced political support for CCS in these countries (Lipponen et al., 2017). Other public opinion challenges stem from CCS being viewed as a technology competing with renewables, and as an excuse by incumbent fossil fuel companies to continue with ‘business as usual’ (Lipponen et al., 2017). Other factors contributing to ‘fluctuating’ political support is the cost and the long time it can take to build large-scale CCS facilities (Bui et al., 2018; Lipponen et al., 2017). Large-scale CCS facilities can cost several billion dollars and take up to a decade to build (Bui et al., 2018; IEA, 2016; Lipponen et al., 2017), and cost has been cited as a reason for the cancellation of specific projects in both the UK and Australia (Bui et al., 2018; Lipponen et al., 2017). The long build times of large-scale CCS means “investments being made by today’s political leaders will bear fruit in future decades” (Lipponen et al., 2017, p. 7586). Such ‘long termism’ does not always get the priority in a political world with yearly budgets and short election cycles. Moreover, the many ‘failed’ CCS projects might make policy-makers wary of further CCS investments. As noted by both the IEA and Lipponen et al., the number of projects which have been proposed but have failed to materialize, outnumber successful projects “by a factor of two to one” (IEA, 2016, p. 25; Lipponen et al., 2017, p. 7587).

Given the scale of CCS envisioned in scenarios, transporting the carbon from the point of capture to the point of storage may become a challenge of its own. Globally, estimates show that there should be enough capacity to “geologically store vast amounts of CO2 permanently” (Fuss et al., 2018, p. 11), however, in some regions “there could be storage bottlenecks” (Fuss et al., 2018, p. 11). Transportation both over long and short distances may, therefore, be necessary. The two main suggested modes of transportation are through pressurized pipelines and by ship (Bui et al., 2018). Ship transportation is expected for transportation over large distances, while “the vast majority of transportation will occur via pipeline” (Bui et al., 2018, p. 42). Building large networks of CO2 pipelines not only comes at significant costs, but may also face public acceptance and NIMBY (not in my back yard) problems. One study of public acceptance of CCS in Switzerland found “people do not seem willing to live near any type of pipeline” (Wallquist, Seigo, Visschers, & Siegrist, 2012, p. 81). A similar study in Germany also identified transport and storage as “‘hot spots’ affecting CCS-acceptance” (Arning et al., 2019, p. 242). Thus, while CO2 pipelines already exist at some scale – more than 6500 kilometres worldwide (Bui et al., 2018) – transportation of CO2 at the scale envisioned in scenarios may face significant public acceptance problems. It is worth noting that while the theoretical storage capacity for CO2 appears to be significant (Fuss et al., 2018), the location of storage sites may face similar NIMBY problems (Arning et al., 2019; Braun, 2017; Wallquist et al., 2012).

Taken together, the uncertainties and recent developments in large-scale CCS truly highlight the severity of the challenge outlined by 2 °C scenarios. While the hurdles for CCS are large, it is worth remembering that “for many industrial applications there is currently no alternative to CCS for reducing the CO2 emissions that are inherent to the manufacturing process.” (Bui et al., 2018, p. 73). Moreover, given the scale of emission reductions outlined in most 2 °C scenarios, CCS in some form will most likely be required to provide sufficient negative emissions. In the past 10 – 20 years, building and deploying large-scale CCS has been more expensive, challenging, complex, and time-consuming than anticipated (Bui et al., 2018; IEA, 2016; Lipponen et al., 2017). This will have to change quickly if we wish to follow the trajectories of most 2 °C scenarios.

6.2. Key Challenges for BECCS

Challenges related to CCS in general are also relevant for BECCS, it is bioenergy with CCS after all. However, BECCS comes with a series of extra challenges and uncertainties on top of the ones which apply to all CCS. This section will focus on those challenges and uncertainties. In particular, it will focus on challenges related to land and water use, and how these factors may lead to conflicts with other sustainability challenges such as food security, water security, and biodiversity loss.

The ‘idea’ behind BECCS is that you plant energy crops which during their lifetime sequester CO2 from the atmosphere, you then use the energy crops to produce energy, and sequester the CO2 released in the process with CCS. In theory, and/or in small scale, an ‘unproblematic’ process which could provide both energy and negative emissions. When you crank BECCS up to the scale in most scenarios, however, significant real-world challenges appear (Boysen et al., 2017; de Coninck et al., 2018; Fajardy, Chiquier, & Mac Dowell, 2018; Fajardy & Mac Dowell, 2017; Fuss et al., 2018; Heck, Gerten, Lucht, & Popp, 2018; P. Smith et al., 2015). Perhaps the most important of these extra challenges is land use. Smith et al. calculated the land requirements of sequestering approximately 12 billion tonnes of CO2 per year through BECCS[25]. They estimate removing 12 billion tonnes of CO2 through BECCS per year will require between 380 and 700 million hectares (Mha) of land (P. Smith et al.,

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[25] Smith et al. actually calculated the land used required for removing 3.3 billion tonnes of *carbon* a year through BECCS (P. Smith et al., 2015). 3.3 billion tonnes of *carbon* is the equivalent of just above 12 billion tonnes of *carbon dioxide (CO2)*. (3.3 * 3.67 = 12.111). See methods.

2015). To put these numbers in perspective, current land use for cereal[26] production is approximately 720 million hectares globally (Bui et al., 2018; World Bank, 2018). Thus, the estimated land required for BECCS in the median 2 °C scenario equals 53-97% of all land currently used for cereal production (Bui et al., 2018; P. Smith et al., 2015; World Bank, 2018). That equals 7–25% of total agricultural land (all pastures and croplands included), and 25–46% of arable and permanent cropland combined[27] (de Coninck et al., 2018; P. Smith et al., 2015). As Smith et al. point out "this range of land demands are 2–4 times larger than land identified as abandoned or marginal. Thus, the use of BECCS (…) on large areas of productive land is expected to impact the amount of land available for food or other bioenergy production, as well as the delivery of other ecosystem services" (P. Smith et al., 2015, p. 5). It is worth noting that the land-use in the Smith et al. study assumes "widely applicable, high-productivity dedicated energy crops" (P. Smith et al., 2015, p. 5), and that the land-use range presented above (380 – 700 Mha) could be much wider depending on the efficiency of the crops deployed. A similar study, which excluded direct and indirect land use changes, found BECCS land-use requirements for ~12 billion tonnes CO2 sequestered a year could go as high as 2.4 billion hectares (Fajardy & Mac Dowell, 2017). No wonder then, that the availability of land is considered a "fundamental limiting factor" (Fuss et al., 2018, p. 9) for BECCS. These land requirements could put the scale of BECCS in 2 °C scenarios in conflict and competition with other sustainability challenges, such as food security and prevention of biodiversity loss (Fuss et al., 2014; Fuss et al., 2018; Heck et al., 2018). The significant land use could even put BECCS in competition with other decarbonization options such as afforestation.

Water use is a second aspect of BECCS which could put it in competition with other sustainability challenges. Smith et al. estimates sequestering ~12 GtCO2/yr through BECCS would require roughly 720 cubic kilometres of fresh water per year. 720 cubic kilometres of fresh water "represents an additional use of ~3% of the freshwater currently appropriated for human use" (P. Smith et al., 2015, p. 6). It is worth noting, however, that some studies

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[26] Cereals "include wheat, rice, maize, barley, oats, rye, millet, sorghum, buckwheat, and mixed grains" (https://data.worldbank.org/indicator/AG.LND.CREL.HA)

[27] The OECD defines these terms in this manner "Agricultural land is defined as the land area that is either arable, under permanent crops, or under permanent pastures. Arable land includes land under temporary crops such as cereals, temporary meadows for mowing or for pasture, land under market or kitchen gardens, and land temporarily fallow. Land abandoned as a result of shifting cultivation is excluded. Land under permanent crops is cultivated with crops that occupy the land for long periods and need not be replanted after each harvest, such as orchards and vineyards. This category excludes land under trees grown for wood or timber." Source: https://data.oecd.org/agrland/agricultural-land.htm, retrieved on 17.april.2019.

estimate water use much higher than Smith et al. (de Coninck et al., 2018; Fajardy & Mac Dowell, 2017). Regardless, there is a possibility high deployment of BECCS could put pressure on water resources in some regions – a topic worthy of further research. Without an analysis of the water use increase in specific regions, it is difficult to properly discuss the consequences BECCS at the scale envisioned in 2 °C scenarios could have on water security, but, as Smith et al. puts it "with human pressures on freshwater increasing, water use could act as a significant limitation to implementation of high-water-demand NETs such as BECCS" (P. Smith et al., 2015, p. 6). It is also worth noting that 1.2 billion people currently live in "absolute water scarcity" (Fajardy & Mac Dowell, 2017, p. 1390). Moreover, research suggests there may be trade-offs between the land and water use concerns related to BECCS (Fajardy et al., 2018; P. Smith et al., 2015). In short, the studies found that if you try to limit the total water use from BECCS the land use may increase, and vice versa (Fajardy et al., 2018; Heck et al., 2018; P. Smith et al., 2015). For instance, Smith et al. found:

> "Irrigated bioenergy crops were estimated to double agricultural water withdrawals in the absence of explicit water protection policies, (…). Land requirements for bioenergy crops would greatly increase (by ~40%, mainly from pastures and tropical forests) if irrigated bioenergy production was excluded, meaning that there will be a trade-off between water and land requirements if bioenergy is implemented at large scales." (P. Smith et al., 2015, p. 6)

Based on the land and water use of BECCS, some studies argue that BECCS at the scale seen in 2 °C scenarios would be in direct conflict with many sustainability challenges (Boysen et al., 2017; Heck et al., 2018). In a study of the potential effects of large-scale BECCS on the biosphere, Heck et al. concluded that pathways relying on large amounts of BECCS "bear the risk of triggering potentially irreversible changes in the Earth system" (Heck et al., 2018, p. 153) and that "relying on BECCS as a key decarbonization strategy should be considered highly risky." (Heck et al., 2018, p. 153). Their study argues that if we wish to remain strictly within the 'precautionary principle of the planetary boundaries' presented in Steffen et al. (Steffen et al., 2015), "the potential for negative emissions from dedicated bioenergy plantation is marginal" (Heck et al., 2018, p. 153). Indeed, they place its potential as low as approximately 220 million tonnes of CO2 sequestered per year through BECCS[28] (Fajardy et al., 2018; Heck et al., 2018). Worth remembering then, that of the 150 two-degree scenarios with data on total BECCS, only 13 have BECCS sequestering less than 2.5 billion tonnes of

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[28] They place it at 60 million tonnes of *carbon* pr. year. 60 * 3.67 = 220,2.

CO2 in 2100. And the median scenario has 12 billion tonnes of CO2 sequestered through BECCS in 2100.

Other challenges and uncertainties for BECCS exist. For instance, many small-hold farmers may be indirectly or directly influenced by the large-scale deployment of BECCS. More than one billion of these farmers may be influenced, with both potentially positive and negative effects (Fuss et al., 2018). There are also concerns about BECCS effectiveness in actually providing negative emissions, as potential land-use changes could lead to significant CO2 emissions (Fuss et al., 2018; Harper et al., 2018). For instance, Harper et al. found “where bioenergy crops replace ecosystems with high carbon contents could easily result in negative carbon balance and therefore may be unwise” (Harper et al., 2018, p. 9). This, again, could have an effect on how much land is available to provide negative emission through BECCS.

Public acceptance is another key uncertainty/challenge for BECCS, as it is for CCS in general. NIMBY challenges related to storage and transportation of CO2 could arise for BECCS as it has for ‘conventional’ CCS. While some studies argue links to agriculture may increase the public acceptance of BECCS compared to fossil CCS, others argue “the transportation of massive quantities of biomass may make it less acceptable than CCS.” (Nemet et al., 2018, p. 12). Moreover, BECCS may face significant public acceptance challenges due to its high land use, and consequent conflicts with afforestation and food security (Nemet et al., 2018). For now, however, it appears public knowledge about BECCS is low (Nemet et al., 2018), as such, it can be difficult to assess the ‘true’ public acceptance of the technology.

As with CCS itself, the speed and scale of BECCS in scenarios is a huge challenge. The median capacity in 2030, across the scenarios presented in this thesis, is 65 million tonnes of CO2 sequestered annually through BECCS. Given the current large-scale capacity of 1 million tonnes, the median scenario requires an annual growth rate of 52% between 2020 and 2030. Reaching the median 2050 scenario, with a BECCS capacity of just above 4.2 billion tonnes sequestered in 2050, equals sustaining an annual growth rate of 32% between 2020 and 2050. For a solution which requires both large-scale land use change, coordination of large numbers of individual farmers, and rapid upscaling of large-scale CCS, that is an enormous challenge. Especially since, as mentioned, there is currently only one large-scale project in planning (Nemet et al., 2018).

6.3. Key challenges and uncertainties for other NETs

This section will present some of the key challenges for other negative emission solutions. It will focus mainly on afforestation and direct air capture but will touch briefly upon the other technologies as well.

6.3.1. Afforestation

Even though afforestation is the most ‘natural’ of suggested negative emissions, it comes with its own set of potential challenges and uncertainties. There is some disagreement in the literature on the total potential for CO2 sequestration from afforestation, ranging from the potential to sequester as much 12 billion tonnes of CO2 per year in 2100 to as little as 540 million tonnes per year (Fuss et al., 2018). According to the SR15, the sequestration potential of afforestation in 2050 ranges from 1–7 GtCO2/yr in the literature, but this is “narrowed down to 0.5–3.6 GtCO2 yr−1 based on a number of constraints” (de Coninck et al., 2018, p. 343). As with BECCS, a key challenge is the challenge of land use. To provide ~12 billion tonnes of negative emissions per year in 2100, afforestation is estimated to require 970 million hectares of land (P. Smith et al., 2015). That equals 20% of total agricultural land, and 64% of arable plus permanent crop area (P. Smith et al., 2015). Moreover, the estimated water use equals just above one billion cubic kilometres of fresh water per year in 2100 (P. Smith et al., 2015). The estimated land and water use for afforestation for the same amount of negative emissions is thus even higher than for BECCS. As such, afforestation faces many of the same challenges as BECCS in terms of conflicts with other sustainability issues and food and water security. While afforestation in some areas could have a positive effect on biodiversity in some ecosystems, it could have a negative effect on biodiversity in others (de Coninck et al., 2018). One way to alleviate concerns of biodiversity loss is to use forest native to the local regions where afforestation occurs, however, this could involve planting trees with a lower sequestration efficiency, thus reducing the negative emission potential of afforestation (Hoegh-Guldberg et al., 2018).

The Albedo effect could prove to be one of the key constraining factors on available land for afforestation as a tool to provide negative emissions (Fuss et al., 2018; P. Smith et al., 2015). Albedo refers to the sun’s rays being reflected by surfaces as opposed to being absorbed by them. Simply explained, while a white surface will have a high albedo, and reflect a large percentage of the sun’s rays, a dark surface will have a low albedo absorbing a larger percentage of the rays and heating the surface more rapidly. This means afforestation could affect the albedo in many regions, as “the albedo of lighter-coloured and less-dense vegetation (for example, food crops and grasses) is much greater than that of trees." (P. Smith et al., 2015, p. 3) Indeed, in high latitudes afforestation could contribute to accelerating warming, and in temperate regions the net benefits of afforestation are "uncertain or net neutral" (Fuss et al., 2018, p. 16).

There are also concerns about the permanence of afforestation as a CO2 storage/sequestration solution (de Coninck et al., 2018; Fuss et al., 2018; P. Smith et al., 2015). Not only do forests require time to grow, they also saturate, meaning their potential to draw in carbon is reduced over time. (P. Smith, 2016; P. Smith, Haszeldine, & Smith, 2016) Moreover, the risks of fires and other forms of degradation could lead to the carbon being remitted to the atmosphere (de Coninck et al., 2018; Fuss et al., 2018). Taken together, these factors can reduce the effectiveness of afforestation as a negative emission solution over time (Fuss et al., 2018; Hoegh-Guldberg et al., 2018).

6.3.2. Direct air capture

Unlike afforestation and BECCS, direct air capture (DAC) has a low impact on land use in and of itself, and can avoid the competition for land outlined in the previous sections (de Coninck et al., 2018; Fuss et al., 2018; P. Smith et al., 2015). However, direct air capture is a very energy intensive technology. When compared to the CO2 concentration in a gas or coal power plant the CO2 concentration in the atmosphere is highly diluted (Bui et al., 2018). Removing CO2 through direct air capture thus requires significantly more energy than 'conventional' CCS. Smith et al. estimates removing ~12 billion tonnes of CO2 per year through DACs would require 156 exajoules (EJ) of energy per year (P. Smith et al., 2015). According to the IPCC, current global primary energy supply is 600 EJ annually (de Coninck et al., 2018). As such, sequestering 12 GtCO2/yr through DAC in 2100 could mean adding an extra 26% of current total energy consumption on top of whatever other energy requirements would exist in a given year. If that extra energy use was to come from solar or wind, DAC could, indirectly, have significant impacts on land use after all (P. Smith et al., 2015). If, on the other hand, that energy came from fossil sources like natural gas, the emission from the energy source could negate much of the negative emissions from DAC, rendering DAC less useful (Fuss et al., 2018). As noted by Fuss et al. if DAC "is powered with coal, the CO2 emissions from fueling the plant would be greater than the CO2 captured" (Fuss et al., 2018, p. 17).

The key challenges for DAC, however, may stem from how early the technology is in development, and consequently, how much is still uncertain about the technology's future. The cost estimates for DAC, for example, come with huge disagreements in the literature, and ranges from 20 – 1000 US dollars per ton of CO2 removed (de Coninck et al., 2018). Given that most scenarios have negative emissions in the billions, the discrepancies could have a huge effect on the total cost of DAC. The technology is "arguably at a nascent stage" (Nemet et al., 2018, p. 13), with no large-scale facilities. Some smaller projects exist, like a facility in Iceland using the waste heat of a geothermal power plant to adsorb CO2 (Nemet et al., 2018). However, scaling up from these small projects to a scale which can have an impact on climate change mitigation in coming decades is an enormous challenge. DAC being at such an early stage in development makes a proper assessment of its challenges and uncertainties difficult. For instance, Bui et al. notes:

> "For DAC to be at all practicable, the systems will need to operate at high capacity factors. Almost no work has been done on long-term operation of these systems. There are trace impurities in the air and since such a large amount of air is processed, they can have an adverse impact on DAC systems. Also, these systems must be able to stand up to the elements. Depending on where they are located, this includes water, wind, cold, and sandstorms. So far, the DAC literature is silent on these issues." (Bui et al., 2018, pp. 71-72)

Fuss et al., meanwhile, lists "unexpected environmental side-effects" (Fuss et al., 2018, p. 20) as potential constraints, while the IPCC notes that "both optimistic and pessimistic outlooks exist" (de Coninck et al., 2018, p. 346) for the technology. In short, direct air capture technology is at an early stage of development, and as such still comes with several uncertainties. Meanwhile, in the world of 2 °C scenarios, the median emissions are net-negative by 2060. For DAC to be a significant mitigation technology in coming decades, development and deployment must thus happen very rapidly.

6.3.3. Soil carbon sequestration and biochar

Soil carbon sequestration has an estimated sequestration capacity of 2.3–5.3 billion tonnes per year (de Coninck et al., 2018). Soil carbon sequestration also comes with some potential benefits, namely improved yields from crops, as well as improved soil health and quality (de Coninck et al., 2018; P. Smith, 2016). Unlike BECCS and afforestation, soil carbon sequestration may actually have a positive effect on food security (de Coninck et al., 2018). Indeed, soil carbon sequestration appears to come with less potential negatives side-effects than many other NET solutions (Fuss et al., 2018; P. Smith, 2016). It does, however, come with an important drawback. Like afforestation, soil carbon sequestration would saturate over time, meaning the sequestration potential "is large at the outset, but decreases as soils approach a new, higher equilibrium value, such that the potential decreases to zero when the new equilibrium is reached." (P. Smith, 2016, p. 1323). Depending on local conditions, this saturation happens after 10 – 100 years (P. Smith, 2016). Moreover, unless the necessary practices are maintained, the carbon stored in the soil can be reemitted. Unlike many other NETs, however: "Soil carbon sequestration is immediately deployable since the agricultural and land management practices required (…), are generally well known by farmers and land managers" (Fuss et al., 2018, p. 28). While it may not be a long-term solution, it could, with the right practices and policies, help provide negative emissions in the short-term. A key challenge to make this achievable is the challenge "of moving from dispersed land use decisions to managed and coordinated ones to enable scale up" (Nemet et al., 2018, p. 14).

Biochar, much like soil carbon sequestration, could theoretically help increase crop productivity, however, there are still uncertainties related to this (Haider, Steffens, Moser, Müller, & Kammann, 2017). Biochar might also reduce soil water loss (Haider et al., 2017). Like most NETs, biochar comes with its own collection of uncertainties and challenges (Haider et al., 2017; Kammann et al., 2017). Among the uncertainties are uncertainties related to how microorganisms in the soil will be affected by high use of biochar, and whether the use will lead plants to be more vulnerable to droughts, pathogens, etc. (Fuss et al., 2018). Moreover, the use of biochar can influence albedo by darkening the soil (P. Smith, 2016), and the production of biochar may release particles which can "reduce air quality and cause a positive direct and indirect radiative forcing" (Fuss et al., 2018, p. 26). Both these aspects could reduce the warming mitigation effects of biochar application (Fuss et al., 2018). While the application of biochar does not require land use change – since it can be applied to current cropland – the biomass required for biochar production could require significant amounts of cropland. ~1 billion tonnes of CO2 sequestered per year from biochar could require 40–260 million hectares of land (P. Smith, 2016)[29]. Finally, as with some other potential NETs, "large-scale trials of biochar (…) are still missing. Feasibility, long-term mitigation

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[29] The estimates from Smith are based on "0.3 GtCeq. yr $^{-1}$" (P. Smith, 2016, p. 1319). I assume the C refers to *carbon* not *carbon dioxide* – this is in line with P. Smith's other papers (see (P. Smith et al., 2015) for example). Thus, 0.3 GtCeq. yr $^{-1}$ *3.67 = 1.101 GtCeq. yr $^{-1}$, in the text presented as ~1. Worth noting, however, that the SR15, when referring to the same Smith (2016) paper, presents the same number as if "0.3 GtCeq. yr $^{-1}$" refers to *carbon dioxide* (see: (de Coninck et al., 2018, p. 345)). Here I work under the assumption that this is a typo in the SR15 and base my discussion on the numbers in the original paper.

potentials, side-effects, and trade-offs therefore remain largely unknown.” (Fuss et al., 2018, p. 26).

6.3.4. Enhanced weathering and ocean alkalinisation

The biggest challenge and uncertainties for enhanced weathering (EW) is perhaps summarized by this citation: “The largest research gap is missing field experiments that consider real scales, which evaluate the full impact of EW on biogeochemical cycles, biomass and carbon stocks in the soils, and the plants” (Fuss et al., 2018, p. 21). The estimated CO2 removal capacity for enhanced weathering ranges from 0.72 – 95 billion tonnes of CO2 per year, and from 0.1–10 billion tonnes per year for ocean alkalinisation (de Coninck et al., 2018). Put another way, the potential capacity is highly uncertain. Equally uncertain are challenges related to deployment, scaling and the maturity of the solutions, with the IPCC noting “deployment at scale” may require decades (de Coninck et al., 2018, p. 345). Due to the several uncertainties, the cost estimates also vary profusely. In short, most things are still uncertain about these solutions – including their potential positive/negative side-effects, and our knowledge about them stem mainly from “model studies and theoretical discussion” (Fuss et al., 2018, p. 23)

6.3.5. Ocean Fertilization

Ocean fertilization is the final of the potential NETs to be discussed in this section. Like some of the NETs outlined above it comes with many uncertainties. As with ocean alkalinisation, ocean fertilization is at a very early stage, and “only small-scale field experiments and theoretical modelling have been conducted” (de Coninck et al., 2018, p. 346). Ocean fertilization may also come with many potential side-effects, including reductions in long-term ‘ocean productivity’, further increase in ocean acidity, a decrease in the ocean’s oxygen concentration, and increased emissions of the climate gasses methane and nitrous oxide (Chisholm, Falkowski, & Cullen, 2001; Williamson et al., 2012). Combined with ocean fertilization’s “very low overall potentials to sequester CO2 on a longer time scale” (Fuss et al., 2018, p. 24), this led Fuss et al. to conclude that ocean fertilization “ is not a viable negative emissions strategy when performed with sustainability issues under consideration” (Fuss et al., 2018, p. 24). This echoes the findings of others. For instance, Chisholm et al. argue, “the known consequences and uncertainties of ocean fertilization already far outweigh hypothetical benefits” (Chisholm et al., 2001, p. 310).

This section has presented the key challenges and uncertainties of CCS and the various negative emission solutions. The next section will briefly present the term ‘feasibility’, before I move on to discussing the implications of everything which has been presented in this thesis.

7. ‘Feasibility’ – a presentation of the term and related issues

Is this *feasible*? Can it be done and how? These, and others, are questions I aim to contend with in the discussion section of this thesis. However, before barging headfirst into a discussion aimed at shedding light on the impenetrable darkness of the future, we must first try to make sense of the impenetrable vagueness of the term *feasibility*. It is a term which very much finds itself at the centre of any discussion of what is possible, and at the centre of any discussion on the scale of CCS, BECCS, mitigation solutions and potential mitigation pathways. As such, this section of the thesis will first present the term, before looking at the term through the lens of integrated assessment models (IAMs).

As hinted at in the paragraph above, the term feasibility comes with a certain degree of vagueness , and can be “interpreted or defined in a number of ways” (Loftus et al., 2015, p. 94). In the SR15, the IPCC holds that “no single answer exists as to the question of whether it is feasible to limit warming to 1.5°C. This implies that an assessment of feasibility would go beyond a ‘yes’ or a ‘no’.” (Allen et al., 2018, p. 71). Meanwhile, in their 5th assessment report, the IPCC further notes how “in many cases, statements about feasibility are bound up in subjective assessments of the degree to which other characteristics of particular transformation pathways might influence the ability or desire of human societies to follow them” (Clarke et al., 2014, p. 420). ‘Beyond a ‘yes’ or a ‘no’’, ‘interpreted or defined in a number of ways’, ‘bound up in subjective assessments’ – feasibility, then, is perhaps not as exact a term as one would wish for when assessing the real-world possibilities of mitigating climate change. “Roughly, a state of affairs is feasible if it is one we could actually bring about” writes Gilabert and Lawford-Smith (2012, p. 809), before they continue, “but there are many questions to ask about the conditions under which we are justified in thinking that we could bring about a political state of affairs” (Gilabert & Lawford-Smith, 2012, p. 809). In short, something is feasible if it can actually be brought about and made to happen, but assessing *what* is feasible will generally involve some form of subjective assessment. Thus, in the real world, we may not be able to determine feasibility in an absolute sense. Instead, we must look at the data, and have an open and critical discussion about pathways and mitigation solutions based on what the data and current knowledge is telling us. I will return to discuss questions related to this in the discussion chapter of the thesis. However, irremovable uncertainties to the side, when looking at and assessing IAMs and their output, we should be aware of how feasibility is 'viewed' in these models.

In the world of IAMs, feasibility, or at least *infeasibility*, is generally measured by clear physical constraints. As previously noted, "beyond cases where physical laws might be violated to achieve a particular scenario (…), these integrated models cannot determine feasibility in an absolute sense." (Clarke et al., 2014, p. 424). This means the outputs of IAMs, and the mitigation scenarios they produce, can provide useful information for discussion about feasibility, information like "rates of deployment of energy technologies, rates of reductions in global and regional emissions, aggregate economic costs, financial flows among regions, and links to other policy objectives such as energy security or energy prices" (Clarke et al., 2014, p. 424). However, IAMs do not provide a proper assessment of the real-world feasibility of the socio-technical developments in the scenarios they create. While they can, to some extent, model certain technical, economic, and geophysical constraints, thus labelling certain scenarios *infeasible*, they cannot properly assess whether scenarios which are feasible within the realm of models are *actually feasible* in the real world. As Riahi et al. explains:

> "Infeasibility is thus an indication that under a specific model parameterization the transformation cannot be achieved. It provides useful context to understand technical or economic concerns. These concerns need to be strictly differentiated from the feasibility of the transformation in the real world, which hinges on a number of other factors, such as political and social concerns that might render feasible model solutions unattainable in the real world. While there might also be solutions in the real world that are not anticipated by the models, we interpret infeasibility across a large number of models as an indication of increased risk that the transformation may not be attainable due to technical or economic concerns." (Riahi et al., 2015, p. 19)

"These concerns need to be strictly differentiated from the feasibility of the transformation in the real world" (Riahi et al., 2015, p. 19). Thus, the existence of a mitigation scenario does not in itself mean its suggested pathway is feasible. When one couples IAMs relationship to real-world feasibility with both the knowledge of how idealized the assumptions in IAMs are, as well as with the true scale and uncertainties facing CCS and NETs – it becomes clear that it is time to have a critical discussion about 'where we should go from here'.

Before moving on to the discussion section of this thesis, I would like to point out two points which are directly relevant for any assessment of the feasibility of mitigation pathways and climate targets.

The first point is this: “An emission trajectory as suggested by the current nationally determined contributions (NDCs) would already lock remaining 2 °C pathways deeply into NETs dependence” (Fuss et al., 2018, p. 35). Meaning, if in the coming decade countries manage to implement policies in line with their current intended national contributions, we will end up locked into a future where NETs are unavoidable for reaching the 2 °C target. Furthermore, “if NDC ambitions are not increased before 2030, exceeding the 1.5 °C goal can no longer be avoided” (UNEP, 2018, p. XIV). Worth noting then, that “collectively, G20 members are (…) not yet on track to realize their NDCs for 2030.” (UNEP, 2018, p. XVII). To spell it out clearly, if countries ‘only’ reduce emissions in line with current NDCs we will be entirely dependent on NETs to reach the 2 °C target, however – at current rates – we are not on track to implement these NDCs.

The second highly relevant point for any assessment of the feasibility of mitigation pathways and climate targets is uncertainty, geophysical and otherwise. As an example, consider what was mentioned earlier in this thesis, namely that climate sensitivity is still one of the key unknowns in climate science. And that, in the SR15, the ‘equilibrium climate sensitivity’ is described as ‘likely’ to be in the 1.5 to 4.5 °C range (Cubasch, 2013; Rogelj, Shindell, et al., 2018), but that research suggests the lower limit “could be revised upwards, which would decrease the chances of limiting warming below 1.5°C in assessed pathways” (Rogelj, Shindell, et al., 2018, p. 103). As Lamontagne et al. put it: “To achieve a tolerable future, we must also have the good fortune of living in a world with low climate sensitivity. Failure to rapidly increase abatement all but guarantees failure over a very wide range of climate sensitivities.” (Lamontagne, Reed, Marangoni, Keller, & Garner, 2019, p. 4). In short, within the bounds of scientific uncertainty, there is a real possibility that even *if* countries implement their NDCs, and even *if* we manage to build NETs at the massive scale required, we may still fail to limit global warming to 2 °C.

Consider further these other uncertainties which are inherent in the SR15 and the models behind it:

(1) “There is considerable uncertainty in how future emissions of aerosol precursors will affect the effective radiative forcing from aerosol–cloud interaction. The potential

future warming from mitigation of these emissions reduces remaining carbon budgets and increases peak temperatures" (Rogelj, Shindell, et al., 2018, pp. 157-158). I.e. there is 'considerable uncertainty' as to how, and/or how much, the reduction of air pollution from aerosols precursors will influence temperatures.

(2) "Modelled pathways that limit global warming to 1.5°C with no or limited overshoot involve deep reductions in emissions of methane" (IPCC, 2018b, p. 14). Meanwhile, in the real world, "the rise in atmospheric methane (CH4), which began in 2007, accelerated in the past 4 years" (Nisbet et al., 2019, p. 318). Furthermore, "if growth continues at similar rates through subsequent decades, evidence (…) demonstrates that the extra climate warming impact of the methane can significantly negate or even reverse progress in climate mitigation from reducing CO2 emissions" (Nisbet et al., 2019, p. 319). As Nisbet et al. point out, exactly what is driving the recent emission rise in methane is not yet fully understood, with geophysical feedback loops, sink saturation, and/or fossil fuels all acting as potential culprits (Nisbet et al., 2019).

(3) Feedback loops. As pointed out in the SR15, "the reduced complexity climate models employed in this assessment do not take into account permafrost or non-CO2 Earth system feedbacks, (…). Taking the current climate and Earth system feedbacks understanding together, there is a possibility that these models would underestimate the longer-term future temperature response to stringent emission pathways" (Rogelj, Shindell, et al., 2018, p. 104). When discussing the remaining carbon budget, the SR15 also notes, "uncertain Earth system feedbacks such as permafrost thawing would further reduce the available budget. (…). As a result, only medium confidence can be assigned to the assessed remaining budget values for 1.5°C and 2.0°C and their uncertainty." (Rogelj, Shindell, et al., 2018, p. 107). Meanwhile, in the real world, Turetsky et al. argue "permafrost is thawing much more quickly than models have predicted, with unknown consequences for greenhouse-gas release. Researchers urgently need to learn more about it" (Turetsky et al., 2019, p. 33).

Taken together, these uncertainties can have a significant impact on the feasibility of SR15 scenarios.

This section has first briefly introduced the term feasibility, before looking at how 'feasibility' in IAMs may differ from 'feasibility' in the real world. It then presented a few factors, other than the once most relevant for this thesis, which may influence the feasibility of the 1.5 °C and 2 °C targets. While the discussion of this thesis will focus mostly on IAMs, CCS and NETs, these uncertainties presented here should not be forgotten – as these uncertainties could greatly influence whether the pathways and scenarios presented in the SR15 *actually* would limit global warming to 1.5/2 °C. Keeping these other factors and uncertainties in the back of the mind, it is time to move on to the discussion section of this thesis.

8. Discussion

Allow me to summarize what has been presented in this thesis so far. IAMs are simplified, idealized and miss out on many of the key characteristics of real-world transitions and decision making. Meanwhile, real-world transitions are messy and difficult to steer. This makes it likely that sustaining the required speed of the build-out of CCS and NETs will be more difficult in the real world than in scenarios. To achieve the necessary emission reductions within the assumed carbon budget, most scenarios rely on rapid reductions by 2030. Most scenarios require CCS, BECCS and/or negative emission measures to remove CO2 from the atmosphere at a large scale. Most scenarios assume CCS and BECCS/NETs to have been introduced at some scale by 2030, and at very large scales by 2050. CCS, BECCS and most other NETs come with significant real-world challenges. Some of these challenges risk putting the scale – of NETs in particular – in direct conflict with other sustainability goals. To achieve the scale of CCS and NETs in median scenarios in 2030, these technologies must, in the coming decade, sustain a faster development rate than solar PV has had in the last 30 years. Large-scale CCS and BECCS are huge projects which generally require several years of planning and construction before being ready, currently planned projects fall far short of what is required in most scenarios. Successfully implementing current nationally determined contributions (NDCs) would mean overshooting the 1.5 °C target and make us fully dependent on NETs to achieve the 2 °C target. Many countries are currently not on track to realize their NDCs. Moreover, IAMs come with some key geophysical uncertainties which risk downplaying the speed and scale of emission reductions needed to reduce warming to 1.5 °C and 2 °C. In short, if we rapidly reduce emissions, rapidly overcome the many uncertainties and challenges CCS and NETs are faced with, and rapidly build them out at an enormous scale – thus managing to sustain the speed imagined in idealized scenarios – we *might* successfully limit global warming to 2 °C, as long as we are ‘lucky’ enough to live in a world where uncertain geophysical realities don’t exacerbate the problem.

The goal here is not to depress you, I promise. The goal is to summarize the knowledge and data which will form the basis of the coming discussion. Can CCS and NETs mitigate climate gas emissions at the scale they do in 2 °C scenarios? What can IAMs learn from transition literature? Are these scenarios feasible, are they probable? When it comes to mitigating climate change, how many uncertainties are we willing to take? Do we gamble on uncertain technologies and potentially cost-effective solutions, and hope it is enough? Or do we take a long hard look at several other factors and potential mitigation solutions? Do we accept what Turnheim & Nykvist points out, namely that "no historical precedent of socio-technical transition can be found that has not involved fundamental re-configurations of not only technologies, but also markets, practices, norms and values concomitantly" (Turnheim & Nykvist, 2019, p. 777), or are we convinced our current values and systems are 'right' and 'good' – and that keeping them should preclude any radical action to mitigate climate change? In short, what are the implications of the data presented in this thesis, and where do we go from here?

8.1. A discussion of what's feasible

When this thesis was first conceived of, I set out to analyse whether CCS and NETs can mitigate CO2 emissions at the scale they do in 2 °C scenarios. As the incredible complexity of scaling up these technologies has unfolded before me, so too has an acceptance that an 'objective' assessment of their feasibility is beyond one man's grasp. Thus, this section will not hold any ultimate answers on feasibility. Instead, it will engage critically with key points presented earlier in the thesis. It will keep in mind that any assessment of future feasibility is "bound up in subjective assessments" (Clarke et al., 2014, p. 420), and encourages you, the reader, to assess the data, weigh it critically, and agree or disagree as your subjective assessment develops. While this section does not claim to hold the final answers, it will not shy away from presenting 'subjective assessments.' However, any such assessment will be either preceded or followed by arguments based on the data presented earlier in the thesis.

This section is structured as follows, first it will discuss the feasibility of CCS, it will then move on to discuss the feasibility of NETs in general and BECCS in particular (since it is by far the most common in scenarios). Building on the discussion of the feasibility of CCS and NETs, I will then move on to discussing the feasibility of the mitigation scenarios in the SR15 and the implications for climate change mitigation.

8.1.1. CCS – 'Still Muddling, Not Yet Through'[30]

If there is one scenario development I consider close to being classifiable as *infeasible*, it is the scale of CCS in 2030 in most scenarios. 100 of 148 scenarios consistent with a 66% chance of 2 °C has a CCS sequestration capacity above 500 million tonnes per year. Only twelve scenarios have a CCS capacity below 200 tonnes per year in 2030. As previously stated, planning and building large-scale CCS plants takes a considerable amount of time. And, in the past, the number of CCS projects which have been proposed but have failed to materialize, outnumber successful projects two to one (IEA, 2016, p. 25; Lipponen et al., 2017, p. 7587). If all currently operating and planned projects come online on time, and at the maximum estimated potential capacity, the global CCS capacity in 2028 would be ~80 million tonnes per year. Of course, new projects could be planned over the next few years, but "CCS is largely absent from the Nationally Determined Contributions and lowly ranked in investment priorities" (de Coninck et al., 2018, p. 343). Thus, the idea that the total annual capturing capacity in 2030 will be more than double the capacity of all currently planned and operating projects – as it is in 137 of 148 scenarios – may be feasible under 'specific model parameterization', but – given what we know about transitions and large-scale CCS – it sounds highly unlikely in the real world.

'Feasible' or not, what these numbers make clear is that if we wish to follow the pathways presented in most scenarios, numerous CCS facilities must be planned and approved over the next few years. To be explicit, if we wish to follow the pathways of most scenarios in the SR15, CCS must have its breakthrough now, not in seven, not in ten, and not in fifteen years. Given CCS' recent history, given the lack of private and public commitment, given the many challenges CCS are facing, it is very difficult to see how CCS, in the coming decade, can sustain an annual growth rate higher than the recent annual growth rate of solar PV. Putting solar panels on rooftops is one thing, building the facilities and infrastructure required for large-scale CCS is quite another. As Bui et al. put it, "if there were to be unambiguous, serious political commitment to meeting a 2 °C target, then all large energy firms would eagerly lobby for CCS, but for most (and many politicians), their preferred alternative is continued unabated fossil fuel use." (Bui et al., 2018, p. 88). With what we know about socio-technical transitions and innovation in mind, building the ~500 large-scale facilities required for the median capacity in 2030 could prove challenging even *if* the political commitment was there. Given the current lack of commitment, building the facilities and infrastructure

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[30] Lindblom (1979)

required to go from 18 to ~500 large-scale facilities in ten years appears implausible. When it comes to CCS in 2030, barring an incredible technological breakthrough and/or immediate and broad political commitment from several governments, failing to reach the scale envisioned in most scenarios appears to be the more likely future.

Beyond 2030, the outlook for CCS becomes more difficult to assess. The extra time increases the likelihood of significant strides in both political commitment and technological development. However, by 2050, the scale of CCS in scenarios has also increased enormously. At ~9.9 billion tonnes, the median annual CCS capacity in 2050 is ten times higher than in 2030, and only one scenario has an annual capacity of less than ~1.5 billion tonnes per year by mid-century. Going from current capacity to the median capacity requires CCS to sustain a growth rate of about 20 percent per year over thirty years. Of course, any 'missing' capacity in 2030 would make the speed required between 2030 and 2050 that much higher. For instance, if the 2030 capacity was to only consist of all currently planned and operating projects operating at maximum estimated capacity – equalling a capacity of ~80 million tonnes per year – CCS would need to sustain an annual growth rate of about 27 percent between 2030 and 2050. As comparisons, consider this from Höök et al.:

"Petroleum energy output grew from virtually nothing in 1870 to nearly 3,000 Mtoe in the 1970s. However, annual growth rates were only around 7% during most of that period" (Höök, Li, Johansson, & Snowden, 2011, p. 27). And this from Lin and Liu, "from 1999 to 2008, the average growth rate of coal production of China was 11.37%, which was almost twice as much as that of 5.8% from 1982 to 1996" (Lin & Liu, 2010, p. 513).

While these numbers compare apples to oranges (by comparing energy output and production to technology scale up, and by comparing the fuels which drive economic output to CCS' handling of 'CO2-waste'), they should help put the required growth of CCS in perspective. If we exclude the 'LowEnergyDemand' scenario (Grubler et al., 2018), which has no CCS throughout the century, the scenario with the lowest CCS capacity in 2050 has a sequestration capacity of 1.47 billion tonnes per year in 2050 (Huppmann, Kriegler, et al., 2018). Thus, even reaching the scenario with the second lowest capacity in 2050 requires opening a new average large-scale CCS facility about every second week between 2020 and 2050[31], and annual growth rates of about 8 percent to be sustained over 30 years.

As already mentioned, if we use the median scenario as the point for discussion,

> “in 2050 the CCS industry will need to be larger by a factor of 2–4 in volume terms than the current global oil industry. In other words, we have 35 years to deploy an industry that is substantially larger than one which has been developed over approximately the last century, resulting in the sequestration of 8–10 GtCO2 per annum by 2050” (Mac Dowell et al., 2017, p. 244)

And while Mac Dowell et al. further note, “this is an exceptionally challenging task, similar in scale to wartime mobilization, but it is a task we should not be daunted by” (Mac Dowell et al., 2017, p. 244), I would like to point out that we now have only 30 years, and that the challenge of the task is growing increasingly exceptional. Whether the task is daunting is a question for subjective evaluation. Whether the task is feasible also requires some degree of subjective assessment. Whether the success of the task is probable – to the point that it serves a rational strategy for mitigating climate change – that is a political question with potentially enormous ramifications for future generations. In my assessment, it is a task which is feasible within the physical laws of the universe. Do I think that makes it realistic? Not really. Do I think it is probable? In a world where we know transitions are ‘messy’, nonlinear, unpredictable, and difficult to control, and current investments and political commitment to CCS is low (de Coninck et al., 2018; Geels et al., 2016; O’Brien, 2018; Turnheim et al., 2015) – no, not at all. Given the many uncertainties CCS are facing, and the many inherent geophysical uncertainties related to climate change, I would argue it should be considered a very risky mitigation strategy.

I will not discuss the feasibility of CCS in 2100 at any length, for that it is too far into the future for any reasonable discussion or ‘subjective assessment’ of feasibility. Instead, I will offer a reminder that the median capacity in 2100 is 16.2 billion tonnes per year, which equals building ~2 large-scale CCS facilities every week between 2020 and 2100. Reaching the median capacity would require CCS to sustain an annual growth rate of 8 percent over 80 years. In short, to follow the trajectory of most 2 °C scenarios, the commitment to CCS must

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[31] Own calculation: 1472.607 MtCO2/yr – 37 MtCO2/yr = 1,435.607 MtCO2/yr,
1435.607 MtCO2/yr / 1.94 MtCO2/yr = 740 facilities
52 weeks * 30 years = 1560 weeks. 740 facilities / 1560 weeks = 0.47 facilities/week

not only be immediate, it must also be sustained for 80 years or more, and – in the median scenario – grow faster than oil ever did.

This section has argued that the scale of CCS envisioned in most 2 °C scenarios is likely to be unrealistic. It is worth mentioning that this goes against the conclusions of some studies, a study by Vaughan and Gough, for example, concluded that "the technology assumptions for CCS were judged to be realistic, suggesting that CCS assumptions do not confront its physical or technical limits" (Vaughan & Gough, 2016, p. 7). While it could be true that the scale of CCS is physically and technically possible, and that many of the key constraints/challenges stem from "social acceptability and policy frameworks" (Vaughan & Gough, 2016, p. 4), the lack of political commitment and social acceptability cannot simply be swept under the rug. Society – and especially global society – is not a homogenous entity were everyone is pulling in the same direction, with the same goals and priorities. To base our assessments of what is feasible in the real world on idealistic assumptions that this is about to change is, in my view, poor science. We may like to pretend that if technological challenges are overcome all will be well, and global society will take on the role of a "fully informed benevolent social planner" (Staub-Kaminski et al., 2014, p. 3). That, however, goes against what social sciences tell us about how socio-technical transitions happen, and how political decisions are made. It also goes against what is happening in the empirical world. I'm hard-pressed to imagine Scott Morrison's newly elected government in Australia, Jair Bolsonaro in Brazil, or Donald Trump in the USA (to name a few) will suddenly turn into benevolent climate change mitigating social planners, just because it is technically possible to build CCS at this scale. Thus, while techno-economic assessments of the scale of CCS is useful to highlight the true scale of mitigating climate change, they are ill-equipped to assess real-world feasibility.

Given that socio-technical transitions are messy, non-linear events, full of conflict and disagreement, there is a very real risk that even *with* the right political commitment the scale of CCS in 2030/2050 would be a difficult challenge. Excluding hopes and wishes, it is thus difficult to find good arguments for why ~500 large-scale CCS facilitates will be constructed in the coming decade, and for why annual growth rates of ~20 percent will be sustained over thirty years. CCS is likely to be needed for limiting global warming to anything close to 2 °C. However, based on the data presented in this thesis, I would argue the scale of CCS in scenarios is more improbable than probable. Basing our current mitigation policies on 'only' following the trajectories of most SR15 scenarios might well prove unwise. If the goal is risk management, our mitigation strategies should reflect that going forward.

As a final note on CCS, sometimes it is interesting to compare where we are today with older academic literature, for instance, consider this from an article form 2013, "IEA argues in its CCS Roadmap (IEA, 2009) the need for 100 large scale commercially operational CCS projects in 2020 in order for CCS to be on track for a substantial contribution to CO2 mitigation." (Nykvist, 2013, p. 685). Today there are 18 large-scale CCS facilities. If ten years from now we are equally far from our roadmaps and pathways, we will by all likelihood be locked into one of two futures, (1) one with a high NETs and/or geoengineering capacity, or, (2) one with temperatures surpassing 2 °C. As we are about to see in the following section, the first of those futures is faced with severe uncertainties.

8.1.2. Feasibility of NETs – high-stakes gambling with unknown odds

"*Victory is a fleeting thing in the gambling business. Today's winners are tomorrow's blinking toads, dumb beasts with no hope.*" – Hunter S. Thompson[32]

This section will focus on the feasibility of NETs. However, given the technology's proliferation in scenarios, extra attention will be given to BECCS. It will first discuss the feasibility of BECCS, before moving on to discussing the other technologies and NETs from a more general viewpoint.

8.1.2.1. Feasibility of BECCS

The first time I read about the scale of BECCS and negative emissions in IPCC scenarios, I thought I had misunderstood something. The attempts to clear up my own 'misunderstanding' began the research that eventually culminated in this thesis. In the SR15, 141 of the 164 scenarios consistent with a 66% chance of limiting warming to 2 °C or less have net negative emissions in 2100, and net emissions in the median scenario are -8.9 GtCO2/yr. 8.9 billion tonnes of CO2, 'sucked out' of the atmosphere, every year. Quite impressive, especially considering the SR15 notes how most NETs "remain largely unproven to date and raise substantial concerns about adverse side-effects on environmental and social sustainability" (Rogelj, Shindell, et al., 2018, p. 121). Mind you, the -8.9 billion tonnes per year are the net emissions, so if there still are CO2 emissions occurring, the actual NETs' capacity must be even higher. And indeed, it is higher. Of the 150 scenarios consistent with 2 °C and with data

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[32] http://www.espn.com/espn/page2/story?page=thompson/011218

on total BECCS, the median BECCS sequestration capacity in 2100 is 12 billion tonnes per year.

As shown earlier in the thesis, removing 12 billion tonnes of CO2 per year with BECCS is likely to come with significant challenges. Not only does BECCS need to grow enormously and rapidly, sustaining annual growth rates of 32% between 2020 and 2050 to reach the median 2050 capacity, it also comes with challenges and uncertainties which might make its scale both unsustainable and infeasible. As discussed in the previous section, scaling up the required CCS capacity is a challenge in itself, but BECCS also comes with the need to convert millions of hectares of land to bio-crops. This could require polices and/or coordination efforts to get farmers across the globe to change their crop production, which, in turn, means directly or indirectly influencing “more than 1 billion small-holder farmers” (Fuss et al., 2018, p. 13). In the real world, this could provide significant governance and public acceptance challenges. Currently, there are very few studies of the public acceptance of BECCS (Nemet et al., 2018).

Even when ignoring governance factors and the speed of the transitions, the scale of BECCS is a huge challenge. Sequestering ~12 billion tonnes of CO2 could require 25–46% of arable and permanent cropland combined, equalling 7–25% of total agricultural land (de Coninck et al., 2018; P. Smith et al., 2015). The water use of BECCS is also expected to be very large, estimates range from hundreds of cubic kilometres of fresh water per year, to thousands of cubic kilometres per year (de Coninck et al., 2018; Fajardy & Mac Dowell, 2017; P. Smith et al., 2015). Taken together, these factors may place BECCS in direct conflict with both biodiversity, food security and water security. Given that climate change’s impacts on food and water security, as well as on biodiversity loss, are some of the reasons for climate change mitigation in the first place, gambling on BECCS does come across as a rather odd choice of mitigation strategy. As pointed out earlier in the thesis, one study argues relying on large amounts of BECCS “bear the risk of triggering potentially irreversible changes in the Earth system” (Heck et al., 2018, p. 153) and that “relying on BECCS as a key decarbonization strategy should be considered highly risky.” (Heck et al., 2018, p. 153).

Vaughan and Gough’s study – which concluded “the technology assumptions for CCS” were realistic (Vaughan & Gough, 2016, p. 7) – also concluded “our results suggest that IAM scenarios use unrealistic assumptions regarding the extent of bioenergy deployment that is possible and unrealistic assumptions about the development of adequate societal support structures (…) needed to enable large-scale negative emissions" (Vaughan & Gough, 2016, p. 7). Indeed, the SR15 itself notes "BECCS mitigation potentials are not necessarily sufficient for 1.5°C-consistent pathways" and "there is uncertainty about the feasibility of timely upscaling" (de Coninck et al., 2018, p. 343). One would think the point of using IAMs to create mitigation scenarios would be to figure out which solutions have 'necessarily sufficient' potentials and 'feasible' timely upscaling, so policymakers could base their mitigation policies on feasible mitigation strategies. Instead, the median BECCS capacity is 4.2 billion tonnes of CO2 sequestered per year in 2050, and only 19 of 150 scenarios sequester less than five billion tonnes per year in 2100.

In short, it should be abundantly clear to any reader of this thesis that there are several and significant uncertainties about the feasibility of large-scale BECCS. Having assessed both the scale of BECCS in scenarios – and BECCS' many challenges and uncertainties – I would argue that most mitigation scenarios in the SR15 should be considered highly speculative. Moreover, based on the sever uncertainties, the significant scale-up, and the very serious potential conflicts with other sustainability challenges – I would argue a mitigation strategy aimed at scaling up BECCS to the level seen in scenarios, is much more likely to fail than to succeed.

To be clear, I am not arguing against continued research and investment into BECCS. Better knowledge about the technology and its real-world mitigation potential is both welcome and needed. BECCS could turn out to be a useful mitigation solution even at smaller scales than in scenarios. However, I agree with Heck et al., relying on BECCS should be considered highly risky (Heck et al., 2018), and, like Vaughan and Gough, I would argue IAMs make unrealistic assumptions about the scale of bioenergy that is possible (Vaughan & Gough, 2016). Thus, my objections to the scale of BECCS are based on the same principles as my objections to the scale of CCS. Given the many challenges and uncertainties BECCS are facing, basing our current mitigation policies on 'only' following the trajectories of most SR15 scenarios might prove to be unwise. An enormously risky gamble, the cost of which would have to be paid by future generations.

I will now take a brief look at the feasibility of other NETs, before closing off this section by discussing the feasibility of negative emissions in more general terms.

8.1.2.2. Feasibility of afforestation

Afforestation comes with the benefit of being a tried and tested ‘technology’ and does – on paper – appear to be a decent short to medium term negative emission solution. Look a little closer, however, and things appear to be a little less clear. First of all, as with most NETs, there is high uncertainty about the real-world sequestration potentials of afforestation. As noted in the SR15, “the full literature range gives 2050 potentials of 1–7 GtCO2 yr^{-1} (low evidence, medium agreement), narrowed down to 0.5–3.6 GtCO2 yr^{-1} based on a number of constraints” (de Coninck et al., 2018, p. 343). Given afforestation’s effect on the albedo effect, the tropics serve as the most likely candidate for afforestation for the purpose of negative emission (Fuss et al., 2018; Houghton, Byers, & Nassikas, 2015), yet “there are too few studies explicitly covering the tropics” (Fuss et al., 2018, p. 34). One study operates with 500 million hectares of available land for afforestation in the tropics (Houghton et al., 2015). If forest could successfully be planted on all 500 million hectares, it could sequester approximately 3.6 billion tonnes of CO2 per year in 2050. However, due to saturation, the sequestration would decline towards zero by the end of the century (de Coninck et al., 2018; Fuss et al., 2018; Houghton et al., 2015). Saturation, combined with the danger of carbon being reemitted to the atmosphere through forest degradation, means there are doubts about afforestation’s long-term effectiveness as a mitigation solution. (de Coninck et al., 2018; Fuss et al., 2018).

Negative emissions from afforestation come at even higher land and water demands than BECCS (de Coninck et al., 2018; P. Smith et al., 2015). If afforestation is done by using native species and restoring natural ecosystems, it could have positive effects on biodiversity (Fuss et al., 2018; Hoegh-Guldberg et al., 2018, p. 266). However, afforestation with biodiversity preservation in mind could reduce afforestation’s effectiveness as a negative emission solution, as it would use native species of tree instead of more ‘efficient’ species (Fuss et al., 2018; Hoegh-Guldberg et al., 2018).

Much like BECCS, afforestation comes with governance challenges, and could require the coordination of a multitude of actors across the globe. So far, there has been little academic attention on the public acceptance of afforestation (Nemet et al., 2018). This is in spite of afforestation potentially having impacts on local livelihoods, farmers, and local landscapes (Fuss et al., 2018; Nemet et al., 2018).

Given afforestation’s total sequestration potential, combined with saturation and permeance issues, afforestation is unlikely to provide negative emissions at the scale required in most scenarios in the long run. In the short term, afforestation’s sequestration effects could be limited, since forests need to grow to reach their maximum sequestration potential. However, if afforestation efforts started now, it could be a good contributor to CO2 sequestration over the coming century. Of course, in the real world, afforestation does not appear to have started now, and in the period 2010-2015 we lost 6.5 million hectares of natural forest per year (UNEP, 2019). In short, like BECCS and CCS, afforestation could be a contributing mitigation factor, but it is no silver bullet, and it comes with several challenges and uncertainties.

8.1.2.3. Feasibility of other NETs

I will not offer a very detailed discussion of the rest of the potential NETs solutions. The reason for this is twofold, (1) they are not currently heavily used in mitigation scenarios, (2) most of them are at such an early stage of development that any assessment of real-world feasibility is fraught with even more uncertainty than for the technologies discussed above. In place of a deep discussion of each individual solution, the rest of this section will first offer brief discussions of the key constraints of soil carbon sequestration and direct air capture, before moving on to discussing the scale of NETs in scenarios in more general terms.

Soil carbon sequestration appears to come with fewer negative side-effects than most NETs. In fact, the biggest challenges for soil carbon sequestration appears to stem from governance and coordination factors. As noted by Nemet et al., a key challenge is the challenge of “moving from dispersed land use decisions to managed and coordinated ones to enable scale up” (Nemet et al., 2018, p. 14). This, of course, means that even though the solution is “immediately deployable” (Fuss et al., 2018, p. 28), it, like all NETs, faces the enormous challenge that is coordinating a global response to climate change mitigation. For instance, “only few studies examine the practical issues of implementing soil carbon sequestration in the developing countries, where biophysical as well as socio-economic challenges may diverge substantially from the existing knowledge base.” (Fuss et al., 2018, p. 34). Much like afforestation, soil carbon sequestration is likely to have a smaller total sequestration capacity, and its potential would decrease over time due to saturation. There are also uncertainties about the solutions capacity to permanently store carbon. Thus, soil carbon sequestration may not be a good long-term solution, but if governance challenges could be overcome, it is perhaps the ‘lowest hanging fruit’ in the short-term.

Direct air capture may be the NETs with the highest 'wildcard' factor. Unlike BECCS, DAC facilities could be placed near storage locations, and could, compared to BECCS, reduce the amount of transportation and CO2-related infrastructure necessary for large-scale CO2 sequestration. Furthermore, DAC comes with fewer direct land-use challenges than most NETs. Of the known challenges, energy use and the speed of the required upscaling are, in my view, key to the potential feasibility of DAC. For DAC to go from a few small projects today, to providing negative emissions at the scale seen in most scenarios within the next one to three decades is difficult to imagine. Believing DAC diffusion can be 'guided' to rapidly achieve the required scale goes against what we know about how innovation and transitions happen in the real world. Moreover, given DAC's early stage of development, there could be several unknown challenges, and, as such, DAC suffers from the uncertainty issues of most NETs. Given the enormous scale of negative emissions imagined in most scenarios, my conclusions on the feasibility of DAC can be no different than my conclusions for BECCS. Getting DAC to the required scale over the next three to eight decades, is more likely to fail than to succeed. Could DAC be one of many future mitigation solutions, certainly. Should more research, investment, and deployment continue and be increased – if the goal is mitigation – definitely. But gambling on DAC providing negative emissions at the scale required in SR15 scenarios comes with huge risks.

At the potential chagrin of their proponents, I will lump my discussion on biochar, enhanced weathering, ocean alkalinisation and ocean fertilization into this one paragraph. These technologies are either missing large-scale trials and/or field experiments. They come with several and sever uncertainties, thus, their feasibility remains unknown. Further research into these potential mitigation solutions is needed, but basing our mitigation policies and strategy on their existence is, again, an enormous gamble.

Before concluding this section on the feasibility of NETs, I should point out that one potential way to alleviate some of the challenges and negative side-effects of individual NETs would be through the development and diffusion of more than one technology (Fuss et al., 2018; Nemet et al., 2018). For instance, deploying both DAC and BECCS could lead to a large CO2 sequestration capacity while alleviating some of the total land use (for BECCS) and energy use (for DAC) concerns. The potential for a portfolio of NETs needs to be further explored. For now, a portfolio approach is "often absent from the NETs discussion" (Minx et al., 2018, p. 17). The limited research that has been done on NETs portfolios does seem to indicate that "adding a second NET to the mitigation portfolio increases the negative emission potentials while reducing mitigation costs" (Fuss et al., 2018, p. 9). It is worth noting that Fuss et al. base this claim on "integrated assessment evidence" (Fuss et al., 2018, p. 9). As such, this assessment risks missing out on many of the real-world challenges of scaling up more than one technology to the scale of gigaton CO2 sequestration. Moreover, even if two or more NETs could be developed at scale, each technology could still require sequestration capacities in the billions of tons per year, and could still encounter many of the challenges outlined in this thesis (Nemet et al., 2018). Regardless, more scenarios exploring the effects – and the required scale of – multiple NETs in a portfolio should be a focus for further research. For now, it remains a largely underexplored approach in mitigation scenarios.

8.1.2.4. The feasibility of negative emission technologies

The challenges and uncertainties for NETs are many and large. Yet they are included in nearly every single mitigation scenario, and, in most scenarios, they are included at a truly enormous scale. Based on the data presented in this thesis I cannot help but agree with what the climate scientists Kevin Anderson and Glen Peters wrote in 2016, "negative-emission technologies are not an insurance policy, but rather an unjust and high-stakes gamble. There is a real risk they will be unable to deliver on the scale of their promise." (Anderson & Peters, 2016, p. 188). Indeed, it is a conclusion often repeated in recent papers on negative emissions and negative emission technologies. Minx et al. concluded, "it seems crucial in the light of the prevailing uncertainties surrounding all NETs to keep the dependence on NETs for achieving the climate targets as small as possible" (Minx et al., 2018, p. 17). Fuss et al. argue, "based on our assessment, large-scale deployment of NETs, as implied by some of the current literature on 1.5 °C scenarios, appears unrealistic given the biophysical and economic limits that are suggested by the available, yet still patchy, science today." (Fuss et al., 2018, p. 35). Perhaps most tellingly, in their review of the literature on the innovation and upscaling of NETs, Nemet et al. found:

> "Given that the broader innovation literature consistently finds long time periods involved in scaling up and deploying novel technologies, there is an urgency to developing NETs that is largely unappreciated. This challenge is exacerbated by the thousands to millions of actors that potentially need to adopt these technologies for them to achieve planetary scale. This urgency is reflected neither in the Paris Agreement nor in most of the literature we review here." (Nemet et al., 2018, p. 1)

Allow me to add my voice to the small but growing choir. NETs at this scale might be theoretically and physically feasible, it may be possible in idealized models which miss out on many human interactions, transition dynamics, and real-world decision-making challenges. It is also highly unlikely in the real world. Based on where we are, where we need to go, and the current lack of action, a mitigation strategy based on NETs sequestering CO2 in the several billions per year in 2050 is much more likely to fail than to succeed. From a risk management perspective, it is an exceedingly risky gamble. If we follow the trajectories of most SR15 scenarios and NETs fail to deliver, future generations could be locked-in to the high-temperature world we sought to mitigate. Gambling on NETs and 'winning' equals handing over the largest part of the bill of climate change mitigation to future generations. Gambling on NETs and 'losing' could equal handing future generation a globe where high temperatures are locked-in, and where the worst potential effects of climate change become reality. This should be better reflected in IAMs, in mitigation scenarios, and in any discussion on climate change mitigation and where to go from here.

I will attempt to begin this process in the coming sections. First, I will discuss what the status of CCS and NETs mean for the feasibility of current 2 °C scenarios, then I will move on to discuss how to improve IAMs, and what potential solutions/pathways they might be missing, finally, I will round off by discussing what the findings of this thesis imply for climate change mitigation going forward.

8.1.3. The feasibility of SR15 2 °C scenarios

"There is no sun without shadow, and it is essential to know the night." – Albert Camus, in 'The Myth of Sisyphus.'[33]

Limiting global warming to 1.5 or 2 °C by following the trajectories of SR15 scenarios, is it feasible? Before giving an answer, let us consider a few unfortunate findings:

- In the median scenario, global emissions have been reduced by ~42% from current levels by 2030. By 2050 all 164 scenarios have more than halved annual emissions compared to the current level (Huppmann, Kriegler, et al., 2018). In 2018, fossil emissions rose by about 2 percent compared to 2017 emissions (Le Quéré et al., 2018).
- In the median scenario, the CCS capacity in 2030 equals ~500 average large-scale CCS facilities (Huppmann, Kriegler, et al., 2018). There are currently 18 large-scale CCS facilities in operation and 25 in various stages of planning. CCS is largely absent

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[33] Camus (2018, p. 123)

from the current nationally determined contributions (NDCs) in the Paris Agreement (de Coninck et al., 2018).

- Successfully implementing current NDCs would lock in a high-NETs dependence for 2 °C pathways (Fuss et al., 2018). Many countries are not on track to meet current NDCs (UNEP, 2018).
- By 2100 the net CO2 emissions in the median scenario is -8.96 billion tonnes per year. Negative emission technologies are at very early stages of development, and most NETs come with sever uncertainties and several challenges. Negative emissions are also absent from current NDCs (Nemet et al., 2018).
- The models which make current mitigation scenarios have idealized decision making and miss out on many of the key constraints and characteristics of real-world transitions. Real-world transitions are messy and difficult to steer. It’s not about simply ‘deploying’ a technology – or, in the case of mitigation, several technologies.
- Most scenarios require rapid declines in methane emissions (IPCC, 2018b, p. 14). Methane emissions have been rising since 2007, and the rate of the increase has accelerated in recent years (Nisbet et al., 2019). The mitigation scenarios presented in this thesis do not properly reflect geophysical feedback loops such as permafrost melting (Rogelj, Shindell, et al., 2018). In the real world, “permafrost is thawing much more quickly than models have predicted, with unknown consequences for greenhouse-gas release” (Turetsky et al., 2019, p. 33).

Is limiting global warming to 1.5 or 2 °C by following the trajectories of SR15 scenarios feasible? No, not based on current efforts. It might be physically feasible, but it is highly unlikely. Barring immediate and radical mitigation action, we are likely to fly past 2 °C or more before the end of the 21st century. It may not be the news you want, but it’s what the data is telling us. IAMs show it is still possible in idealized computer models, but the feasibility of models is not the feasibility of the real world. Based on how truly challenging limiting global warming to 1.5 °C or 2 °C appears in scenarios which miss out on both behavioural realism and potential feedback loops, I would argue that the scientific data is quite clear. Limiting global warming to less than 2 °C by following the trajectories of SR15 scenarios is most likely no longer plausible. Any slim chance of feasibly limiting global warming to 2 °C or less is likely to depend on immediate and radical emission cuts. There are currently no to few signs that, that is about to happen on a global scale. Nothing indicates that current efforts will cut emission by ~40 percent in the coming decade, and nothing indicates that large-scale NETs or CCS will have developed to the necessary scale. For every ton of sequestration CCS and NETs fail to deliver, more must be done elsewhere. For every year without emission cuts, the required scale of NETs grows.

When discussing the role of climate researchers and scientific advisors, the climate researcher Oliver Geden argues:

> “It is by no means their task to spread optimism about the future achievements of climate policy. Instead, to provide high-quality expertise, it is sufficient to critically analyze the risks and benefits of political efforts and contribute empirically sound—and sometimes unwelcome—perspectives to the global climate policy discourse.” (Geden, 2016, p. 796)

This sentiment is echoed by Hickel and Kallis:

> “As scientists we should not let political expediency shape our view of facts. We should assess the facts and then draw conclusions, rather than start with palatable conclusions and ignore inconvenient facts.” (Hickel & Kallis, 2019, p. 15)

Based on what is happening in the real world, combined with what models tell us are necessary, limiting global warming to 2 °C or less is increasingly unlikely. How people and policymakers should react to that are entirely political and value-based decisions. In my view, however, scientist and academics should offer the most reasonable conclusions they can derive from the data they find. To cite Mr Geden once more:

> “Consider the following thought experiment: assume that during the course of the IPCC Sixth Assessment Cycle, the research community adopts standards for assessing the achievability of climate stabilization targets more realistically, and, for instance, communicates its findings in a slightly different way. Instead of saying “yes, meeting the 1.5 °C target is still feasible, but only if A, B and C happens”, the core message would be “no, meeting the 1.5 °C target is currently not plausible, unless governments implement A, B and C” (Geden, 2018, p. 382)

Based on the findings of this thesis, I would take it one step further:

“No, meeting the 1.5 °C target is currently not plausible, unless governments implement A, B and C” (Geden, 2018, p. 382), and public opinion shifts towards accepting radical climate solutions, and we are lucky with both technological breakthroughs and the geophysical realities of currently uncertain geophysical feedbacks.

In short, immediate and radical action may make limiting global warming to 1.5 °C and 2 °C possible, but even with radical action it is not guaranteed, and success appears more unlikely than likely. Such are the unfortunate realities of the real world. Does that mean we should throw our hands up in the air, give up, and let warming be warming? Well, that is a political decision, but from my subjective view, no – that is not the most reasonable conclusion. However, if the goal is mitigating average global temperatures to close to 2 °C, it is time to accept what reality is telling us about the enormity of the challenge. No technology, indeed, no mix of technologies, is likely to solve mitigation on their own – if the goal is climate change mitigation, it takes exceptional and radical action, not in 10 years, not in 15, but now. This message seems to have hit home in the minds of children who have taken to the streets to protests, but policymakers appear to be either living in denial, or not taking the Paris Agreement targets seriously. That, of course, is their prerogative, but they need to be made abundantly aware that if they still wish to limit global warming to 2 °C or less, it is now or never – and potentially they have already left it too late.

In the following sections, I will discuss what this means for mitigation science, integrated assessment models, and real-world mitigation strategies.

8.2. Mitigation science – on neutrality, elephants, and improvements

One must be allowed to wonder, what is the status of mitigation science when 137 of 150 SR15 scenarios end up relying on BECCS, a highly speculative mitigation solution, at an enormous scale? When one of the key solutions in mitigation scenarios is described as "an unjust and high-stakes gamble" (Anderson & Peters, 2016, p. 188), as "unrealistic" (Fuss et al., 2018, p. 35; Vaughan & Gough, 2016, p. 7), and as something which "should be considered highly risky" (Heck et al., 2018, p. 153)? When the very report which presents the scenarios notes how "BECCS mitigation potentials are not necessarily sufficient" and that "there is uncertainty about the feasibility of timely upscaling" (de Coninck et al., 2018, p. 343). When the same report notes how most NETs "remain largely unproven to date and raise substantial concerns about adverse side-effects on environmental and social sustainability" (Rogelj, Shindell, et al., 2018, p. 121)?

What is the status of mitigation science, when IAMs, one of the key scientific tools for assessing mitigation policies, "make restrictive assumptions about the behaviour of social actors" and assume "that actors have complete information, perfect foresight, rational decision-making" (Geels et al., 2016, p. 578)? When IAMs miss out on how policymakers "are usually constrained by their dependence on other actors (such as firms, electorates and civil society)" (Geels et al., 2016, p. 578)? When IAMs "restrict consideration of a wider range of policy instruments" (Geels et al., 2016, p. 578)? When IAMs assume "that policymakers are mostly motivated by cost considerations and climate change problems", while "real-world policymakers (…) seek to reconcile climate objectives with a range of other normative goals and objectives (Geels et al., 2016, p. 578)? When IAM assumptions mean "the social complexity of transformation processes is downplayed or ignored in favour of technical solutions and behavioural approaches" (O'Brien, 2018, p. 153)? When the scenarios favour NETs over short-term mitigation, because they are "affected by the way the future is discounted into present terms" (Chen & Tavoni, 2013, p. 70), and when some argue that "NETs enter IPCC scenarios for the wrong (discounting), not for the right reason (hedging uncertainties)" (Bednar et al., 2019, p. 1)? From a risk management perspective, what is the status of mitigation science when most scenarios rely on highly speculative technological solutions, whilst simultaneously making optimistic assumptions about non-CO2 drivers (such as methane), and excluding geophysical uncertainties such as feedback loops?

In short, what do the findings of this thesis imply about the current status of mitigation science, and how can it be improved? These questions will be addressed in the coming sub-sections.

8.2.1. 'Neutrality' and elephants in mitigation science

"Lastly, it will be realized that the sun occupies the middle of the universe. All these facts are disclosed to us (...), if only we look at the matter, as the saying goes, with both eyes." – Nicolaus Copernicus[34]

The SR15 notes, "removing BECCS and CCS from the portfolio of available options significantly raises modelled mitigation costs" (de Coninck et al., 2018, p. 343). But if CCS/BECCS at this scale turns out to be infeasible, then it is not the most 'cost-effective' mitigation solution, then it is not a mitigation solution at all, but rather a failed gamble which potentially locks in a high-temperature future. Indeed, one of the many political decisions which must be made when it comes to choosing mitigation solutions, is whether we should 'gamble' on what is theoretically feasible – a cost-effective pathway with no room for any

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[34] In 'On the Revolutions of the Heavenly Spheres' (Copernicus, 2017, p. Kindle Location 439)

mistakes or failure – or, whether we should take a more probabilistic approach, not asking ourselves whether suggested solutions are theoretically feasible, but if they are probable. If we conclude that they are not probable, we need to ask ourselves whether we should still ‘gamble’ on them alone, thus potentially saving money and resources. Or, if instead of gambling on cost-effectiveness, we should reduce the risk of failure by exploring a wider set of potential solutions, thus risking doing too much – spending and changing more than strictly necessary – but with the potential benefit of a greater chance at mitigating the issue at hand. Whether our mitigation strategy should be based on cost-effectiveness or on minimizing risks from climate change is a political choice, it cannot be taken ‘scientifically’, for that there are too many value-based and ethical decisions involved. However, when the most influential climate research body, the IPCC, base the mitigation chapters of their reports primarily on the output of integrated assessment models which use “economics as the basis for decision making” (Clarke et al., 2014, p. 422) and therefore “tend towards normative, economics-focused descriptions of the future” (Clarke et al., 2014, p. 422), it cannot be considered an entirely neutral choice. As has been argued in the field of science and technology studies:

> “Instead of science providing a single objective answer, the scientific process generates numerous socially-constructed truths that are products of the questions asked, the people doing the science, values of funding organisations and epistemological commitments about methodological appropriateness” (Evensen, 2019, pp. 428-429).

The questions scientists ask, and the tools scientists employ, will influence the outcome. If you ask idealized models to find ‘cost-effective’ mitigation pathways, they will generate idealized cost-effective scenarios. If you use tools based on normative economic assumptions to ask normative economic questions, they will garner a normative economic response. If you introduce high discount rates, the models will favour late century negative emissions over short-term emission cuts. Basing our mitigation scenarios on these assumptions is a normative value-based choice.

As mentioned earlier in the thesis:

> “A number of scenarios show that limiting global warming to 1.5 °C can be achieved without the deployment of BECCS, while the majority of scenarios use it. (…) highlighting that different societal preferences and strategies can result in vastly different outcomes.” (Huppmann, Rogelj, et al., 2018, p. 1029)

How then do we justify mitigation science focusing so intently on so few “societal preferences and strategies”? Why do IAMs so often focus on cost-effectiveness, if other “societal preferences and strategies” exist? And when we know actors in the real world don’t simply weigh idealized costs and benefits (Geels et al., 2017)? How can we compare and assess different strategies when almost every single scenario relies so heavily on the same or similar strategies, while simultaneously ignoring and failing to assess other strategies?

The stated principles and procedures of the IPCC is to “provide policy-relevant but not policy-prescriptive information on key aspects of climate change” (IPCC, 2010) and “IPCC reports should be neutral with respect to policy” (IPCC, 1998, p. 1). Whether advertently or inadvertently, by relying so heavily on the outputs of IAMs, and by having IAMs explore such a low variety of potential futures, current mitigation science cannot be considered ‘neutral’. To increase the neutrality of the IPCC’s mitigation chapters there needs to be a broader exploration of various solutions, a broader acknowledgement that IAMs (as they are currently used) are not politically neutral, and to better highlight that, indeed, different societal choices lead to different outcomes.

As an example of the lack of ‘political neutrality’ in current mitigation scenarios, consider the following fast-growing elephant in the room.

- “For recent decades, the growth in global CO2 emissions can be explained mainly by the growth in economic activity corrected for decreases in the fossil-fuel carbon intensity (FFCI) of the global economy” (Peters et al., 2011, p. 2)
- “estimates of global CO2 emissions (…) for 2017 suggest an increase of 1.2 percent. The main drivers of the increase are higher gross domestic product (GDP) growth (about 3.7 percent) and slower declines in energy, and especially carbon, intensity” (UNEP, 2018, p. XV).
- “On a global level, CO2 emissions have increased steadily, falling only during periods of economic recession” (Hickel & Kallis, 2019, p. 8)
- “Higher energy demand was propelled by a global economy that expanded by 3.7% in 2018, a higher pace than the average annual growth of 3.5% seen since 2010.” (IEA, 2019, p. 4)
- “Economic growth, particularly in emerging economies, will continue to put upward pressure on energy demand and emissions.” (IEA, 2019, p. 24)

- Absolute decoupling of the economy "is unlikely to happen fast enough to respect the carbon budgets for 1.5°C and 2°C against a background of continued economic growth." (Hickel & Kallis, 2019, p. 12)

To be explicit, emission growth is driven by economic growth. Yet none, zero, not even one, of the scenarios in the SR15 assess the mitigation potential of limiting or halting economic growth (Huppmann, Kriegler, et al., 2018). That cannot be justified scientifically. In the words of Hickel and Kallis,

> "there are no scientific grounds upon which we should not question growth (…). It seems likely that the insistence on green growth is politically motivated. The assumption is that it is not politically acceptable to question economic growth and that no nation would voluntary limit growth in the name of the climate or environment; therefore green growth must be true, since the alternative is disaster." (Hickel & Kallis, 2019, p. 15)

When the result of the 'political' choice of not questioning economic growth leads to mitigation scenarios highly reliant on truly speculative assumptions about real-world dynamics and technological development, what is the status of current mitigation science? In the words of Oxford economist Kate Raworth, "GDP growth shifted from being a policy option to a political necessity, and the de facto policy goal. To enquire whether further growth was always desirable, necessary, or indeed possible, became irrelevant, or political suicide" (Raworth, 2017, pp. Kindle Locations 606-608). But scientists cannot allow the political considerations of their time decide what can and cannot be scientifically explored – if that was the case, Copernicus could never have formulated his model of the solar system, and the earth would still be the centre of the universe.

To be clear, I am not arguing that degrowth is the best solution, that cost-effectiveness should not be explored, nor that the discount rate should be ignored. Nor am I saying that climate mitigation scenarios with limited growth/degrowth are more feasible than scenarios relying heavily on BECCS. Policies aimed at limiting growth and/or degrowth are likely to come with several side-effects and public opinion challenges of their own, and should by no means be assumed to be 'automatically' feasible. What I am doing, however, is pointing out that it is currently practically impossible to have an in-depth discussion or assessment on the benefits and drawbacks of different mitigation solutions. Why? Because practically every single scenario adopts techno-fixes and socio-economic assumptions fully drenched in the political assumptions of their time. To have every scenario assume continued economic growth and high discount rates is not apolitical, it is simply perceived that way because it is in line with current political paradigms. Exploring a wider range of potential pathways would not only be better science, it would, in fact, be *less* political – as it would provide policymakers with a better understanding of a broader range of policy options. ‘Forcing’ techno-fixes down policymakers’ proverbial throats, whether done advertently or inadvertently, is an expression of political choice. Presenting mitigation scenarios based mainly on the idealized techno-economic assumptions of IAMs is a political choice. Only by allowing for the exploration of a wider set of mitigation solutions can the ‘politics’ of IAMs be reduced, and mitigation science be improved. The homogeneity of current mitigation scenarios, combined with their normative economic assumptions, their idealized decision making, their lack of behavioural realism, and inclusion of speculative technologies at an enormous scale, mean current mitigation science offer a poor understanding of the ‘best’ policies for mitigating climate change. Thus, while IAM scenarios manage to highlight the true scale of climate change mitigation, they are poor tools for informing the ‘best’ policy for climate change mitigation in the real world. They are good tools for weighing certain solutions against each other, and for revealing certain dynamics and interplays, but not the best tools for showing realistic pathways to limiting climate change in the real world. Good for assessing costs of one technology compared to another, bad at reflecting how decisions and innovation really happen. Good for showing the need for immediate emission reductions if the goal is 2 °C, bad at assessing the ‘true’ real-world feasibility of certain pathways and developments.

I am not accusing the IPCC, the integrated assessment modelling community, nor mitigation science of being consciously politically biased. Instead, I am pointing out that current approaches are clearly shaped by current societal paradigms. This, of course, makes sense – but when current socio-economic paradigms are the key drivers of both climate change and is causing what appears to be the “sixth mass extinction event in Earth history” (UNEP, 2019, p. 142), mitigation science cannot allow itself to be limited to only exploring solutions which are ‘politically expedient’. Thus, mitigation science must diversify. IAMs must be used to explore a wider set of socio-economic futures, and more scenarios should explore pathways without speculative technological developments. Furthermore, IAM approaches need to be immediately supplemented with insights from social sciences about real-world dynamics. The real world is not a computer model, mitigation science must reflect that.

8.2.2. Mitigation science – suggested improvements

To summarize, if the goal of mitigation science is to explore the cheapest way to mitigate climate change, based on uncertain and idealized assumptions which miss out on real-world dynamics, then all is well. If the goal is to offer 'realistic' assessments of a wide range of policy options to help inform policymakers, then improvements are required. Below I outline some suggested improvements and potential research areas going forward.

- Mitigation scenarios must reflect current knowledge from the social sciences better. Either the behavioural realism of IAMs must be improved, and/or there must be a much closer engagement from social scientists. Insights from innovation and transition literature, as well as from political science, must be better integrated into either the models and/or the papers and reports which present them. Challenges related to public opinion, decision-making process, and the realities of how innovation happens cannot be ignored in mitigation scenarios, as they are among the key constraints and drivers of real-world transitions. As Van Vuuren et al. puts it "IAM modellers typically assume that technologies are deployed on the basis of economic and technical considerations alone" (van Vuuren, Hof, van Sluisveld, & Riahi, 2017, p. 904). We know that is not the case in the real world, and this needs to be better reflected in future mitigation scenarios. Whether this is best done by 'improving' IAMs, making them even more complicated and complex, or by supplementing IAM outputs with more scientific 'scrutiny' from other branches of science is a point worthy of further discussion and research.
- Mitigation scenarios and IAMs must be much more diverse. They should explore a much wider set of assumptions and a much wider set of solutions. More models and scenarios exploring lifestyle changes, changes in consumption patterns, and/or a much wider range of socio-economic developments must be developed.
- More scenarios excluding speculative technologies at a huge scale must be developed. If the models cannot reach temperature targets without speculative assumptions, this should be made clearer and communicated better.

I am not saying scenarios exploring large-scale BECCS and/or CCS should be excluded. Exploring scenarios with optimistic technological development, rapid innovation and deployment is welcome. However, a much wider set of assumptions, and a much wider set of solutions need to be explored in tandem. Given the significant challenges BECCS and CCS are facing, if policymakers choose to base their mitigation policies on SR15 scenarios, the most likely outcome is a world locked-in to warming which exceeds the targets of the Paris Agreement. From a risk management perspective, basing mitigation policies on scenarios which ignore uncertain geophysical feedback loops, the severe uncertainties CCS/NETs are faced with, and the real-world dynamics of transitions, is a poor strategy. Modellers and scientist from all relevant branches should take this to heart and explore a wider range of mitigation options. Social scientists should be much more involved in mitigation discussions and should not be afraid to tackle questions of 'feasibility'. Finally, mitigation science cannot allow itself to only explore what is perceived as 'politically' permissible – that would be a huge step back for the scientific method – and is unlikely to reveal all the mitigation solutions available.

8.3. Where do we go from here?

This thesis does not argue 'against' CCS. It does not argue 'against' NETs. If the goal is climate change mitigation, research and investments in a wide range of mitigation solutions should both continue and be increased. Indeed, if we are to have a chance of limiting global average temperatures to less than 2 °C above pre-industrial levels, I believe we most likely will need CCS, some form of NETs, and a multitude of other technological improvements. In the discussion of whether the current transition to decarbonize the economy can happen faster than historical transitions, I fall on the side of yes. Yes, there is definitely a chance that "political will and a societal sense of urgency" (Sovacool & Geels, 2016, p. 233) can lead to the introduction of policies which "change markets and selection environments or even phase-out technologies before they are written off". However, we should acknowledge that the scale of these technologies, as imagined in most scenarios, is unlikely to be realistic, and that faster does not equal fast enough. In the real world, technologies are not simply 'deployed'. Innovation, transitions, and diffusion of technologies are messy processes. While policies can be introduced in an attempt to steer the transition, and to speed it up, even policies cannot change the nature of the beast – and the beast of socio-technical transitions is more complex than changes in technology mixes and 'deployment' of technologies. Based on the assumption that the assessment presented in this thesis is correct, and the scale of CCS and NETs in scenarios is implausible in the real world, the following section will (briefly) discuss what the implications are for climate change mitigation going forwards. The goal here is not to present the 'right' path, but to begin to discuss what to do if the required scale of these technologies is not realistically achievable.

If there is one thing mitigation scenarios make very clear and which needs to be highlighted, pointed out, underlined, shouted ad infinitum, it is this:

Any delay to rapid emission reductions is likely to lock in either:

1. Very high NETs dependence
2. Dependence on more radical geoengineering solutions (such as solar radiation management).
3. A high-temperature future.

The longer emissions grow, and the longer it takes before they are reduced, the greater the need for speculative technological solutions becomes. As already pointed out, if current NDCs are an indication of where emissions will be at in 2030, we will most probably be locked-in to a future which either surpasses 2 °C, or be highly dependent on NETs to get there (Fuss et al., 2018; Nemet et al., 2018; Riahi et al., 2015). If NETs and CCS at the scale in most scenarios proves impossible, one of those futures can be excluded. That would leave us with a hypothetical reality in which any delay to rapid emission reductions locks in either:

1. Dependence on more radical geoengineering solutions (such as solar radiation management).
2. A high-temperature future.

Let us take a quick look at the first of those hypothetical futures. While an in-depth review of solar radiation management falls beyond the scope of this thesis, a brief overview can say a lot. The SR15 notes how solar radiation management methods “face large uncertainties and knowledge gaps” (IPCC, 2018b, p. 14), “holds risks of changing precipitation and ozone concentrations and potentially reductions in biodiversity” (de Coninck et al., 2018, p. 347), how solar radiation management could “worsen negative effects from continued ocean acidification” (de Coninck et al., 2018, p. 351), and how it could lead to “issues with local agency, and possibly worsening conditions for those suffering most under climate change” (de Coninck et al., 2018, p. 351). The SR15 also highlights how there are several potential ethical challenges and sever governance challenges related to solar radiation management (de Coninck et al., 2018). In short, when it comes to solar radiation management, “it is not yet clear whether the benefits would exceed the harms and risks from its deployment” (MacMartin, Ricke, & Keith, 2018, p. 13). Finally, and perhaps most relevant for the discussion in this thesis, the SR15 notes how “literature only supports SRM [solar radiation modification] as a supplement to deep mitigation” (de Coninck et al., 2018, p. 347).

Thus, if we return to our hypothetical futures, if CCS and NETs in the scale of scenarios proves infeasible – as I have argued it is – and if solar radiation management only serves "as a supplement to deep mitigation" (de Coninck et al., 2018, p. 347), then we are left with two main hypothetical futures:

1. One with immediate and rapid emission reductions
2. One with temperatures exceeding 2 °C or more.

Which leads me to the following conclusion – if the goal is climate change mitigation – we have to stop pretending incremental technological change will get us there. Indeed, we have to stop pretending that technological change alone is 'enough'. We have to accept what the data is telling us, namely that CCS and NETs are unlikely to sequester as much CO2 as they do in mitigation scenarios. Thus, emission reductions must go even faster than in most scenarios. Remember, even in the scenarios presented here – the ones I have argued have 'speculative' amounts of CCS and NETs – median CO2 emissions are 42 percent lower in 2030 than they are today. Those reductions will not come from changes in technology alone. We have to accept that "emissions reductions in line with 1.5°C are not empirically feasible except in a de-growth scenario" (Hickel & Kallis, 2019, p. 13), and that an absolute decoupling of GDP from emissions "is unlikely to happen fast enough (…) against a background of continued economic growth" (Hickel & Kallis, 2019, p. 12). We have to accept what insights from transition theory is telling us, namely that "no historical precedent of socio-technical transition can be found that has not involved fundamental re-configurations of not only technologies, but also markets, practices, norms and values concomitantly" (Turnheim & Nykvist, 2019, p. 777). In short, if the goal is climate change mitigation, we have to accept the true enormity of the challenge. That includes facing unfavourable realities. That includes exploring broader lifestyle changes and changes to consumption patterns. That includes questioning socio-economic rationales.

In the words of energy historian Vaclav Smil:

> "Only if one were to equate the quality of life, or the accomplishments of a civilization, with the mindless accumulation of material possessions, would the rising consumption of energy be an inevitable precondition. But such a primitive perspective excludes the multitude of moral, intellectual, and esthetic values whose inculcation, pursuit, and upholding have no links to any particular level of energy use" (Smil, 2004, p. 559).

Similar arguments hold true for the continued growth of many economies. The side-effects of current societal structures and paradigms have been scientifically known for decades. Modern socio-economic systems, norms, and values drive environmental degradation. Only by exploring values, solutions and policies which stray outside of current societal paradigms can we have an informed discussion on the best way forward. Deciding whether the benefits are worth the costs fall on the table of politicians and philosophers, but to be able to weigh that decision they need a true understanding of where we stand today. Based on the analysis presented in this thesis, I would argue it is very clear where we find ourselves:

Should rapid short-term emission reductions prove impossible, should a more radical socio-economic transition prove unwanted and/or infeasible, well, then the future is likely to be one where global average temperatures continue to increase.

9. Conclusion

"We can't save the world by playing by the rules. Because the rules have to be changed. Everything needs to change. And it has to start today." – Greta Thunberg[35]

This thesis has presented the scale of carbon capture and storage and negative emission technologies in climate change mitigation scenarios. It has performed a critical comparison of the envisioned scale of these technologies, their current real-world status, and the challenges they are facing. It has further presented the integrated assessment models behind the scenarios and compared the assumptions of these models with knowledge from the field of socio-technical transition literature. It has argued that integrated assessment models have idealized and oversimplified assumptions about socio-technical transitions, and miss out on several real-world constraints for the upscaling of technologies. Based on the data and analysis presented in this thesis, I have argued that the scale of CCS and NETs in mitigation scenarios is unlikely to be achievable in the real world. And, by extension, that limiting global warming to 2 °C above pre-industrial temperatures is unlikely to be feasible if we opt to 'only' follow the trajectories of scenarios presented in the IPCC's special report on the 1.5 °C target. I have further argued that current mitigation science and strategies are 'blinded' by current socio-economical paradigms, are not 'politically neutral', and are failing at assessing the true range of potential mitigation options. For instance, even though we know economic growth is driving emission growth, none of the scenarios in the SR15 explore the mitigation

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[35] https://www.fridaysforfuture.org/greta-speeches#greta_speech_tedx. Retrieved on the 8th of June 2019.

potential of limiting or halting economic growth. This cannot be justified scientifically and only limits our understanding of potential mitigation options. Based on the findings, I have presented suggestions for improvements to mitigation science, this includes suggestions that mitigation science would benefit from more input from social sciences, and that mitigation science needs to attend closer to the 'realism' and real-world feasibility of mitigation scenarios. I have argued more research exploring the mitigation potential of changes in lifestyles, consumption patterns, and broader socio-economic changes is required.

Based on all the aforementioned factors, this thesis has argued that immediate and radical emission cuts are likely to be absolutely necessary for limiting temperatures to 2 °C above pre-industrial temperatures. It has further argued that emission reductions at the scale required will not be brought about by technological change alone, but is likely to require changes to the broader socio-economical structures and values of society. While the theoretical possibility for technological breakthroughs, decoupling of the economy, and rapid diffusion of mitigation technologies exist – the assumptions of current mitigation scenarios are neither in line with current empirical data nor with current knowledge on the speed and dynamics of transitions. Basing our mitigation strategies on wishful and idealized assumptions about technological developments and the speed of decoupling is an exceedingly risky mitigation strategy. Gambling on techno-fixes, in the face of real-world geophysical uncertainties, is very likely to lock in a high-temperature future. Thus - from a risk management perspective – if the goal is climate change mitigation, "*everything needs to change. And it has to start today.*"[36]

In conclusion, if we carry on pretending speculative technologies will save the day, and refuse to acknowledge that broader change is needed, we are likely to lock-in a high-temperature future. By trying to avoid change in the broad socio-economic structures of society, we may be forced down paths which lead to even more radical changes in the long run. Due to inherent geophysical uncertainties, doing nothing may lead to the most radical change of all. Only when we accept the stark reality of where we are, can we start having honest political and scientific discussions on the best path forward. Climate change is not a cliff's edge we are working to avoid, we are over the edge, the question is how far we will let ourselves fall.

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[36] Source: Greta Thunberg, https://www.fridaysforfuture.org/greta-speeches#greta_speech_tedx. Retrieved on the 8th of June 2019.

10. Appendix

This appendix briefly outlines which scenarios are included/excluded from the analysis of CCS and BECCS. These paragraphs are included for reproducibility and will not be of much interest to 'casual' readers of this thesis. While this may sound very technical, it is mainly describing which scenarios are excluded/included when selecting different variables in the IAMC 1.5 °C Scenario Explorer.

The data on CCS in SR15 scenarios stem from the 148 scenarios in the database which both are consistent with a 66 percent chance of limiting warming to 2 °C or less and have data on 'CCS (TOTAL)'. Of the 164 scenarios, this excludes 16 scenarios. It excludes 11 scenarios from the study/model referred to as AIM SFCM in the database. These 11 scenarios assess socio-economic factors and future challenges for the 1.5 °C target – for more on these scenarios, see Liu et al. (2018). The last five excluded scenarios stem from the study/model referred to as C-Roads, which explores interactions between emissions reductions and carbon dioxide removal – for more on these scenarios see Holz, Siegel, Johnston, Jones, and Sterman (2018). The reason these 16 scenarios are excluded is that they do not have 'Total CCS' included as an option in the scenario database – which is not surprising given the focus of these studies.

The data on BECCS in SR15 scenarios stem from 150 scenarios in the database which are consistent with a 66 percent chance of limiting warming to 2 °C or less and have data on 'Biomass w/CCS (Total)' in the scenario database. This excludes the 11 AIM SFCM scenarios mentioned above. This also excludes two EMF33 scenarios, and the 'LowEnergyDemand' scenario – for more on these scenarios see Bauer et al. (2018) and Grubler et al. (2018). The reason these scenarios are excluded is that they do not have 'Biomass w/CCS (Total)' included as an option in the scenario database. Why the final three scenarios are not included when selecting the 'Biomass w/CCS (Total)' variable in the database is not immediately clear. However, the 150 scenarios included give a good overview of the use of BECCS in scenarios. Thus, their exclusion has little effect on the general overview of BECCS in SR15 scenarios.

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