Carbon budgets and equity measures combined – Defining a long-term emissions reduction target for Finland in line with the Paris Agreement and global equity

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Abstract:

In this thesis the changed paradigm of international climate policy from negotiated top-down targets of the Kyoto era to the new, Paris Agreement bottom-up mitigation contributions, NDCs is introduced. NDCs are submitted to the UNFCCC on the basis of what countries consider as their fair share of efforts in line with global warming targets, equity considerations and national circumstances. This means that normative decisions on fairness need to be made when selecting a long-term target required by the Paris Agreement.

For this purpose, a framework was developed for considering some of the key issues that emerge in examining long-term climate policy. Different equity measures exist for assessing fairness, of which Equality, Ability to Pay and Historic Responsibility were selected as the ones to consider, since they are the most unambiguous as formulas and are the most prevalent in carbon budget allocation studies. The Paris Agreement temperature targets can be calculated into carbon budgets, of which the most recent IPCC estimation for the 1.5 degree budget was selected and subsequent global emissions subtracted from. To be able to consider all sources and sinks of GHGs, the carbon budgets are applied GHG budgets instead of purely carbon budgets and all emissions and sinks reported in national GHG inventories are included, which are reported in line with IPCC 2006 guidelines. While not a completely accurate utilisation of the carbon budget, this approach is sufficient for examining climate policy ambition.
The equity calculations for allocating the GHG budget to countries for the period of 2020-2050 produced an emissions reduction pathway while the land-use sector net sink was kept fixed according to the historical average with an illustrative pathway for required additional emissions removals. These results were presented in graphs, and key figures pointed out, such as the mitigation rate, the year GHG neutrality occurs, what the 2050 end result is as a reduction of emissions compared to 1990, and at what rate emissions removals are required to increase.

The goal of suggesting a long-term climate policy target in line with climate science, equity and 1.5 global carbon budget was successful in part; all the set conditions were successfully applied and a calculation alongside a demonstrative graph with specific key targets was produced. However, some of the results were unrealistic for applying to real life conditions, such as the amount of emissions removals required in some cases. Mitigation rates, which were fixed as linear, were very drastic in some cases, which might not be possible in present conditions. Contrary to what initially was set out to discover, GHG neutrality targets to be achieved in the 2030s for most cases transpire as the most significant result. GHG neutrality is however only a milestone toward a long-term target, which based on these case studies is a significantly over 100% emissions reduction target.

Keywords:
Climate Change, Mitigation, Climate Policy, Paris Agreement, Equity, Carbon Budgets

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Tiivistelmä:

Kansainvälinen ilmastopolitiikka on siirtynyt Kioton aikakauden ns. top down -sopimisisesta Pariisin sopimuksen mukaiseen bottom up -lähestymistapaan. Tämän lähestymistavan keskiössä on kansallisesti määrätyt panokset, nk. NDCt. Muodostaessa NDC:itä maiden on pohdittava, mikä on heidän reilu panoksensa globaaleihin ilmastotoimiin huomioiden oikeudenmukaisuus, ilmastomuutoksen rajoittaminen tiettyyn lämpötilaan sekä omat kansalliset erityisolosuhteet. Tämä tarkoittaa, että kukin maa tekee normatiivista pohdintaa päättäessään globaalisti reilusta pitkän aikavälin ilmastotavoitteestaan Pariisin sopimuksen määräämällä tavalla.

Pitkän aikavälin ilmastopolitiikan tavoitteen suunnittelun tueksi on tarve kehittää uudenlainen kokonaisvaltainen lähestymistapa. Oikeudenmukaisuuden arvioimiseksi on olemassa erilaisia periaatteita, joista tähän analyysiin valittiin tasajako, maksukyky ja historiallinen vastuu, koska ne ovat kaikkein yksiselitteisimpiä ja ovat myös yleisimpiä tieteellisessä kirjallisuudessa hiilibudjettien jakamisen osalta. Pariisin sopimuksen lämpötilatavoitteet voidaan laskea hiilibudjeteiksi, joista valittiin viimeisin IPCC-arvio 1,5 asteen budjetista ja arvion päivittämiseksi vähennettiin siitä budjetin julkaisun jälkeiset päästöt. Jotta kaikki kasvihuonekaasujen päästölähteet ja nielut voitaisiin ottaa huomioon, hiilibudjetteja sovellettiin hiilidioksidiekvivalentteina. Kaikki kansallisissa kasvihuonekaasuinventaarioissa ilmoitetut päästöt ja nielut, jotka raportoidaan IPCC 2006 -ohjeiden mukaisesti, sisällytettiin analyysiin. Vaikka hiilidioksidiekvivalenteiksi muuntaminen ei ole täysin korrekti hiilibudjetin hyödyntämistapa, se riittää tässä yhteydessä työkaluksi tutkiessa ilmastopolitiikan tavoitteita suhteessa Pariisin sopimukseen.

Tässä opinnäytetyössä tehdyt oikeudenmukaisuuslaskelmat, joissa päästöbudjetti jaettiin maakohtaisesti vuosille 2020–2050, tuottivat vähentämispolun päästöille. Maankäyttösektorin nettonielu pidettiin koko kauden vakiona tasolla, jolla se kaudella 1990-2018 oli mittauksien mukaan ollut. Tulokset esiteltiin kuvaajina ja lukuina, joista ilmeni vaadittu päästöjen vähennystahti, hiilineutraaliuden saavutus, vuoden 2050 päästövähennys verrattuna vuoteen 1990 ja tarvittava negatiivisten päästöjen määrä.

Työn tavoite oli tuottaa työkalu pitkän aikavälin ilmastopolitiikan arviointiin ilmastotieteen, oikeudenmukaisuuden ja 1,5 globaalin hiilibudjetin mukaisesti. Toisin kuin alun perin oli ajateltu, merkittävimmäksi tulokseksi osoittautui hiilineutraaliustavoitteiden ajoittuminen 2030-luvulle useimmissa tapauksissa vuoden 2050 sijaan. Hiilineutraalius on kuitenkin vain virstanpylväs kohti pitkän aikavälin tavoitetta, joka tämän opinnäytetyön perusteella olisi oltava huomattavasti yli 100 prosenttia verrattuna vuoteen 1990.

Avainsanat:
ilmastonmuutos, päästövähennykset, ilmastopolitiikka, Pariisin sopimus, oikeudenmukaisuus, hiilibudjetit

Säilytyspaikka:
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Abbreviations

BECCS	Bioenergy with carbon capture and storage
CCS	Carbon capture and storage
CO_2(e)	Carbon dioxide (equivalent)
CBDR	Common but Differentiated Responsibilities
COP	Conference of the Parties
ETS	Emissions Trading Scheme
ESD	Effort Sharing Decision
GDP	Gross Domestic Product
GHG	Green-house gas
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land-use, land use change and forestry
Mt	Megaton, million tons
NDC	Nationally Determined Contributions
PPP	Purchase power parity
TAB	Threshold avoidance budget
TCRE	Transient Climate Response to cumulative CO_2 Emissions
TEB	Threshold exceedance budget
UNFCCC	United Nations Framework Convention on Climate Change

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1. Introduction

International climate change policy has changed in recent years. Previously, during the Kyoto process emissions reductions were set by the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) in a top-down process – countries were allocated targets as a result of negotiations. This fell through in the end, and in the next evolution of UNFCCC climate policy a bottom-up approach was agreed on in the Paris Agreement. The bottom-up approach of the Paris Agreement is based on Nationally Determined Contributions (NDCs) and the goals of the agreement; each country brings to the table their fair share of efforts in line with temperature targets, equity considerations and national circumstances. The Paris Agreement is a global, legally binding international treaty, which includes the statement that global warming should be limited to 2 degrees while striving for limiting warming to 1.5 degrees. All UN member states agreed on the Paris Agreement and its corresponding COP decision. To evaluate efforts on a global scale, all of the 197 countries of the UNFCCC are required to present their long-term low greenhouse gas emission development strategies reaching to 2050 by 2020. To date, 14 countries[1], or Parties to the Agreement as they are legally known, have produced their strategies to the UNFCCC, so an overwhelming majority are still working on their own submissions. NDCs are also submitted and reviewed for evaluating global efforts in five-year periods in a global stocktake by the UNFCCC. These stocktakes determine, whether the direction of NDCs is sufficient in regard to the Paris agreement goals and submitted long-term strategies.

To be able to assess the NDCs properly, the academic world is digging deep to discover how much we can emit into the atmosphere and avoid the worst effects of climate change. One of such an approach is determining carbon budgets – the calculation on how much carbon can be emitted, so the cumulative emissions, until a certain global warming level is reached, or surpassed (Matthews et al. 2009). The estimations for carbon budgets left for humanity's use vary (Rogelj et al. 2016). The more they are researched, the more complexity is discovered, and knowledge on the remaining carbon budget is continuously

[1] Canada, Germany, Mexico, United States, Benin, France, Czech Republic, United Kingdom, Ukraine, Republic of the Marshall Islands, Fiji, Japan, Portugal and Costa Rica (https://unfccc.int/process/the-paris-agreement/long-term-strategies November 30th, 2019).

updated (Millar et al. 2017). At the same time, the effects and related costs spread unevenly across the world as cause and affect are not felt equally.

Equity and fairness have been key points in climate policy since the start of global climate policy at the Rio Earth Summit of 1992 and the subsequent UNFCCC summits. Greenhouse gases (GHGs) causing climate change are global pollutants and the atmosphere where they end up a common-pool resource (Edenhofer et al. 2014). This means that effort need to be truly global to include all countries and to avoid freeriding. As part of international climate policy negotiations between countries, equity measures can be important in taking negotiations further (Lange et al. 2007) as all issues are considered *'in the light of different national circumstances'* (UNFCCC 2015). Equity measures in the context of climate policy are widely considered in scientific literature, and particularly in the case of carbon budgets. The Paris Agreement and the novel bottom up approach provide much for countries' consideration.

Part of the process of working on these submissions can be thought to be interpreting what the Paris Agreement actually says in regard to deciding on national efforts. An essential element of the Paris Agreement, which is presented in Article 4, paragraph 1 is *'to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century'* (UNFCCC 2015). The timeframe presented here is relatively clear, but the wording of it does leave it open for interpretation. Indeed, the obvious conclusion is that net zero emissions, or in the words of the Agreement a '*balance of emissions and sinks*', are required sometime in the time period after 2050. But there are other aspects worth consideration which also affect timing of net zero emissions, when reading further into the Agreement.

Since the beginning of the UNFCCC, there has been a recurring phrase: Common but Differentiated Responsibilities (CBDR). The idea behind the CBDR is that there is the obligation for everyone to act, but not at equal levels. In general, this means wealthy countries, who have prospered from polluting activities during their development, have caused most of the effects of anthropogenic global warming, and thus should take a stronger role in its mitigation. The CBDR concept is a good guideline for safeguarding many goals for societies' welfare, but again causes trouble for negotiating with countries who are moving towards or overtaking major emitters in the world. In the Paris Agreement and its fourth article, the CBDR is paraphrased into the need for goals to be achieved *'on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty*' (Article 4 in UNFCCC 2015). For wealthy countries such as Finland, with a per capita GDP triple the average global per capita GDP (World Bank 2018), this means it is time to step up.

Not only global justice, but also the scientific realities of climate change, require us to hustle. The emphasis of early action is continuously sprouting up, with the issues of overshoot[2], feedback loops[3] and tipping points[4] creating unsettling scenarios for humanity's future and the Intergovernmental Panel on Climate Change (IPCC) Special report of 1.5 degrees Global Warming showing us the vast difference between 1.5 and 2 degrees (IPCC 2018). The Paris Agreement does its best to convey the urgency of the situation. It says '*[to] aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science*' (Article 4 in UNFCCC 2015). This would then make a strong claim for not too liberal an interpretation with the '*second half of this century*' wording. And not forgetting *'in accordance with best available science'*, which means both in term of the carbon budget but also in social sciences of socio-economic change. Thus, the Paris Agreement gives national governments plenty of aspects to consider when mapping out their long-term plans and interesting opportunities for scientists to study.

Finland, as a wealthy country with large forested areas, high education levels and an agile population size of 5.5 million, is an interesting case study for defining long-term climate policy targets, while taking into account scientific knowledge on carbon budgets and analysis on equity. In this thesis I will examine how the 1.5 °C carbon budget could be allocated to different countries and how different equity principles affect this allocation. I will also look at how land-use sector sinks could play a part in the application of country-specific carbon budgets. I will primarily be studying Finland, but I will also examine some additional case studies to see how well the framework works for different kinds of countries.

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[2] Emitting more than a carbon budget would allow, thus requiring increased sinks and removals, also known as negative emissions.
[3] When one action causes an effect to another, leading to a sum of more than its parts
[4] When a certain level of warming is reached locking us into an unchangeable pathway due

This thesis adds to the environmental economics and burden-sharing literature by developing a cross sector approach and applying it in policy relevant scale and timeframe. In combining the aforementioned carbon budget for limiting global warming to 1.5 degrees, equity considerations and national circumstances, this thesis especially adds to the scientific literature on long-term climate policy targets. The specific contribution of this thesis is the novel way of suggesting fair and sufficient NDCs based on a comprehensive framework of equity, carbon budgets and including all emissions and sinks. This thesis is based on and updates the work previously published as Ollikainen, Weaver & Seppälä: An Approach to Nationally Determined Contributions consistent with the Paris Climate Agreement and Climate Science: Application to Finland and the EU. The Finnish Climate Change Panel, Report 7/2019. *Available online:* https://www.ilmastopaneeli.fi/wp-content/uploads/2019/10/Finlands-globally-responsible-contribution_final.pdf

2. A general framework for forming national climate targets

Returning to the initial research question - how can climate targets in line with climate science and the Paris Agreement be worked out? To answer this, two key theoretical frameworks need to be introduced. To start with, I will examine the concept of carbon budgets for complying with climate science and then move on to looking at the scientific literature on equity criteria as a way for determining a sufficient or fair share in mitigation efforts.

2.1.Defining carbon budgets

Scientific literature agrees on the close to linear relationship between cumulative carbon emissions and global warming (Matthews et al. 2009; Allen et al. 2009), which is however an approximation rather than an exact and predictable result (Collins et al. 2013). The Transient Climate Response to cumulative CO_2 Emissions (TCRE), which can be calculated from different climate models or from past observations on temperature and carbon emissions, describes exactly this relationship (Gillett et al. 2013; MacDougall & Friedlingstein 2015; Matthews et al. 2017). In Gillet et al. (2013) the TCRE is estimated to be 0.8–2.4 °C warming relative to the preindustrial era per 1000 Gt carbon (or 3.667 CO_2 according to Global Carbon Project 2018) emitted, with a median of 1.6 °C per 1000 Gt carbon or 3.667 CO_2. While the simplicity of the TCRE appears appealing for climate policy design, translating this information into how much we can emit in the future is not as simple as could be assumed at first glance.

There are several different ways of estimating the remaining carbon budget, depending on global warming targets, the used data and models, and what it actually is that is wanted to be achieved. Rogelj et al. (2016) provide a good overview of the differences in carbon budgets:

Type 1: CO_2 only budget

The CO_2 only budget is the simplest appliance of the TCRE, since it is formed by calculating how much CO_2 at various probabilities would be emitted for a certain warming scenario to be fulfilled. This is the most straightforward method and it only accounts for CO_2 induced warming. However, we have other greenhouse gases affecting global warming too, which are not considered in this budget. Thus, the CO_2 only budget, which is the most robust carbon budget, is not suited for real life conditions. If the CO_2 only budget was used as an estimate of how much CO_2 we can emit globally and remain within a certain warming limit, global emissions would be too high and warming limits exceeded. Other greenhouse gases need to be accounted for, when looking at a more policy-relevant carbon budget.

Type 2: Threshold exceedance budget (TEB)

In forming the threshold exceedance budget (TEB), multi-gas modelling is conducted including CO_2 and non-CO_2 greenhouse gases and their development in time. This method produces various scenarios rather than a range of figures, so instead of probabilities of outcomes, a percentage of scenarios which produce a certain outcome is used as a measure of confidence. Later, I will use the word probability do describe this, for the sake of simplicity.

The characteristic feature of this type of carbon budget is that it accounts for both a level of non-CO_2 warming and a cumulative amount of carbon at the level of exceeding a set threshold of warming, such as 1.5 or 2 degrees. Non-CO_2 emissions are a deciding factor on the size of the CO_2 budget, so depending on how their development is modelled and how the model is built, the resulting TEB is altered.

Type 3: Threshold avoidance budget (TAB)

As in the type 2 budget, the threshold avoidance budget (TAB) also considers non-CO2 warming. In short, a TAB is based on a calculation, of how much can be emitted while avoiding a temperature threshold with a certain probability. This results in a carbon budget, which for example tells us how much CO_2 can be emitted up to 2050 to avoid 2 degree warming. The TAB budget considers peak warming, at approximately which time global CO_2 emissions are zero.

In addition to the different ways of estimating carbon budgets, their results also vary a great deal. In Table 1 below I have expanded on a compilation of budgets (Hausfather 2018) by adding additional sources and calculations to show the range in the estimates for the remaining carbon budget for 1.5 global warming. The calculation methods for these budgets are TEB or TAB.

Table 1. Remaining carbon budgets for 1.5 C global warming at a 66% probability. Based on figure in Carbon Brief article (Hausfather 2018) with additional sources and calculations.

	Best estimate, from 2018	Budget uncertainty range		Best estimate, from 2020
Millar et al. (2017)	625			541
Goodwin et al. (2018)	693			609
Richardson et al. (2018) HadCRUT	779			695
Richardson et al. (2018) Berkley	467			383
Schurer et al. (2018)	416	325	506	332
Tokarska & Gillet (2018)	395			311
IPCC AR5 ESMs	118			34
Lowe & Bernie (2018)	67	-192	243	-17
IPCC AR5 IAMs		-192	28	
Rogelj et al. (2018) IAMs	193	-182	393	109
Peters (2018) IAM exceedance		318	518	
IPCC SR15	420	210	630	336

Table 1 shows that the range of budgets in tremendous. Global CO_2 emissions are approximately 40 Gt at the moment (Global Carbon Project 2018), so depending on which study we look at, we could even have the equivalent of up to 17 years of today's emissions left. Alternatively, we may have already exceeded the allowable budget; however, the UNEP Gap report 2019 suggests this has not yet happened (United Nations Environment Programme 2019).

The initially simple sounding idea of a global carbon budget thus ends up being very complicated, without even going into the complexity of climate models and data needed to form them. One of the issues of looking at carbon budgets is the need to understand the whole carbon cycle and how it develops in the future. Biologically speaking, if we emit 1 Gt of CO2, the majority of it will end up in the atmosphere and a smaller part of it into ocean and terrestrial sinks, which I will refer to as natural sinks. Figure 1 below from Houghton (2007) shows the difference between carbon emitted and how much ends up in the atmosphere. The gap between the red line (total emissions) and the blue bars (atmospheric increase) shows how much has historically been absorbed into natural sinks. In it also worth noting the fluctuation in the atmospheric increase, showing that it is not a straightforward process, since for example regional vegetation and aquifer changes, and El Nino years affect natural capacities of absorbing carbon. (Houghton 2007)

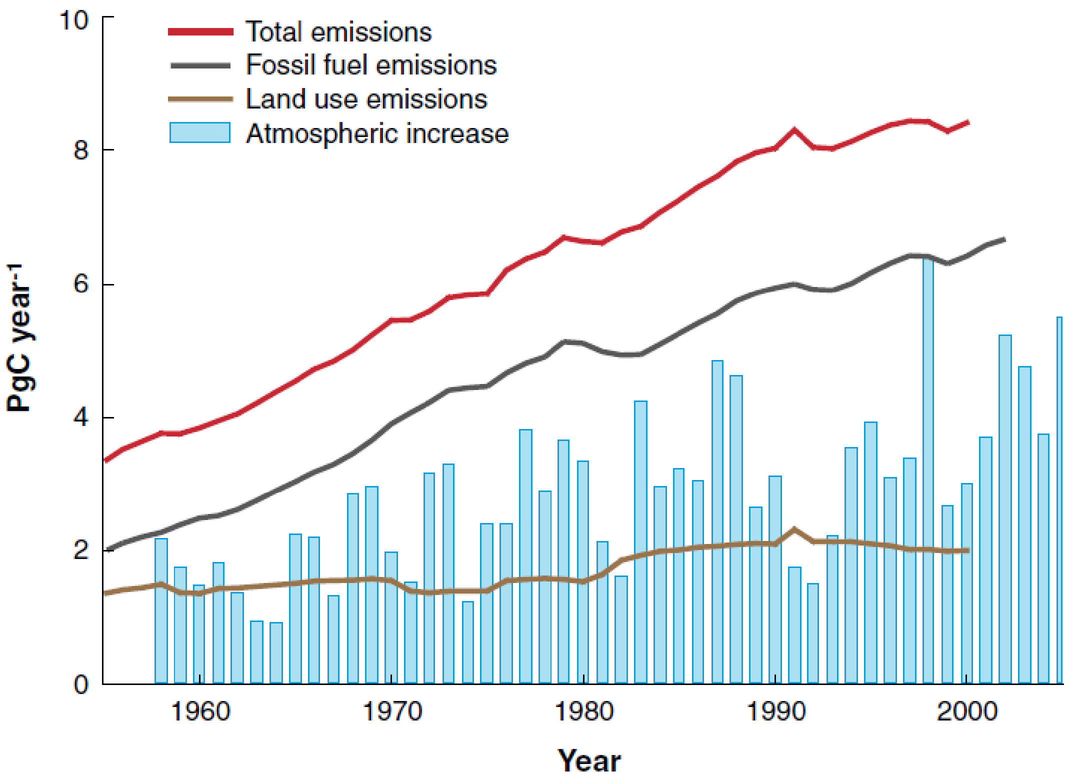

Figure 1. Annual emissions of carbon from the combustion of fossil fuels and from changes in land use, and the annual increase in atmospheric CO_2 (in PgC) over the period 1958 to 2005, from Houghton 2007.

This relationship of atmospheric increase and natural sinks is not fixed and is likely to change. The capability of oceans to absorb carbon lessens when global temperatures rise and cause oceans to warm. Warmer water also decreases biological activity due to its effect on necessary nutrient cycles, which causes less carbon to be absorbed into ocean biomass. Finally, the capability of oceans to take up CO_2 decreases the more CO_2 has already been absorbed. In the case of terrestrial sinks, the effect of CO2 fertilisation to increase photosynthesis does not necessarily lead to significantly higher carbon storage. Other factors, such as nutrients, may become a limiting factor rather than CO_2, and there are diminishing returns on the CO_2 fertilisation effect on plant growth. Even though the fertilising effect of CO_2 has been a factor in the terrestrial carbon sink, its continuity is uncertain. Natural year to year fluctuations also affect the carbon uptake of terrestrial sinks, such as fires or extreme weather conditions. Predictions on the changes in the terrestrial carbon flux are very hard to make, since there is no consensus on the temperature sensitivity of soils, especially in the arctic and boreal regions where there are huge stores of carbon and where simultaneously global warming will be quicker than in other regions. (Houghton 2007).

Since not all emissions end up in the atmosphere, it is worth noting how this is accounted for in national GHG inventories, on which for example UNFCCC commitments are based. In national inventories, most of these ocean and terrestrial sinks are not included. Managed lands are included as well as land-use change emissions, but for example ocean uptake is not part of this inventory (Eggleston et al. 2006). This may lead to some confusion on what the effect of emissions actually is on the atmosphere. However, human activity increases the amount of carbon in the carbon cycle due to the use of fossil fuels, and by releasing carbon from land stores, such as forests, peat lands and soils, alters the timing of the release if carbon compared to the natural cycle. This leads to significantly more carbon in the atmosphere despite natural sinks, such as oceans, absorbing a fraction of it.

In addition to the variations in method, modelling and in resulting budget size, non-CO_2 gases are also relevant for climate policy. There is no similar way to assess how much non-CO_2 can be emitted as in formation of carbon budgets, since the TCRE principle can only be linked to the chemical qualities of CO_2. CO_2 is the most important cause of global warming, since its main source is the use of fossil fuels which adds carbon to the Earth's natural carbon cycle. CO_2 lasts in the atmosphere for a long time – even if all CO_2 emissions were stopped today, the atmosphere would keep warming for decades (Partanen 2018).

So, what is the point of applying such a complex biochemical concept as a carbon budget to climate policy? As discussed in Millar et al. (2016), even though the size of the remaining carbon budget is hard to pin down to one exact number, it is still a useful tool for climate policy. It provides a basis for mitigation policies: carbon emissions need to be eliminated and the path to reaching zero emissions – cumulative emissions - matters. Carbon budgets show that emissions in the past, present and future all effect global warming, thus erasing any illusions on climate change being something for future generations to deal with rather than us today. Showing the effect of cumulative past emissions also provides a useful link to the need for developed countries to take a bigger share in mitigation, per the Paris Agreement.

Criticism on focusing on carbon budgets in the climate policy context have also been also brought forward, and in my opinion, with extremely good reason. For example, Peters in his comment in Nature Geoscience brings together the key arguments in scientific literature against relying too much on carbon budgets (Peters 2018). As discussed earlier in this section, carbon budgets contain levels of uncertainty. Peters brings up this point as an overwhelming obstacle in the use of carbon budgets in climate policy. Peters argues that the high uncertainty undermines the need to commit to action, which could be seen as a reasonable argument based on the range of budget estimates in Table 1 above. The continuous revision of climate models, and collection of emissions and temperature data, do alter the remaining carbon budget. For example, Millar et al. (2017) published one of the first significant papers on the possibility of limiting warming to 1.5 degrees as an existing possibility. In many discussions, this type of publications and results lead to an erroneous conclusion of climate scientist being doomsday prophets who have to go back on their words every few years. Instead, we should be glad it is not vice versa, since global emissions are still growing (Olivier et al. 2018). Even though the remaining carbon budget seems to become larger at each revision, our emissions are not decreasing, which leads to the same key message each time – fossil fuels need to be eliminated.

Peters also remonstrates that many of the different carbon budget scenarios rely on emissions removals after first exceeding a certain level of cumulative carbon in the atmosphere. Emissions can be removed from the atmosphere in several ways: through biological photosynthesis in plants and forests; in technological carbon capture and storage (CCS) in geological formations or mineral form; or by using bioenergy and carbon capture and storage together to replace fossil fuels and recycle carbon (Metz et al. 2005; Haszeldine et al. 2018). The concern over emissions removals has a strong basis, since there are no scalable and economically viable emissions removal technologies yet available (Fuss et al. 2014; Williamson 2016). This means we are putting faith in future innovation or biological processes not fully known, which is risky. What if we back the wrong horse, what if viable technologies do not emerge?

Peters also questions the national policy utility of carbon budgets, which are global by nature and focus on our atmosphere as a single system, while climate policy on the other hand is determined and implemented on national and even subnational levels. However, without any better option, it seems that carbon budgets are reasonable metric for what society is facing in regard to the mitigation challenge. The IPCC in its assessment and special reports usually refers to threshold avoidance budgets, giving confidence that carbon budgets have their use. In this thesis, I have selected a threshold avoidance global carbon budget in line with the IPCC, since a threshold avoidance budget has better policy relevancy than a robust CO_2 only budget, but also a more realistic approach to what needs to happen in emissions development compared to threshold exceedance budgets, when considering criticisms on the risk of relying on future negative emissions technologies. In the sensitivity analysis section, a range of global carbon budgets will be examined, to account for uncertainty in the size of the budget discussed in this section.

Taking a global concept like carbon budgets is difficult to apply unequivocally. In this thesis I will try to overcome especially this issue, but also the others introduced, for which purpose the next section will focus on equity and effort sharing, and the next chapter on data, methods and adjustments.

2.2. What is equity and how it is understood in the context of carbon budgets

There are several ways of determining fairness, equity or justness. Instead of delving into the world of philosophy, history and ethics any further, I will examine some of the most commonly used equity measures or criteria in scientific literature regarding carbon budget allocation or climate policy. In this case I will be looking at equity principles as a method for sharing out the carbon budget, which is comparable to the literature on sharing out emissions permits, but equity can also be utilised as a means to distribute carbon taxes or tax revenue. In this thesis I will be examining equity criteria based on their outcome; what are the required emissions reductions for different countries. (Rose et al. 1998; Metz 2000).

There is no single common way to look at or apply equity in the climate policy context, either in empirical studies or in theoretical works (Bretschger 2013). Instead, there are several different options, and science continues its interest in applying equity despite there not being a single truth, now or ever. In this thesis, the main sources for forming the equity criteria to use in calculations are based on Raupach et al. (2014); Bretschger (2013); Ringius et al. (2002); Höhne et al. (2014); Metz (2000); Mattoo & Subramanian (2012); and Wang et al. (2017).

Equity is the context of climate change is not a single idea; it can be separated into different concepts depending on scope. In his paper, Metz (2000) describe three different scopes of equity: equity between countries (international), equity between groups of people in a country (national or social equity) and equity between generations (intergenerational equity). Equity can also be categorised as equity in the allocation process, equity in initial allocation, or equity in outcome (Rose et al. 1998). Dividing the carbon budget in this case, can be seen as applying equity in the initial allocation, since we are giving a certain quota per country or person according to selected criteria. The scopes of equity that are discussed in this thesis are international and intergenerational, leaving out social equity within a country, as I am looking for insight into a national target which contributes to the global mitigation effort.

The most simple and intuitive distribution of the carbon budget would be in an egalitarian way (Bretschger 2013; Höhne et al. 2014). This means that everyone gets an equal share in the remaining carbon budget and thus the equal right to emit a certain amount of CO_2 within an agreed global carbon budget. The global carbon budget is thus divided equally per capita. An alternative would be to look at equality in outcome, which means per capita emissions in a certain target year should be the same across all people. This would be a more complicated method, since the global carbon budget would have to be allocated into specific emissions reduction pathway for each country by back-casting per capita emissions reduction pathways from the target year to today.

Another approach for allocation is grandfathering, which is sometimes called the inertia or sovereignty principle in the context of carbon budgets (Mattoo & Subramanian 2012; Raupach et al. 2014). Grandfathering is based on the idea that present day national conditions are considered in the allocation process; shares in the global carbon budget are allocated in proportion to current emissions. In practice, this could mean that if a nation's emissions are 10% of global emissions at the beginning of the allocation process, this country would receive a 10% share of the global carbon budget. The rationale behind this is to smooth the path for developed countries with high per capita emissions to make a top-down agreement global agreement acceptable, to consider emitting as an inherent or achieved right, or to make mitigation efforts more affordable. (Rose et al. 1998; Böhringer & Welsch 2004; Mattoo & Subramanian 2012).

Further equity principles can be derived by building on top of the egalitarian principle. From the previously mentioned types of equity, we can bring intergenerational equity into the mix by accounting for past emissions, or what is sometimes referred to as emissions or carbon debt (Matthews 2016). The principle idea is, in line with the link between cumulative emissions and global warming, emissions in the past must be included into the realm of equity consideration; large emitters in the past should have less emissions allocation in the future, since it is cumulative carbon which affects the atmosphere.

For example, in Mattoo & Subramanian (2012) the timeframe which should be considered is discussed. There are arguments for including all emissions since the Industrial Revolution in 1750, when fossil fuels started to be used, or 1850, when industrialisation had spread further. There are two main arguments presented against this. Firstly, in the 1750s and 1850s there was no knowledge of the possibility of causing climate change. Secondly, data on emissions is not reliable enough to provide a specific enough measure of. 1990 is considered to be the year in which we had sufficient scientific consensus on the cause of climate change. Thus, carbon debt should be counted from then on, since emissions were produced in full knowledge of what they were causing in the atmosphere. Another suggested starting point is 1970, which Mattoo and Subramanian themselves pick as the most appropriate time. In 1970, the problem of increased global warming due to carbon dioxide was known (Jackson 2007). Mattoo and Subramanian also suggest that if deciding on 1990 it includes those countries, who rapidly developed during the 1990s allocating to them an equal burden compared to those who had been emitting for decades already and reaped the developmental benefits.

The method for including historic responsibility differs not just in selecting a timeframe, but also in method. Mattoo and Subramanian use a method for calculating a proportion of the carbon budget, while Wang et al. (2015) and Raupach et al. (2014) suggest an absolute calculation method where past emissions higher than the global average directly decrease the emissions allocation for the future. There are differences in the accounted emissions too; some calculations include the highly uncertain land-use change emissions, while others leave them out and focus solely on fossil-based emissions.

A further development on the purely egalitarian allocation of the global carbon budget is to apply a measure for ability to pay, which means that the ability to contribute to mitigation measures and thus who can afford to cut emissions be considered as an equity issue (Wang et al. 2017). The most commonly used metric for ability to pay is national per capita GDP as an indicator for development and welfare (Höhne et al. 2014). Ability to pay as an equity principle is sometimes referred to as capacity to contribute or capability, but this may cause confusion with other considerations such as technological capabilities.

Other commonly known principles, which aren't exactly equity principles, are applied in some contexts too The polluter pays principle, which is widely accepted as a guideline for environmental policy, is perhaps not as suited as such directly as a principle for distributing the global carbon budget, since we are looking for a guideline for initial allocation. It is not clear, how the polluter pays principle should or even could be applied in a global context, instead many argue - with good reason for - cost-efficiency as a mitigation efforts allocation method. We can, however, see that elements of the polluter pays principles exists within the previously presented principles: historic responsibility makes past emissions accountable per the polluter pays principle, and ability to pay is measured by relative economic activity, which can be seen as a rough gauge for consumption levels and thus emissions levels leading to polluter pays again. Figure 2 below from Mattoo and Subramanian (2012) shows how GDP per capita is linked to emissions per capita.

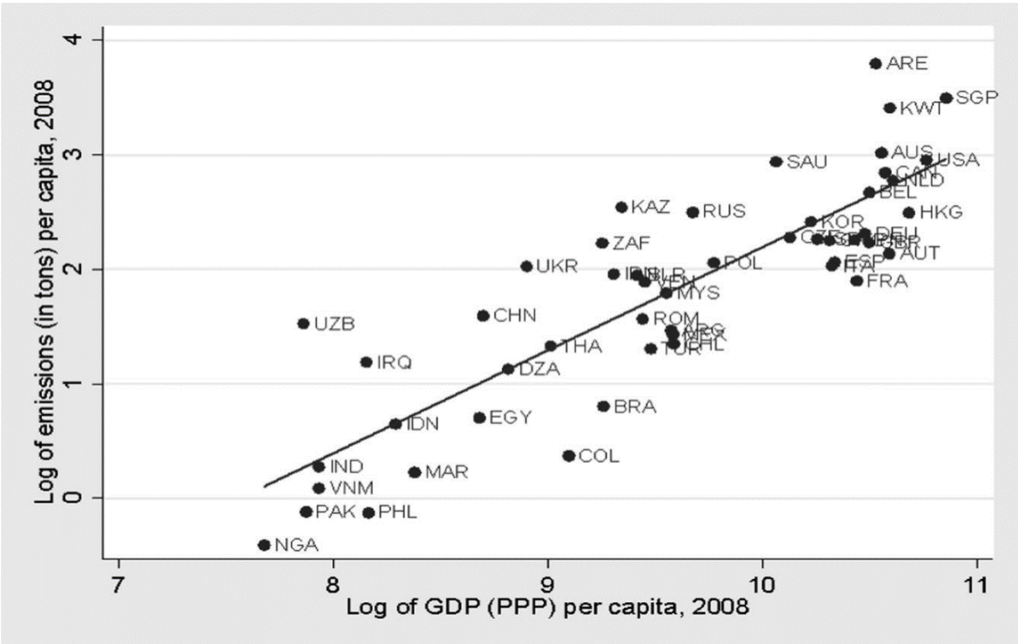

Figure 2. The link between GDP and emission. Source: Mattoo and Subramanian (2012).

Contraction and convergence (C&C) is another way for analysing emission reduction pathways in the context of global carbon budgets. It means emissions in different regions are reduced at different rates which then convergence at a set emissions level in a certain year. There do not seem to be many publications on C&C from recent years as C&C is not an equity principle in itself, but in designing the contraction pathways equity measures could be considered. C&C does however inherently include some elements of equity – the egalitarian principle is applied to the outcome. C&C is thus a topic that is best discussed in the context of emissions pathways but is more difficult to apply in a simple way for sharing out a carbon budget. (Böhringer & Welsch 2004).

After considering the equity principles, the criteria I have selected for this analysis are Equality, Ability to Pay and Historic Responsibility, which I will now present with formulas and some comments on their characteristics and limits. The formulas are developed on the basis of Raupach et al. (2014), Wang et al. (2017), and Mattoo & Subramanian (2012). These criteria were selected to represent three different dimensions – pure egalitarianism, an additional element of capacity to contribute through ability to pay, and accountability for past conscious actions despite the common knowledge of climate change and its causes. An empirical study on international climate policy suggest that these principles, or variations on them, are also the most viable ones for basing climate agreements on or that have been suggested by countries in the UNFCC process (Lange et al. 2007). These criteria and calculations are the same as is Ollikainen, Weaver & Seppälä (2019).

Equality

Simple egalitarian equality is the idea that everyone has equal rights. In the context of carbon budgets, this means that each person in the world has an equal right to the remaining carbon budget. The formula for this calculation results in a per capita carbon budget $q^{e}_{per\ capita}$.

(1.1) $$q^{e}_{per\ capita} = \frac{1}{P} \times Q^{avail}$$

where P is the global population, Q^{avail} is the global remaining carbon budget. Country-level carbon budgets can be calculated by summing up the per capita budgets into national ones with a formula for q^{e}_{avail}

(1.2) $$q^{e}_{avail} = \frac{p_j}{P} \times Q^{avail}$$

where p_j is the population of the country.

Ability to Pay

As previously discussed, another commonly used equity measure is 'ability to pay'. This means that wealthier countries have more capacity for the investments required for reducing emissions and less pressure on societal issues as levels of wellbeing roughly correlate with per capita GDP.

Ability to pay can be assessed by comparing the global average per capita GDP to the per capita GDP of a country. In the case of sharing out carbon budgets, this ratio then determines the amount of the carbon budgets available to that person or nation. In the case of Ability to Pay, $q^{p}_{per\ capita}$ is

(2.1) $$q^{p}_{per\ capita} = \frac{G}{g_j} \times \frac{1}{P} \times Q^{avail}$$

where G is the purchasing power parity adjusted global average per capita GDP and g_j the purchasing power parity adjusted per capita GDP of a country. This can be summed up into a national carbon budget q^{p}_{avail} by:

(2.2) $$q^{p}_{avail} = \frac{G}{g_j} \times \frac{p_j}{P} \times Q^{avail}$$

This method results in a smaller share of the carbon budget the larger the per capita GDP of a country is compared to the global average. Reversely, the smaller the country's per capita GDP is than the global average, the larger the share of the carbon budget it gets. The GDP ratio can be thought of as an extension to the equality calculation, since Ability to Pay is based on the equality per capita carbon budget.

Historic Responsibility

As discussed in the previous section, global warming is caused by cumulative GHG emissions. Therefore, it is reasonable to argue that past emissions should be accounted for when considering equity.

When sharing out the carbon budget, this means everyone has the equal right to the sum of both past and future emissions. In this case, we must determine a starting point for calculating emissions. The per capita carbon budget $q^{h}_{per\ capita}$ according to Historic Responsibility can be calculated as

(3.1) $$q^{h}_{per\ capita} = \frac{1}{P}\left(Q^{avail} + Q^{hist}\right) - \frac{1}{p_j} \times q_{hist}$$

where Q^{hist} are global historic emissions from the base period onward and q_{hist} are the national historic emissions of a country ($\frac{1}{p_j} \times q_{hist}$ equals to per capita historic emissions in a certain country). On a national level:

$$(3.2) \qquad q^{h}_{avail} = \frac{p_j}{P}\left(Q^{avail} + Q^{hist}\right) - q_{hist}$$

The new element in this calculation compared to the previous ones is the addition of a timeframe reaching into the past. But how to determine this starting period? To recall, some analysis suggests 1990 as a good starting point, as this is when climate policy started and there was consensus on anthropogenic causes of global warming. An alternative would be to use 1850 (or even 1750), which is the time of industrialisation and the beginning of fossil-fuel based economies.

Further thoughts

As mentioned in the beginning of this chapter, determining what is fair and equitable is not an easy task and not something for one author to decide on. Alongside the three equity measures presented here, there are several others. The three criteria I have selected are also limited in their ability to fully account for equity in the way they are defined. For example, those who have been historically responsible for emissions are also in many cases those who are now developing climate friendly technology for the use of everyone in the world. For example, in Figure 3 below is an example of a study on clean technologies expressed as innovation indicators. This positive effect gets overlooked in a simple analysis of responsibility.

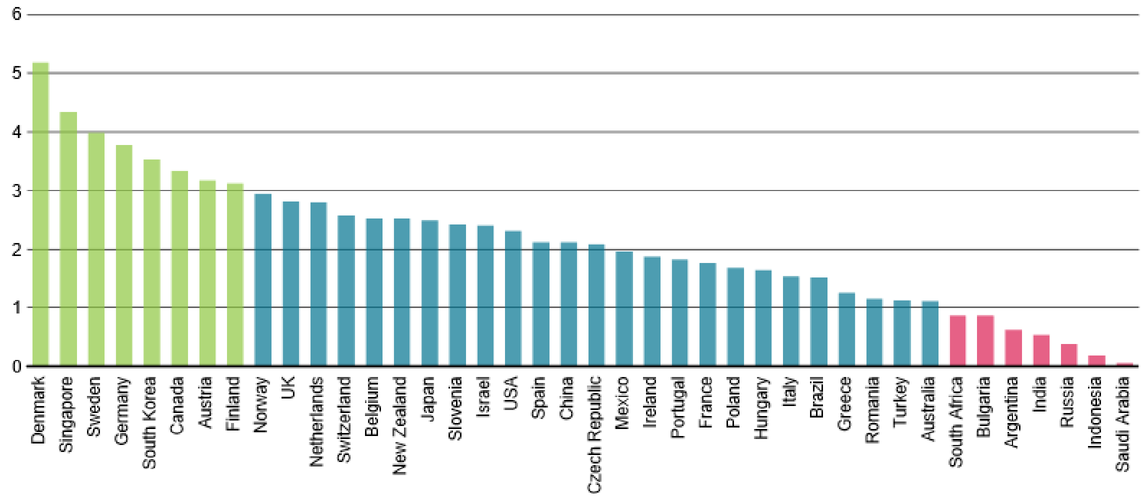

Figure 3. Commercialised Cleantech Innovation in 2017 in the Global Cleantech Innovation Index (Sworder et al. 2017).

In addition, instead of having all different equity principles as separate cases, all different equity measures can be combined into one indicator with different criteria having either equal or varied weights. The weight parameters in the case of this analysis could be s_e, s_p, and s_h, for Equality, Ability to Pay and Historic Responsibility respectively, in a formula in line with Raupach et al. (2014):

(4) $$q^{ind} = s_e q^e + s_p q^p + s_h q^h, \text{where } s_e + s_p + s_h = 1$$

However, even with such an approach as a weighted calculation, determining the weights brings us back into the dimension of ethics and deciding on which element is more important than some other one. There is no one truth on which equity measure is the best, and it is not my purpose in this thesis to try and determine that either. Instead, the idea is to see how the results of these three equity calculations differ or align, when applied in a country-based approach.

3. Applying theory to practice and the data used

Mitigation pathways in line with carbon budgets focus on fossil and process-based CO_2 emissions but in this thesis, I apply carbon budgets and their sharing principles in an adjusted way to include all sectors and all emissions. The methodology in this thesis is the same as in Ollikainen, Weaver and Seppälä (2019) as is the data, except for revisions to include 2019 in historical emissions and the time period examined is 2020 to 2050 and the addition the United Kingdom as a case study.

3.1. Approach

The purpose of this thesis is to examine emissions in all sectors in line with a 1.5 degree carbon budget for the time period 2020 to 2050, while also accounting for the land-use sector. To be able to do this, selections and adjustments need to be made before putting the framework to use both in regard to emissions and to land-use sector net emissions or sinks.

Carbon budgets

Carbon budgets are calculated solely for CO_2 emissions, with a pathway for non-CO_2 emissions, which isn't usually disclosed alongside the carbon budget (see Chapter 2). For the purpose of this thesis and its attempted comprehensive approach, all GHG emissions are accounted for within the carbon budget. So, the CO_2 budgets are utilized as CO_2 equivalent (CO_2e) budgets, or GHG budgets. In Chapter 4 the term GHG budget will be used in the case studies to indicate that all GHGs are included in these calculations. The effect of this is a deviation from the atmospheric science defining carbon budgets and it also leads to a stricter than necessary national quota per country. This is because we are now including into the budget, or quota, emissions that were initially supposed to be in the quota, thus decreasing the possibility to emit the full quota of CO_2.

Mitigation rates and remaining emissions

Certain selections have to be made for the emissions pathway. The starting point for calculating a national GHG target is to start decreasing emissions linearly from current emissions levels. The reason for using linear pathways is based on EU climate policy, which is designed in linear pathways (European Union 2018). The starting point for the pathway analysis is 2020 and the end year of 2050 is selected to coincide with the long-term low greenhouse gas emission development strategies timeframe required under the Paris Agreement[5].

In the case where the results of this analysis would provide, mitigation targets of closer to 100 % or more, it is reasonable to assume some emissions remain unmitigated to due e.g. high costs, lack of alternatives or as backup energy and precautionary measures (Capros et al. 2014; Rockström et al. 2017). Thus, first I look at what annual mitigation rates a purely linear reduction path would results in. Then I adjust the pathway in such a way that emissions will be decreased at the linear rate up to a point, which is either a 90% or 95% reduction compared to 1990 levels. After this, emissions remain at that level until 2050, and these remaining emissions must be compensated for by emissions removals technologies.

How to consider LULUCF

The Paris Agreement states that the goal of the agreement is *"[…].to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century"* (UNFCCC 2015). There is an ongoing debate on what exactly the phrase *"balance between anthropogenic emissions by sources and removals by sinks"* means, since it depends on how and during which time period we are measuring emissions and sinks. In Ollikainen, Weaver & Seppälä this issue is bypassed by the decision to focus on national emissions and sinks calculated according to IPCC 2016 guidelines and reported to the UNFCCC. This is a feasible approximation of anthropogenic emissions and sinks, since it excludes some non-anthropogenic sinks, such as oceans, and is the best available information available across many countries at this time. The same interpretation is made in this thesis. (Ollikainen et al. 2019).

Climate models on which carbon budgets are based on include global land-use sector emissions and sinks in addition to natural sinks (Peters et al. 2015). However, the specific amounts in the land use sector for each country cannot be drawn out of them, which makes a convincing case for omitting national sinks in a country-specific calculation as it would lead to double-counting. But, the IPCC 1.5 degree report (IPCC 2018) emphasises the need for emissions removals, or strengthened sinks, for keeping within the limits of emissions allowed for remaining at 1.5 degrees. To account for the importance of sinks

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[5] Article 4, paragraph 19.

as part of successful net emissions reduction and to have all sectors combined into a comprehensive approach, the land-use sector is included fully in these calculations. When discussing the net land-use sector sink, I mean the biological sum of emissions (from e.g. land conversion and soil emissions) and sinks (carbon accumulating in soils, forests, and harvested wood products). In the case of a country having a net sink in the land-use sector, this leads to more lenient targets than in the case without the land-use sector, since there is some level of land-use sector sink inherently in carbon budgets already.

Therefore, as these two alterations in dealing with carbon budgets have opposite effects (CO_2e instead of CO_2 makes targets stricter, but including sinks fully makes them more lenient), I assume they balance each other out and feel confident of the reliability of this method. In the section on sensitivity analysis, I will provide results from a more correct approach, accounting for solely CO_2 and only part of the sink as an offset.

The net sink effect of the land-use sector in EU countries has historically fluctuated from one year to another depending on climactic and economic conditions (Eurostat 2018). Thus, it is safe to assume this will happen in the future too. No just between years, but also within each year there is uncertainty on how land-use sector sinks and emissions develop and their measurement reliability (Collins et al. 2013). To make the calculations and visualisations clear and to overcome the issues of fluctuation and uncertainty, the concept of *the average land-use sector net sink* is introduced, which means an assumed average constant value for the land-use sector net sink over a certain time period. I will refer to this as the baseline sink. A selection of baseline sinks will be presented to represent possible future scenarios for the land-use sector. Through this selection of sinks, uncertainty in the size of the possible future net sink can be addressed. Examining the smaller sinks instead of the larger sinks can be a way for taking into account uncertainty over the reported land-use sector sinks and emissions in line with the precautionary principle[6]. This way of addressing sinks is based on the approach in Ollikainen, Weaver & Seppälä (2019).

In some cases, emissions reduction may need to be over 100% to comply with carbon budgets. This means additional emissions removals are required alongside mitigation and the emissions removals provided by the average land-use sector net sink. Negative

[6] The precautionary principle in Kriebel et al. 2001: “taking preventive action in the face of uncertainty” and shifting the burden of proof to the proponents of an activity”. (Kriebel et al. 2001)

emissions technology or other GHG absorbing activities, such as increased land-use sector sinks in addition to the baseline level, are examples of additional removals.

Since the purpose of this thesis is to provide climate policy targets and pathways leading to it, it is worth addressing emissions removals pathways too. To do this and keeping in mind the nature of the land-use sector, in this analysis increasing additional removals is added to the pathway from 2031 onwards. The year 2031 is selected as a compromise to represent a time in the future when we may have viable emissions removal technology available. On the other hand, additional removals in the land-use sector take time to show up in measurements despite immediate implementation, such as the effect of planting tree saplings or increasing the carbon content in agricultural soils. Another reason for selecting 2031 is to look at EU land-use sector climate policy, which will be in place for the first time for the period of 2021-2030. Initiating additional removals from 2031 can be seen as making climate targets more ambitious after learning from the first period of land-use sector climate policy, in line with the Paris Agreement mechanism of continuously increasing ambition. (Ollikainen et al. 2019).

3.2. Data

I this section I will present all the figures used for the calculations in this thesis, and the following sections describe why each figure and source was selected.

Carbon budgets

Carbon budget estimates vary tremendously, as discussed in Chapter 2. For the purpose of this analysis, the most recent IPCC estimate of the 67% probability 1.5 degree budget from Table 2.2 of the SR15 is used (IPCC 2018). The results of sensitivity analysis on this budget will be examined in Table 4 in section 4.4 of this thesis.

The figures for the selected carbon budget are presented in the table below. However, the original carbon budget in the SR15 is for the period starting from January 2018. To adjust for emissions that have occurred since, two years' worth of CO_2 emissions are decreased from this figure to reflect a more suitable carbon budget for starting in January 2020. According to the Global Carbon Project (Global Carbon Project 2018) global CO_2 emissions were approximately 42 Gt in 2017. It is likely emissions have been approximately at this level since, so for the sake of this calculation 2018 and 2019 emissions levels are assumed to remain the same as 2017 emissions were. The resulting new carbon budget from 2020 is therefore 336 Gt, as Table 2.1 shows.

Table 2.1. The remaining carbon budget according to the IPCC special report (IPCC 2018).

	From 1.1.2018	**From 1.1.2020**
Remaining budget for limiting warming to 1.5°C relative to the 1850-1900 period	420 Gt CO_2	420 – (42+42) = 336 Gt CO_2
Uncertainty[7]	-210 to +210 Gt CO_2	

The reason for selecting this carbon budget, is that the IPCC utilises the knowledge of hundreds of scientists in its formation of reports. There may be more recent calculation available, but I am confident in using this IPCC estimation of the carbon budget, which seems to be the most commonly used in the climate policy context.

Emissions and sinks

Currently, only data up to 2017 is available from Eurostat (Eurostat 2018), so this is what will be used for emissions statistics on the countries studied. There may be more up to date data available from national statistics agencies, but as one of the key case studies is the whole of the EU, a single source for statistics including all cases is preferred to make results comparable. These emissions include all GHGs, from both the ETS and non-ETS sectors, and separately from the land-use sector. International aviation is also included in these figures, which is why they differ slightly to the official emissions reports submitted to the UNFCCC[8] and the calculations in Ollikainen, Weaver & Seppälä (2019). Emissions from international aviation in Finland, which is calculated according to use of aviation fuels in Finland, have increased from 1 Mt in 1990 to 2.5 Mt in 2018, which is why I have included them in the calculations of this thesis (Statistics Finland 2019). As in the previous case of adjusting the global GHG budget, emissions in 2018 and 2019 at national

[7] Due to uncertainty in non-CO_2 scenario variation, non-CO_2 forcing and response, TCRE distribution, historical temperature and recent emissions, the uncertainty range is presented as +/-50% (IPCC 2018)
[8] National Inventory Reports submitted to the UN are available from: https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/national-inventory-submissions-2019 Retrieved 4.11.2019. Estimations of emissions from international aviation, i.e. “Emissions from flights that depart in one country and arrive in a different country. Include take-offs and landings for these flight stages.”, but they are not reported I official national statistics. (IPCC 2006)

levels too will be assumed to be equal to 2017. This may not be true in all cases but is a reasonable assumption.

Emissions statistics on the case studies of this thesis are shown in table 2.2 below.

Table 2.2. Emissions and sinks in the EU, Finland, Sweden and Germany (Eurostat 2018).

	EU	**Finland**	**Sweden**	**Germany**	**UK**
Most recent annual emissions Mt CO_2e (2017)	4 483.14	57.50	55.45	936.00	505.4
Most recent LULUCF Mt CO_2e (2017)	-258.07	-20.38	-43.73	-15.19	-9.9
Net emissions Mt CO_2e (2017)	4 225.06	37.12	11.72	920.82	495.5
Emissions in 1990 Mt CO_2e	5 722.89	72.32	72.66	1 263.2	809.9
LULUCF in 1990 Mt CO_2e	-244.98	-14.77	-34.40	-31.3	0.3
Net emissions in 1990 Mt CO_2e	5 477.91	57.54	38.26	1 231.8	810.1
Average LULUCF 1990-2019 Mt CO_2e	-290.21	-21.15	-37.94	-21.3	-6.1

As we can see in Table 2.2, emissions in all these case studies have fallen since 1990. Net sinks have also grown in all cases, except Germany. When looking at net emissions, we can see that the biggest change is for Finland and Sweden when comparing to purely fossil and process-based emissions – for Finland the land-use sector sink covers one third of total emissions, and in Sweden the sink covers approximately 80% of all emissions. In Germany and the EU, the effect is much smaller, approximately 2% for Germany and 6% for the EU.

For global emissions and sinks different sources are needed in comparison to the European case studies. The most comprehensive data on all GHGs was available from Olivier et al. (2018). For the land-use sector FAO's database (2019) contained the most up to date figures. These are presented in Table 2.3 below.

Table 2.3 Global emissions (Olivier et al. 2018) and sinks (FAO 2019).

	World
Most recent annual emissions Gt CO_2e (2017)	50.860
Most recent LULUCF Gt CO_2e (2017)	3.151
Net emissions Gt CO_2e (2017)	54.011
Emissions in 1990 Gt CO_2e	32.910
LULUCF in 1990 Gt CO_2e	4.122
Net emissions in 1990 Gt CO_2e	37.032
Average LULUCF 1990-2019 Gt CO_2e	3.802

These two sources are selected for their clear description of what emissions they cover and from what sectors. Especially in the case of land-use emissions and sinks, the FAO database had the most precise data – other sources, such as the Global Carbon Project (2018) do not specify the categories of land-use emissions and sinks. It is important to know, which emissions and sink are accounted for, since the aim is to stay within the limits of anthropogenic emissions and sinks, per the Paris Agreement.

Population

All of the equity measures presented rely on the idea of a per capita allocation of the carbon budget. For this purpose, we need to estimate both the global and national populations for the time period examined. The number used in this thesis is the average population of the years 2020 to 2050 according to UN projections (United Nations 2017). This source is selected to provide a unified method for population estimation so that results can be comparable. These population projections are based on modelling of fertility, mortality and international migration, and knowledge on current demography (United Nations 2019). The current revision is the 26th in total for this UN population data, which makes it a reliable source for population estimates due the continuous revisions and methodology developments.

It is suitable to use this type of average figure over time, as the emissions pathway is plotted as a linear reduction and the emissions quota is a cumulative quota over time. If this would be averaged out[9] it would result in the same end point as if using annual estimates for both emissions and population. The figures used in this analysis are presented in Table 2.4 below.

Table 2.4. Average populations 2020-2050 in all case studies and the world.

	World	**EU**	**Finland**	**Sweden**	**Germany**	**UK**
Average population in billions/millions 2020-2050	8.844	521.72	5.55	10.80	82.41	71.36

An alternative reliable source for calculating the global average future population is Worldometer, which base their estimations on several different data sources (Worldometer 2020). The result from their estimations is that the global average population over 2020 to 2050 is 8.884 billion people, which is very close to the estimation by the UNDP. However, I decided on the UNDP source due to easier data download and accompanying analyses.

Now that there is an estimate of the population, per capita emissions can be calculated. These are presented in Table 2.5 below.

[9] If the global emissions quota was divided into equal shares for each year, divided by estimated population during each year and summed up into national quotas, we would get the same result as using an average for the whole time period.

Table 2.5. Per capita emissions and net emissions.

	World	EU	Finland	Sweden	Germany	UK
Emissions per capita t CO_2e, (2017) with future average population, without LULUCF	5.75	8.6	10.4	5.1	11.4	7.1
Net emissions per capita t CO_2e (2017) with future average population, with LULUCF	6.11	8.1	6.7	1.1	11.2	6.9
Emissions per capita t CO_2e 1990, with future average population, without LULUCF	3.72	11.0	13.0	6.7	15.3	11.3
Net emissions per capita t CO_2e 1990, with future average population, with LULUCF	4.19	10.5	10.4	3.5	14.9	11.4

Gross Domestic Product (GDP) per capita

As a measure of wealth and wellbeing, GDP per capita is a commonly used measure. The figures used in this analysis are from the World Bank's database (World Bank 2018), and represent GDP based on purchasing power parity (PPP) per capita, in current international dollars. The figures are presented below. It is worth noting, that the absolute values of each GDP per capita is not significant, since what we will be looking for is GDP per capita in relation to the global average.

	World	EU	Finland	Sweden	Germany	UK
GDP, $ PPP adjusted 2018	17 914	43 715	47 930	52 725	53 735	35 450

4. Globally fair pathways for reducing net emissions: Finland

The allocation of carbon budgets for Finland were calculated in Excel and according to the formulas presented in Chapter 3. This resulted in the following national quotas for net emissions from all sectors for 2020-2050, presented in Table 3.

Table 3. National quotas for net emissions from all sectors for 2020-2050 for Finland overall and per capita.

	Equality	**Ability to Pay**	**Historic Responsibility**
Emissions quota for Finland, Mt CO_2e	211 Mt	79 Mt	-440 Mt
Emissions quota per capita, t CO_2e	38 t	14 t	-79 t

These quotas in Table 3 are the amount of net emissions allowed for Finland during 2020-2050. Equality and Ability to Pay have positive quotas, but Historic Responsibility has a negative quota. This means Finland has overused its emissions space in the past (1990 to 2019) compared to the world average, so this must be made up for in the future. All these national quotas can also be presented as per capita quotas, which are presented in Table 3 above in the second row. The per capita budgets reflect the same initial impression as the national quota - given that current national net emissions of Finland are approximately 37 Mt per year and per capita net emissions just under 7 t per year, these quotas, which should cover emissions for 30 years, signal a need for deep cuts in emissions and increased sinks or emissions removals alongside them.

The GHG quota in this analysis is divided into emissions quotas per year by first looking at what linear mitigation rate would be needed in the case of average land-use sector net sink. The results are adjusted so that when emissions reach 7.23 Mt, a 90% reduction, they remain at this level. This results in net emissions larger than the GHG quota, since the average land-use sector net sink is fixed. To correct the result, calculations are made on what additional removals rate is needed per year from 2031 to 2050 to keep the net emissions within the quota. These are the main elements in the framework of translating a set quota into an emissions pathway.

The following sections present the results of each case of equity, with graphs to demonstrate the required linear reduction path and possible additional removals. In each equity analysis, two different national average net land-use sector sink values are used to take into account uncertainty in the future development of the land-use sector and to account for the issue of some amount of the national net sink being inherent to the carbon budget. This chapter is concluded with brief sensitivity analysis on the size of the global carbon budget and national average net land-use sector sink.

4.1. Equality

In the case of Equality, the GHG budget for Finland is the largest of all the three cases of equity. The calculation method for the quota used is presented earlier in Chapter 3, which led to the results presented in Table 3 of this chapter.

The amount of net emissions allowed for Finland in the case of Equity is 211 Mt between 2020 and 2050. Current emissions levels being approximately 56 Mt, this 211 Mt quota would mean less than four years of emissions at the current rate if sinks are not considered. Figures 4a and 4b below demonstrate what this 211 Mt GHG quota would look like according to the set framework of linear emissions reductions up to 90% compared to 1990 levels; after 90% is reached, emissions remain at this level; an average land-use sector net sink of either -21 Mt or -14 Mt; and increasing emissions removals from 2031 onwards.

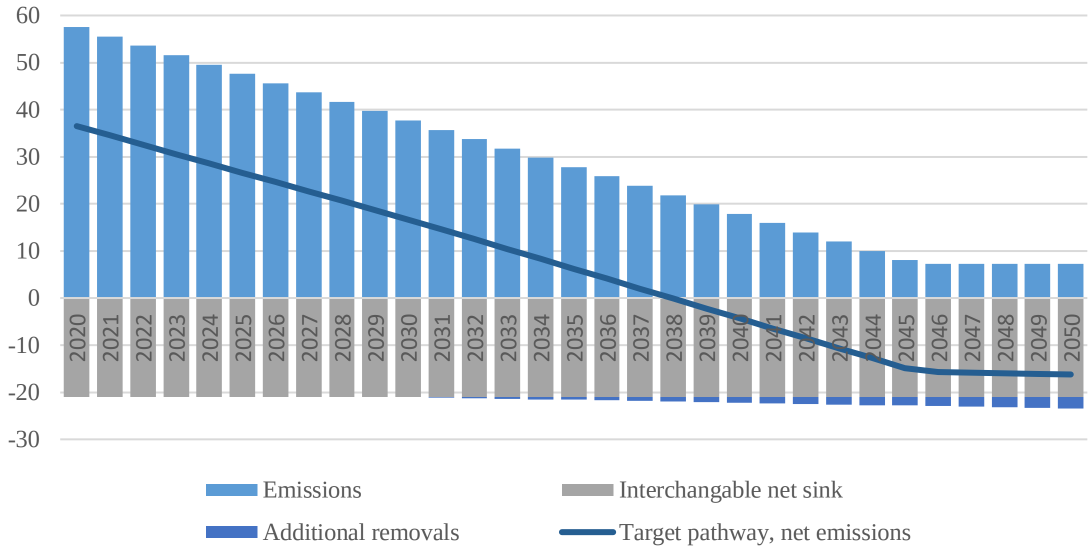

Figure 4a. The global carbon budget divided according to Equality, linear emissions reduction and increased removals, and a net land-use sector sink of -21 Mt for Finland

In the case of the larger net sink of -21 Mt, emissions reduction rates are 1.98 Mt per year up to 2046, when emissions plateau at 7.23 Mt. GHG neutrality occurs in 2038, so three years later than the Finnish government's current target of 2035. Emissions removals increase gradually, by -0.12 Mt per year, leading to -2.46 Mt of additional removals in 2050. The resulting target for 2050 is 93% reduction compared to 1990. This reduction target includes the emissions shown as the lighter blue bars and the dark blue bars indicating additional emissions removals. The reduction percentage *R* compared to 1990 is calculated as follows:

(5) $$R\text{: } \left(1 - \frac{\text{Emissions left in 2050+additional removals in 2050}}{\text{1990 emissions}}\right)\%$$

In this first case of equity, the resulting Equality long-term target percentage-wise is:

(5.1) $$R_{E1}\text{: } \left(1 - \frac{7.23+(-2.46)}{72.32}\right)\% = 93\%$$

Even though the reduction target is less than 100%, when the net effect of emissions and emissions absorbing sinks and removals is considered, Finland is net negative in 2050. All emissions, sinks and additional removals add up to -16.23 Mt.

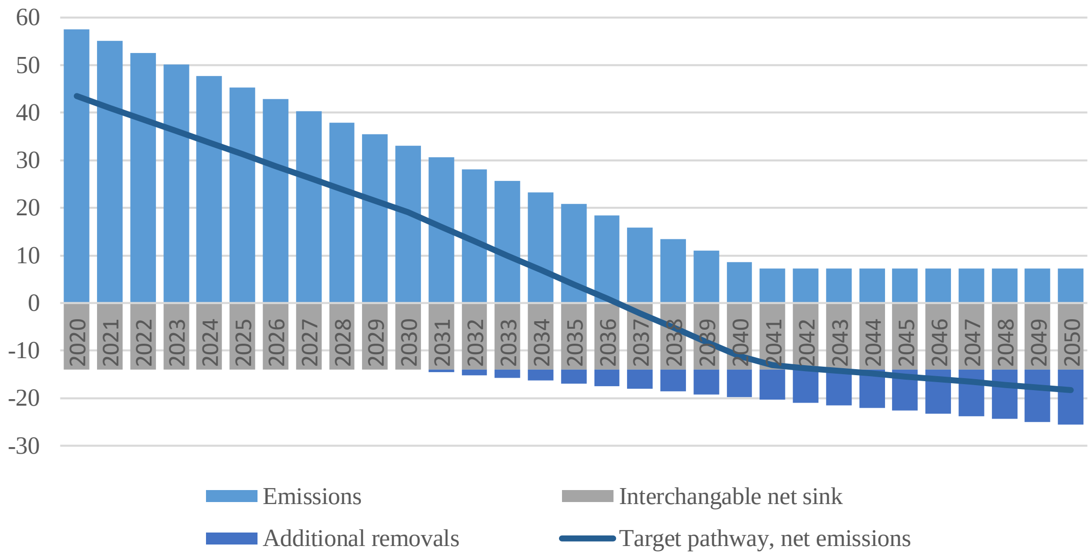

Figure 4b. The global carbon budget divided according to Equality, linear emissions reduction and increased removals, and a net land-use sector sink of -14 Mt for Finland

This next case, shown in Figure 4b above, shows what the Equality quota would mean for Finland, if the average land-use sector net sink is -14 Mt per year. Compared to the previous case, the net sink is 7 Mt smaller and thus intuitively emissions reduction must be higher. This can be seen as the steepening of the emissions reduction pathway shown in the lighter blue bars. The mitigation rate required here is 2.45 Mt instead of 1.98 Mt. The steeper mitigation rate means that emissions plateau in 2041, five years earlier than in the previous case. Another key difference is the need for additional removals, which over doubles. Additional removals are -0.58 Mt per year leading to -11.54 Mt in 2050, instead of the marginal -0.12 Mt annual increase in the previous case. GHG neutrality occurs in 2036, which is still later than the current Finnish target. The resulting reduction compared to 1990 can be calculated as

(5.2) $$R_{E2}: \left(1 - \frac{7.23+(-11.54)}{72.32}\right)\% = 106\%$$

The reduction target is over a 100%, which means that the net effect of emissions and additional removals totals in net negative emission – additional removals must be at least equivalent in size to emissions left. The total net effect of emissions, emissions removals and the average land-use sector net sink add up to a total of -18.31 Mt, compared to 16.23 in the previous case

In both of these cases the end result is the same – net emissions including emissions, land-use sector net sink and additional removals, lead to a 211 Mt net effect on the atmosphere during 2020-2050, per the calculated GHG budget allocation. The difference in these two cases is the assumed average land-use sector net sink, which causes the differences in the mitigation rate, required additional removals and key years of GHG neutrality and emissions plateauing. The end result in 2050 is similar – Finland should be significantly net negative in 2050.

4.2. Ability to Pay

Ability to Pay as the measure for equity decreases the size of the GHG quota for Finland by definition, since Finland's' PP adjusted GDP per capita is higher than the global average. In Chapter 3, the Ability to Pay factor is calculated to be 0.3737. This means that the GHG quota according to Equality is multiplied by 0.3737 and the result is then the GHG quota according to Ability to Pay. In this case, the quota is 79 Mt, which is demonstrated in Figures 5a and 5b below by using the same framework described earlier and applied to Equality.

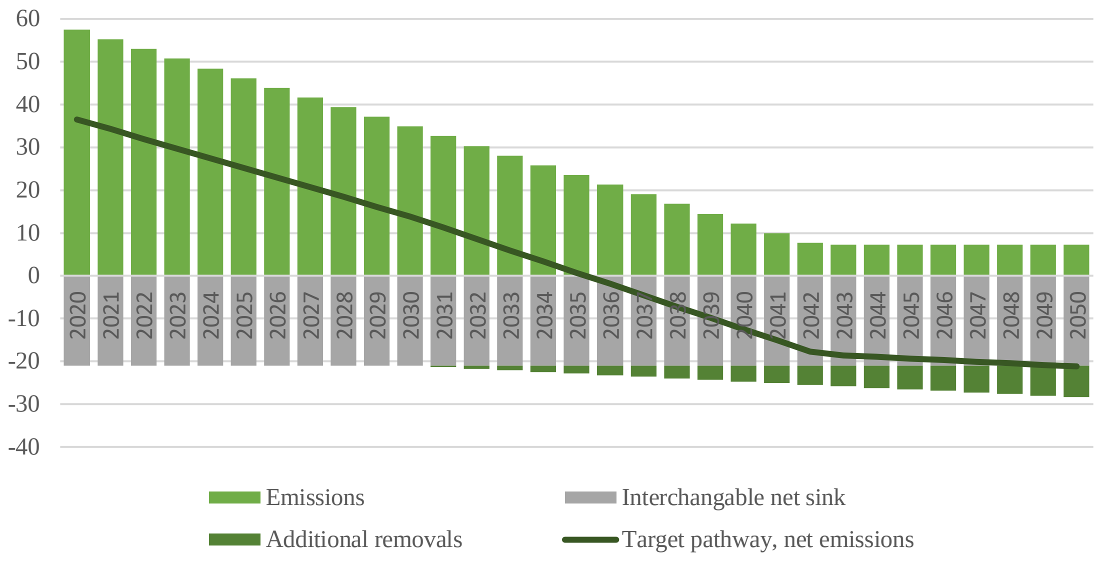

Figure 5a. The global carbon budget divided according to Ability to Pay, linear emissions reduction and increased removals, and a net land-use sector sink of -21 Mt for Finland

When the average land-use sector net sink is -21 Mt per year, the results are as shown in Figure 5a. The annual mitigation rate is 2.26 Mt up to 2042, after which with a 0.47 Mt decrease occurs during 2043, reaching the 90% reduction of emissions to 7.23 Mt in 2043. The mitigation rate changes for the last year, since continuing with the predetermined mitigation rate calculated from the first phase of the analysis would lead to lower than necessary emissions. This is why for the last year, the decrease in emissions is calculated by decreasing 7.23 Mt from the last year of emissions of over 7.23 Mt. GHG neutrality occurs in 2036, almost in line with the current Finnish target. Additional removals increase at an annual rate of -0.37 Mt leading to a total of -7.41 Mt in 2050. The reduction target R_{A1} for 2050 is thus 100%, as calculated below.

(5.3) $$R_{A1}: \left(1 - \frac{7.23+(-7.41)}{72.32}\right)\% = 100\%$$

When considering all emissions, sinks and additional removals, the total sum of net emissions in 2050 is -21.18 Mt. At this point, Finland has already been net negative for half of the time period examined.

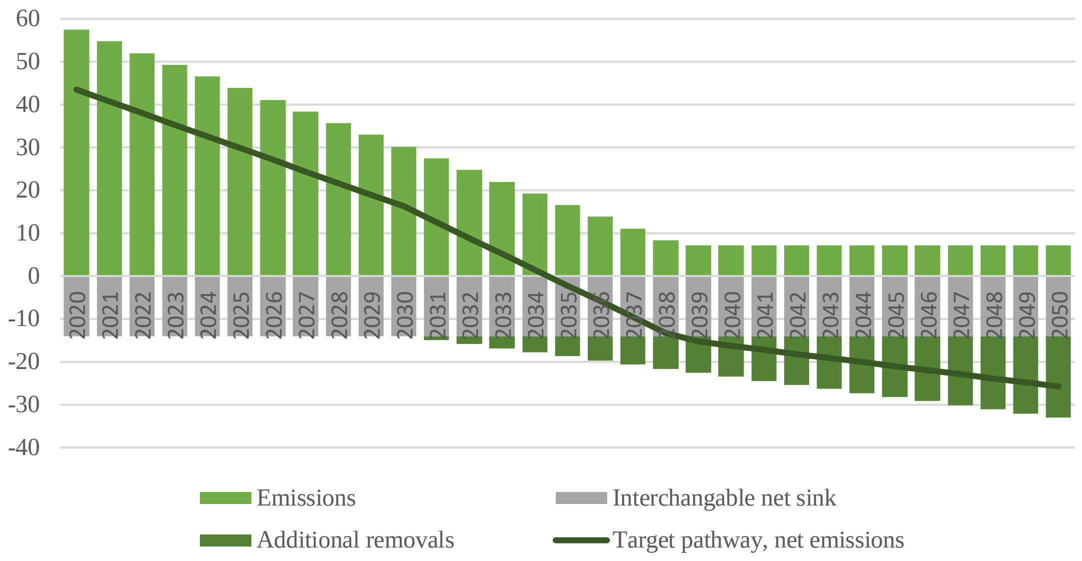

Figure 5b. The global carbon budget divided according to Ability to Pay, linear emissions reduction and increased removals, and a net land-use sector sink of -14 Mt for Finland

The next case with the Ability to Pay quota is with an average land-use sector net sink of -14 Mt per year. Looking at the graph above, we see that the need for additional removals looks larger than in any case before. The rate of additional removals is -0.95 Mt leading to a total of -19.01 Mt, which is over double that of the average land-use sector net sink in this case. Emissions are reduced at an annual rate of 2.73 Mt up to 2038. To 2039, emissions decrease a further 1.12 Mt and then settle at the set 7.23 Mt per year. GHG neutrality occurs in exactly 2035, in line with the Finnish GHG neutrality target. The resulting reduction target can be calculated as previously:

(5.4) $$R_{A2}: \left(1 - \frac{7.23+(-19.01)}{72.32}\right)\% = 116\%$$

This is a significantly over 100% target, meaning that additional emissions removals must be much larger than the remaining emissions level on 7.23 Mt. When calculated, the net effect if all emissions, sinks and additional removals in this case is -25.77 Mt.

In both the -21 Mt and the -14 Mt net sink cases Finland is net negative for half of the time period examined. This means there is 15 years' time to reach GHG neutrality and additional removals need to be considered, since they are key to remaining within the 79 Ability to Pay budget, in both cases.

4.3. Historic Responsibility

The way to apply Historic Responsibility as an equity measure is also to consider adjusted Equality quota like in the case of Ability to Pay, but with a different kind of adjustment. In this case, past emissions divided per capita, which are higher than the global average past emissions per capita, decrease the available emissions quota. Conversely, past emissions divided per capita, which are lower than the global average past emissions per capita, increase the available emissions quota. As discussed previously, the idea is to make past action accountable, since cumulative emissions matter in climate change. To restate, in this analysis historic responsibility is reached to 1990, which can be considered the time from which no government could plead ignorance on the cause and effect of climate change (Mattoo and Subramanian 2012).

As calculated above, the Finnish quota in the case of Historic Responsibility is negative, -440 Mt. This means the net effect on the atmosphere during 2020-2050 must be negative – more emissions must be removed or absorbed by the land-use sector sink than are emitted during the whole 30-year period. At least since 1990, Finland has never been net negative, so instinctively this GHG quota will lead to rapid mitigation and large emissions removal requirements.

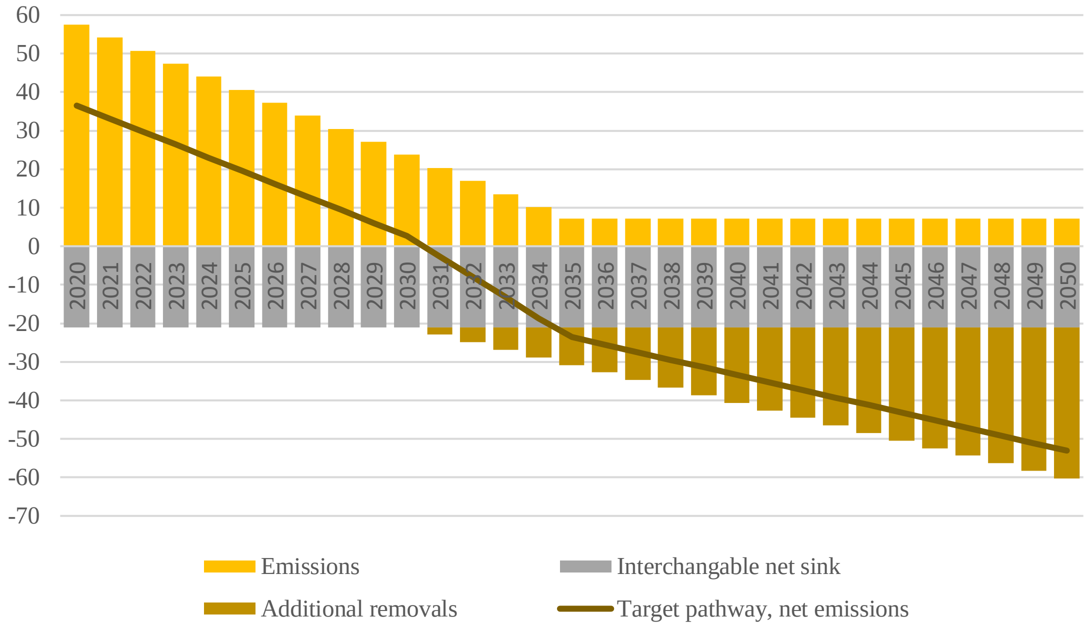

Figure 6a. The global carbon budget divided according to Historic Responsibility, linear emissions reduction and increased removals, and a net land-use sector sink of -21 Mt for Finland

Figure 6a above shows what kind of scenario would result, if the average land-use sector net sink was -21 Mt per year. Looking at the graph, first impressions are that this is a drastic mitigation scenario. The mitigation rate required is 3.38 Mt per year up to 2034 and a further 2.95 Mt is decreased for emissions to plateau from 2035 onwards. It is worth noting, that due to the rapid mitigation rate, emissions decrease quickly and thus GHG occurs already in 2031. The rate of additional removals required are -1.96 Mt per year, which lead to -39.28 Mt in 2050, which is almost double the net sink, as the graph shows. The resulting 2050 target is thus:

(5.5) $$R_{H1}: \left(1 - \frac{7.23+(-39.28)}{72.32}\right)\% = 144\%$$

This 144% target alongside the -21 Mt net sink means that Finland's net effect on the atmosphere in 2050 is -53.05 Mt.

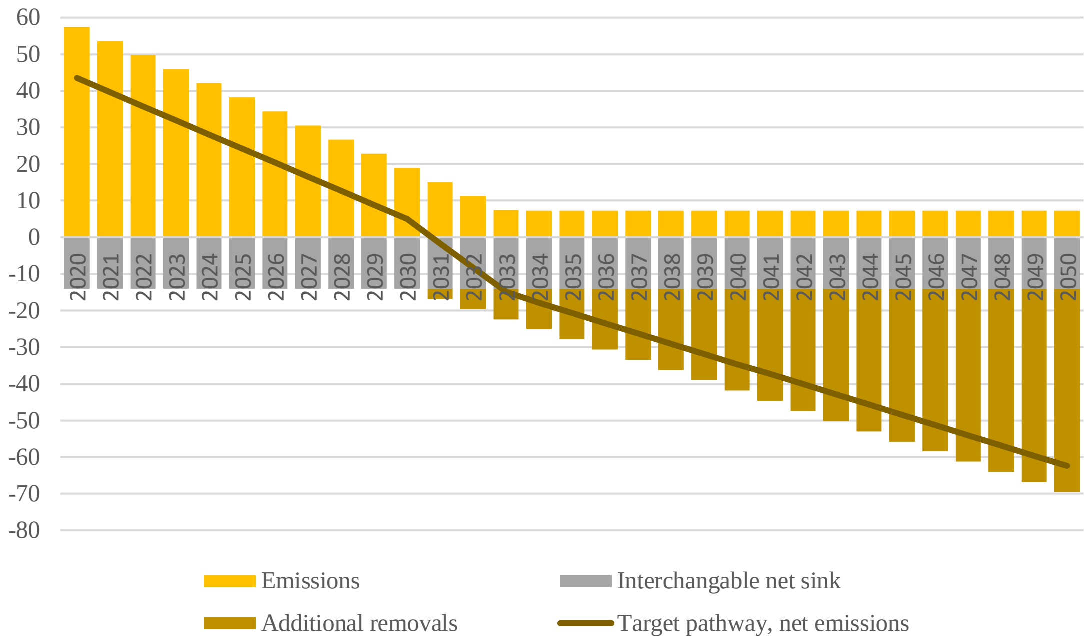

Figure 6b. The global carbon budget divided according to Historic Responsibility, linear emissions reduction and increased removals, and a net land-use sector sink of -14 Mt for Finland

In this next case we see that the smaller average land-use sector net sink of -14 Mt per year further increases the need for emissions removals. If the annual net sink is 7 Mt smaller per year for the entire 30-year period of 2020 to 2050, this means a 210 Mt loss over the whole period compared to a net sink of -21 Mt per year. In the case of Historic

Responsibility this is perhaps most observable, since in the previous cases part of the effect adjusted to the increase in mitigation rates. In Figure 6b above the mitigation rate is 3.85 Mt up to 2033 and a further 0.26 decrease in 2034 leads to emissions plateauing. GHG neutrality occurs in 2031 and the increase in emissions removals is -2.78 per year. Comparing to the case of Equality, the required emissions removals in total were less than this annual increase required here. In 2050 additional removals add up to -55.63 Mt – approximately the magnitude of Finland's present-day emissions. The resulting 2050 target is 167%, as calculated below.

(5.6) $$R_{H2}: \left(1 - \frac{7.23+(-55.63)}{72.32}\right)\% = 167\%$$

In both cases of Historic Responsibility GHG neutrality occurs just after 2030 due to the high of mitigation rates. The -440 Mt GHG quota is achieved by huge amounts of additional emissions removals. In total during 2031-2050 -412 Mt of additional emissions removal units are required, when the average land-use sector net sink is -21 Mt per year. If the average land-use sector net sink is -14 Mt per year, the amount of additional removals required during 2031-2050 is -584 Mt. The mitigation targets for 2050 are 144% and 167%, which are to be expected this high due to the massive emissions removals. This calculation shows that taking responsibility for past emissions in the case of Finland would lead to impractical targets.

4.4. Sensitivity analysis

I will take a look at two approaches for sensitivity analysis. First, I will adjust the size of the global GHG budget while examining the effect of a smaller or larger net land-use sector sink. Second, I will briefly examine an altered framework approach, in which non-CO_2 emissions are not included in the equity framework and the land-use sector is omitted completely.

4.4.1. The effect of the global GHG budget and national net land-use sector sinks

As discussed previously, the carbon budgets themselves have high uncertainty. The IPCC special report on global warming of 1.5 C gives an uncertainty range of approximately +/- 350 Gt. To examine this uncertainty and conduct sensitivity analysis on my results, Table 4 below shows a selection of possible global carbon budgets and how these translate into national targets for Finland. The 420 Gt budget is the same as used in the calculations above, so there are two budgets smaller than this and three larger. The largest budget is close to the IPCC estimation for the 2 degree budget, which is 1 170 Gt from 2018. In this same table, I have also added two new land-use sector sinks; -7 Mt and -28 Mt so one smaller and one larger than the previously examined -14 Mt and -21 Mt net sinks for the purpose of sensitivity analysis on the land-use sector net sink too.

Table 4. Sensitivity analysis on the global carbon budget, national net land-use sector sink and equity measures.

Global carbon budget	Average net sink per year	Equality				Ability to pay				Historic responsibility			
		% in 2050 vs. 1990	Reduction Mt CO2e/a	Emissions plateau in	Removal rate	% in 2050 vs. 1990	Reduction Mt CO2e/a	Emissions plateau	Removal rate	% in 2050 vs. 1990	Reduction Mt CO2e/a	Emissions plateau in	Removal rate
0 Gt			**0**	**Mt CO_2e**			**0**	**Mt CO_2e**			**-651**	**Mt CO_2e**	
	-7 Mt	144 %	3.4	2035	-1.9	144 %	3.4	2035	-1.9	215 %	4.8	2031	-4.5
	-14 Mt	123 %	2.9	2038	-1.2	123 %	2.9	2038	-1.2	190 %	4.3	2032	-3.6
	-21 Mt	105 %	2.4	2041	-0.5	105 %	2.4	2041	-0.5	166 %	3.8	2034	-2.7
	-28 Mt	93 %	2.0	2046	-0.1	93 %	2.0	2046	-0.1	144 %	3.4	2035	-1.9
210 Gt			**79**	**Mt CO_2e**			**30**	**Mt CO_2e**			**-572**	**Mt CO_2e**	
	-7 Mt	136 %	3.2	2036	-1.7	141 %	3.3	2036	-1.8	206 %	4.6	2031	-4.2
	-14 Mt	116 %	2.7	2039	-0.9	120 %	2.8	2038	-1.1	181 %	4.1	2033	-3.3
	-21 Mt	100 %	2.3	2043	-0.4	103 %	2.4	2042	-0.5	157 %	3.7	2034	-2.4
	-28 Mt	91 %	1.8	2048	0.0	92 %	1.9	2047	-0.1	136 %	3.2	2036	-1.7
420 Gt			**211**	**Mt CO_2e**			**79**	**Mt CO_2e**			**-440**	**Mt CO_2e**	
	-7 Mt	124 %	2.9	2038	-1.2	136 %	3.2	2036	-1.7	191 %	4.3	2032	-3.6
	-14 Mt	106 %	2.4	2041	-0.6	116 %	2.7	2039	-1.0	167 %	3.8	2034	-2.8
	-21 Mt	93 %	2.0	2046	-0.1	100 %	2.3	2043	-0.4	144 %	3.4	2035	-1.9
	-28 Mt	83 %	1.5	-	-	91 %	1.8	2048	0.0	124 %	2.9	2038	-1.2
630 Gt			**343**	**Mt CO_2e**			**128**	**Mt CO_2e**			**-308**	**Mt CO_2e**	
	-7 Mt	112 %	2.6	2040	-0.8	131 %	3.1	2037	-1.5	176 %	4.0	2033	-3.1
	-14 Mt	97 %	2.2	2044	-0.3	112 %	2.6	2040	-0.8	153 %	3.6	2035	-2.3
	-21 Mt	90 %	1.7	-	-	97 %	2.1	2044	-0.3	131 %	3.1	2037	-1.5
	-28 Mt	72 %	1.2	-	-	90 %	1.7	-	-	112 %	2.6	2040	-0.8
840 Gt			**475**	**Mt CO_2e**			**177**	**Mt CO_2e**			**-177**	**Mt CO_2e**	
	-7 Mt	103 %	2.3	2042	-0.5	127 %	3.0	2037	-1.3	162 %	3.7	2034	-2.6
	-14 Mt	92 %	1.9	2047	-0.1	108 %	2.5	2040	-0.7	140 %	3.3	2036	-1.8
	-21 Mt	79 %	1.4	-	-	95 %	2.0	2045	-0.2	119 %	2.8	2038	-1.1
	-28 Mt	60 %	0.9	-	-	86 %	1.6	-	-	103 %	2.3	2042	-0.5
1050 Gt			**606**	**Mt CO_2e**			**227**	**Mt CO_2e**			**-45**	**Mt CO_2e**	
	-7 Mt	95 %	2.1	2045	-0.2	122 %	2.9	2038	-1.2	148 %	3.5	2035	-2.1
	-14 Mt	87 %	1.6	-	-	105 %	2.4	2041	-0.5	127 %	3.0	2037	-1.3
	-21 Mt	67 %	1.1	-	-	93 %	1.9	2046	-0.1	108 %	2.5	2040	-0.7
	-28 Mt	48 %	0.7	-	-	82 %	1.5	-	-	95 %	2.1	2045	-0.2

In all but the 2 degree budget, the difference between the largest and smallest average land-use sector net sink represent approximately a 10 year difference in which emission plateau – the smaller the sinks, the earlier emissions plateau due to steep emissions reduction to 90% compared to 1990 levels. The difference in mitigation rates until emissions plateau can be calculated as approximately a 0.5 Mt increase for each -7 Mt lost from the average annual land-use sector net sink in all of the equity cases. No similar pattern is detectable for the removal rate.

Table 4 shows that the size of the GHG budget does indeed affect the 2050 reduction target. The difference between e.g. Historic Responsibility with - 28 Mt net sink is in the

0 Gt GHG budget 144%, while in the 840 Gt budget the same target is 103%. In another instance, in the case of Equality and the -7 Mt average land-use sector net sink, the reduction target with the 0 Gt budget is 144% while for the 800 Gt budget the target is 92%. The difference within a global GHG budget between the smallest and largest average sinks in the 2050 targets is 40 to 50 percentage points in Equality and Ability to Pay, and in Historic Responsibility the difference is 50 to 70 percentage points.

This and other differences in reduction targets can perhaps be seen more clearly in Figure 7 below, which shows emissions reduction targets for 2050 with different net sinks within each equity criterion plotted against the size of the carbon budget. Historic Responsibility remains as the criterion resulting in the most stringent targets, however, the relative difference to Equality and Ability to Pay decreases the larger the global GHG budget is. This is due to the fact that the bigger the global budget gets, the less significant the emissions debt from 1990-2019 is relative to the allocated GHG quota. Also, the targets for Ability to Pay when the GHG budget increases seem to decrease less than they do with Equality. This also accounts for Historic Responsibility catching up with it. Ability to Pay targets decrease less, since the calculation of it is proportional, not absolute, to the Equality budget. In conclusion, sensitivity to the size of the GHG budget is highest with Historic Responsibility and lowest with Ability to Pay.

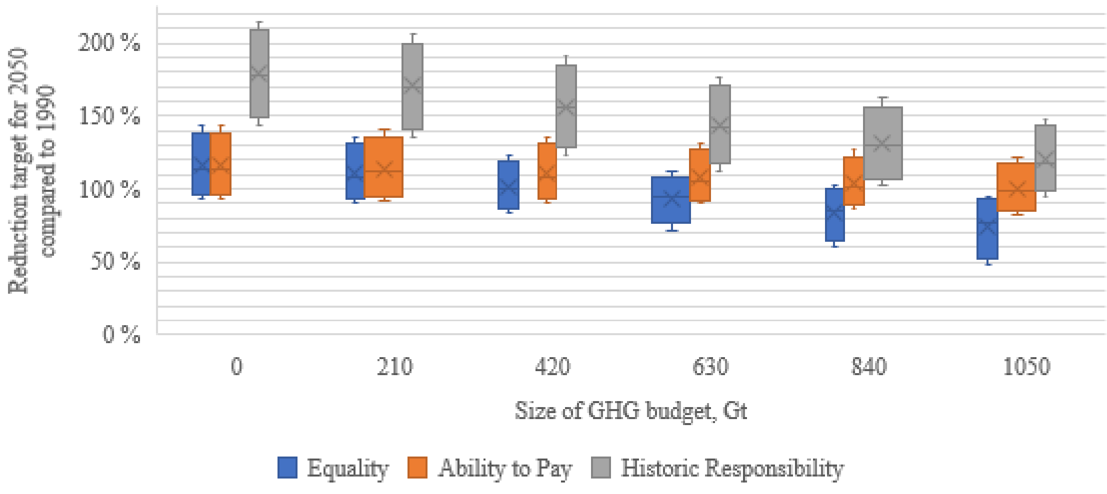

Figure 7. Emissions reduction targets for 2050 with different net sinks within each equity criterion plotted against the size of the carbon budget.

Sensitivity in regard to the size of the land-use sector net sink can be examined in a similar way and produces similar results as sensitivity to the global GHG budget. Figure 8 below demonstrates this. Again, Historic Responsibility changes the most while Ability to Pay changes the least. When the sink is the largest, the range of targets from all equity criteria is the smallest; the large sink helps achieving the Historic Responsibility targets by requiring less emissions removals between 2031-2050. One key difference compared to Figure 7 above is the spread of Ability to Pay targets, which is smaller in all net sink scenarios compared to Equality and Historic Responsibility targets, while in the figure above Equality and Ability to Pay are similar.

Figure 8. Emissions reduction targets for 2050 with different global GHG budgets within each equity criterion plotted against the size of the land-use sector net sinks.

To conclude this part of the sensitivity analysis, Ability to Pay is least affected by changes in the global GHG budget and in the land-use sector net sink. In Equality, all cases of global GHG budgets and the current -14 Mt net sinks resulted in a reduction target of over 80%; also, with precisely the 1.5 degree budget of 420 Gt and all variations of the net sinks the required reduction target is over 80%. In the case of Ability to Pay, the figures are over 90% and for Historic Responsibility 120%.

4.4.2. The effect of omitting non-CO_2 emissions and the land-use sector

One of the key alterations in this thesis to the way carbon budgets are usually utilised was translating them into GHG budgets. The other alteration was to include the land-use sector in full. In Table 5 and Figures 9a, 9b and 9c below I have examined what the results would look like, if the framework was applied to just CO_2 emissions, and the land-use sector was left out completely. Non-CO_2 emissions are assumed to remain proportional to the level of CO_2 emissions, as in 2018 emissions statistics for Finland (18.5%). Non-CO_2 emissions are not contained within the equity calculation, instead they are purely added to the graph in proportion to the CO_2 emissions, which come as the result from the calculation. It is wort noting that the budget according to Historic Responsibility has now changed; by excluding the land-use sector net sink from the 1990-2019 period, the emissions debt carried over to 2020-2050 is even larger leading to a decrease in the quota from -440 Mt to -896 Mt.

Table 5. Comparison between the framework with a -14 Mt net land-use sector sink and an approach omitting the land-use sector and non-CO_2 emissions from the equity analysis.

	Equality 211 Mt		**Ability to Pay 79 Mt**		**Historic Responsibility -896 Mt**	
	CO_2e with -14 Mt sink	CO_2 without LULUCF	CO_2e with -14 Mt sink	CO_2 without LULUCF	CO_2e with -14 Mt sink	CO_2 without LULUCF
Mitigation rate, CO_2	2.4 Mt	2.7 Mt	2.7 Mt	3.0 Mt	3.8 Mt	5.1 Mt
Removal rate	-0.6 Mt	-1.5 Mt	-1.0 Mt	-1.9 Mt	-2.8 Mt	-6.0 Mt
Removals in 2050	-11.5 Mt	-29.2 Mt	-19.0 Mt	-38.9 Mt	-55.6 Mt	-120.5 Mt
2050 target, all GHG	106 %	130 %	116 %	144 %	167 %	257 %

In each equity scenario, the left-hand side column is the calculation presented previously, with the -14 Mt net sink included as well as non-CO_2 emissions. The right-hand side column represents some new results for comparison. The last row in Table 5 contains the mitigation targets for 2050, which are calculated according as the sum of remaining emissions and additional removals compared to 1990. We can see that the new figures are more demanding, with the difference especially clear in the case of Historic Responsibility, where the target is 90 percentage points larger than in the case where land-use sector sinks are accounted for. The three figures below will show these results in a similar way as previous results were presented. The difference here is that the land-use sector is omitted completely, so GHG neutrality occurs purely from the compensating effect of additional removal.

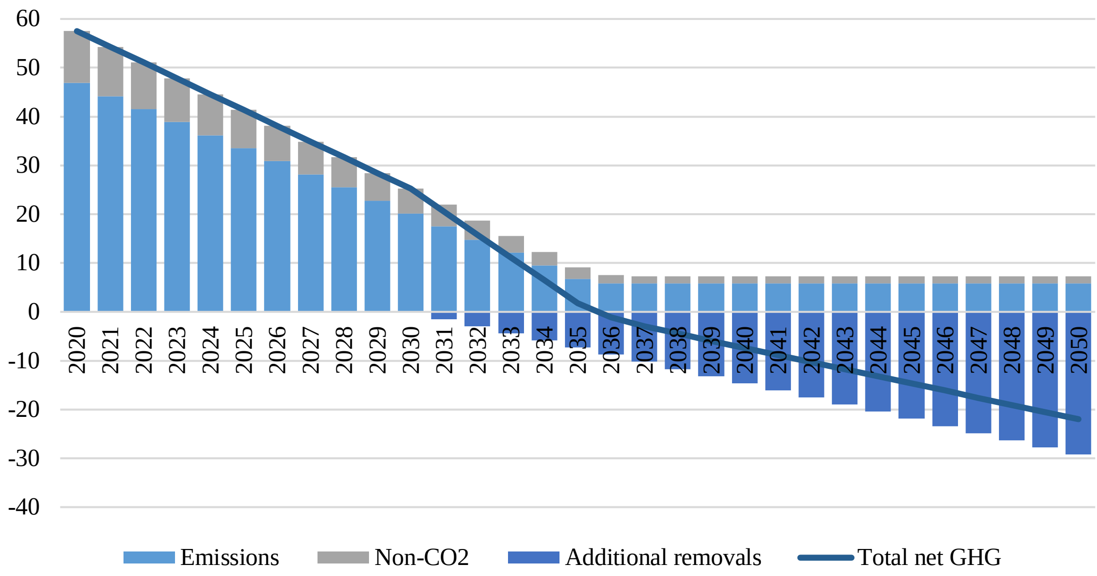

Figure 9a. Equity in CO_2 allocation according to Equality, no land-use sector and external non-CO_2 emissions for Finland.

In Figure 9a, the Equality scenario is plotted out for the period 2020 to 2050. Both of the blue bars, representing emissions and emissions removals are included in the equity calculation and summed together are 211 Mt, per the GHG quota according to Equality. Non-CO_2 emissions are added on top of the CO_2 emissions as grey bars. However, non-CO_2 emission decrease in the same proportion as CO_2 emissions, since they are assumed to remain proportional to CO_2 emissions (18.5%).

GHG neutrality occurs in 2036, which is the same year that emission plateau. In the -14 Mt case emissions plateau in 2041 and GHG neutrality occurs in 2037 – very close to the case presented in Figure 9a. Additional removals in 2050 add up to -29 Mt, which is over double the past average net land-use sector sink. In the -14 Mt case additional removals were a reasonable -11.5 Mt. Interestingly, if we and the -14 Mt and the additional removals of -11.5 Mt we get -25.5 Mt, which is rather close to the additional removals amount of -29 Mt required in the new calculation.

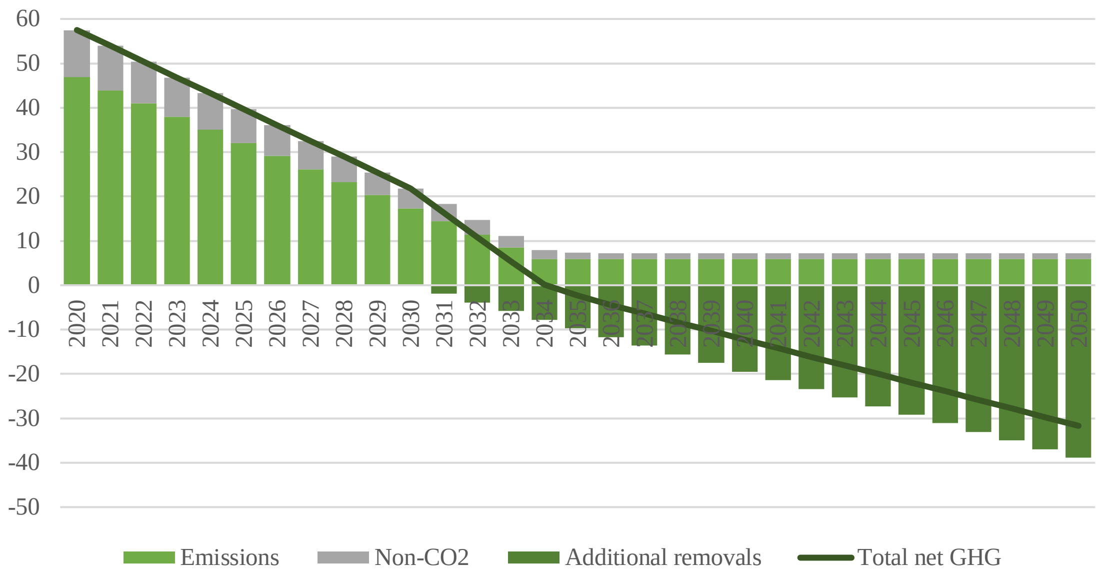

Figure 9b. Equity in CO_2 allocation according to Ability to Pay, no land-use sector and external non-CO_2 emissions for Finland.

Figure 9b show the same results, but for Ability to Pay as the equity measure applied. GHG neutrality occurs in 2034 and emissions plateau three years later. In the equivalent -14 Mt case, GHG neutrality occurs just one year later, in 2035, and emissions plateau in 2039, so two year later than in the case presented in Figure 9b. Required emissions removals stretch further to -39 Mt, which is over double the land-use sector net sink record of -34 Mt in 2009. The difference in reduction targets is 28 percentage points, so less than initially might have been thought when looking at emissions removals required. This is due to the -14 Mt Ability to Pay target also requiring a significant amount, -19 Mt, of emissions removals.

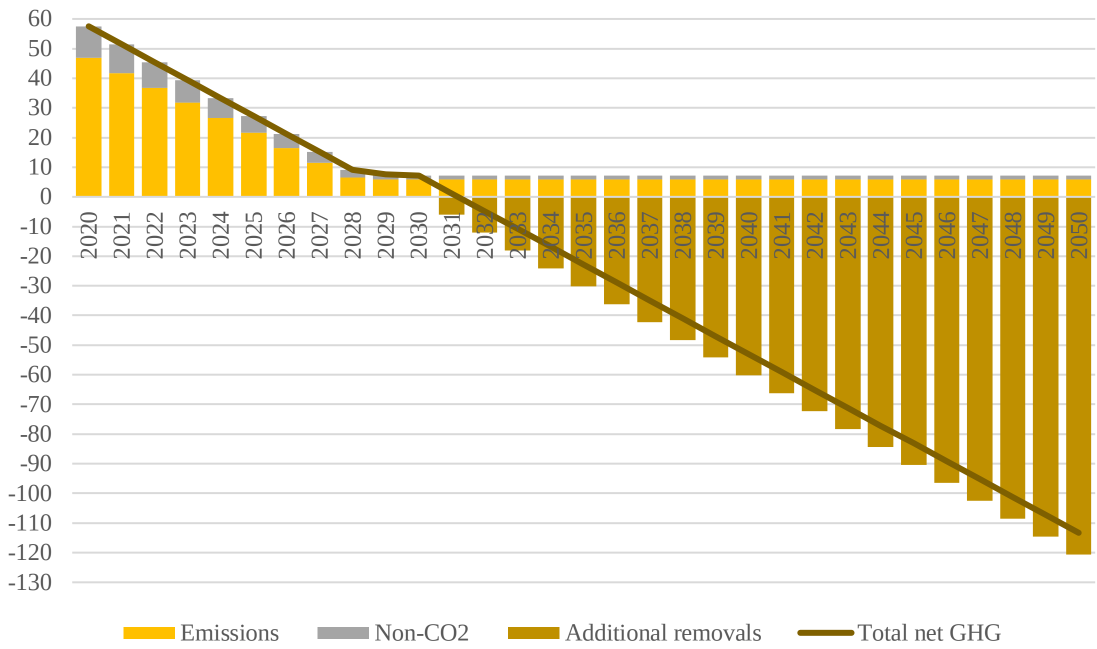

Figure 9c. Equity in CO_2 allocation according to Historic Responsibility, no land-use sector and external non-CO_2 emissions for Finland.

The case of Historic Responsibility looks very unlike any other figures presented for Finland. The GHG budget in this case is much smaller than with the -14 Mt case, and no land-use sector net sink helps soften the mitigation curve. An astounding 257% reduction is required in 2050 with additional removals adding up to -120.5 Mt. In the -14 Mt case, under half of these emission removals would have sufficed. GHG neutrality occurs in 2031 in Figure 9c, while in Figure 6b demonstrating the -14 Mt case we saw that GHG neutrality occurs also in 2031.

In conclusion for sensitivity analysis on the framework methodology, GHG neutrality seems to occur around the same time despite the method (-14 Mt sink or solely CO_2 framework) used, in all equity scenarios. This may be due to the combination of a short time span of 2020 to 2050, small GHG quotas compared to current emission levels and linear pathways, which all contribute to why the net-emissions graph dives down towards negative emissions soon after 2030.

5. Additional case studies

To show how this framework analysis works for other case studies apart from Finland, I will next present four additional case studies: the EU, Sweden, Germany and the United Kingdom. The EU is selected, because Finland is part of the EU and receives its binding climate targets from the sharing out of the EU climate target. Sweden is selected since it is a similar country as Finland in the land-use sector, welfare and geography, but significantly smaller emissions per capita and a different approach to climate policy targets. Germany and the United Kingdom are examined as examples of countries with a larger population, higher past emissions and limited options in the land-use sector. The United Kingdom is additionally an interesting case study, since it has set a long-term climate policy target and has always been a forerunner in climate policy (Lockwood 2013). All these calculations are based on the data presented in Chapter 3.2 and the same approach as applied to Finland.

5.1. European Union

The EU's most recent emissions statistic show that the EU has decreased its emissions from 1990 levels GHG emissions by 22% to 4483 Mt. The net land-use sector sink is at the moment approximately -258 Mt and the average for 1990 to the present is -290 Mt. The land-use sector net sink currently compensates for 6% of fossil and process-based emissions. By these applying emissions statistics and the equity framework to the EU, we get the following GHG budgets for 2020 to 2050:

	Equality	Ability to Pay	Historic Responsibility
Total	19 821 Mt	8 122 Mt	-44 606 Mt
Per capita	38 t	16 t	-85 t

These targets show the same pattern as in the case of Finland; the largest quota is derived from Equality, a much smaller quota from Ability to Pay and Historic Responsibility is significantly negative. Next, I will demonstrate with one graph per equity measure, what kind of emissions pathways this framework would result in. The net-land-use sector sink used will be the average of 1990 to 2019. I have selected to use an average figure rather than the most recent figure to eliminate the effect of high interannual fluctuations discussed previously in Chapter 3.

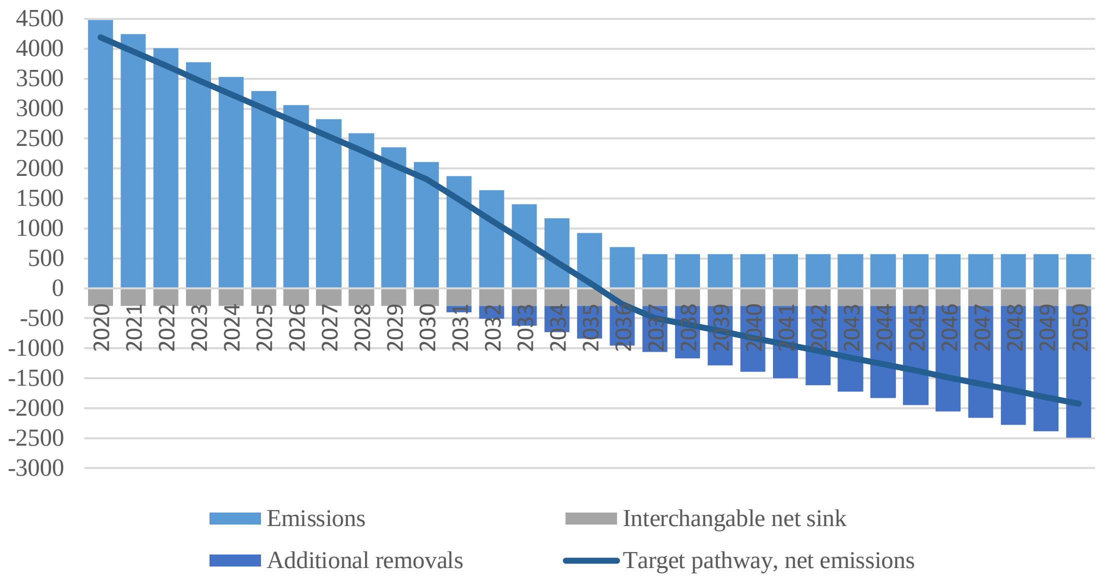

Figure 10a. The global carbon budget divided according to Equality, linear emissions reduction and increased removals, and a net land-use sector sink of -290 Mt for the EU.

Figure 10a above shows that the long-term target in the case of Equality is significantly over 100%. A mitigation rate of 237 Mt is applied annually up to 2037 after which emissions plateau at the level on 572 Mt. GHG neutrality occurs in 2035 due to increased removal of -110 Mt per year form 2031 onwards. In 2050, the effect of remaining emissions and additional removals results in a 129% reduction compared to 1990 emission levels. Total additional removals in 2050 are -2 208 Mt and the net emissions of the EU are 1 926 Mt.

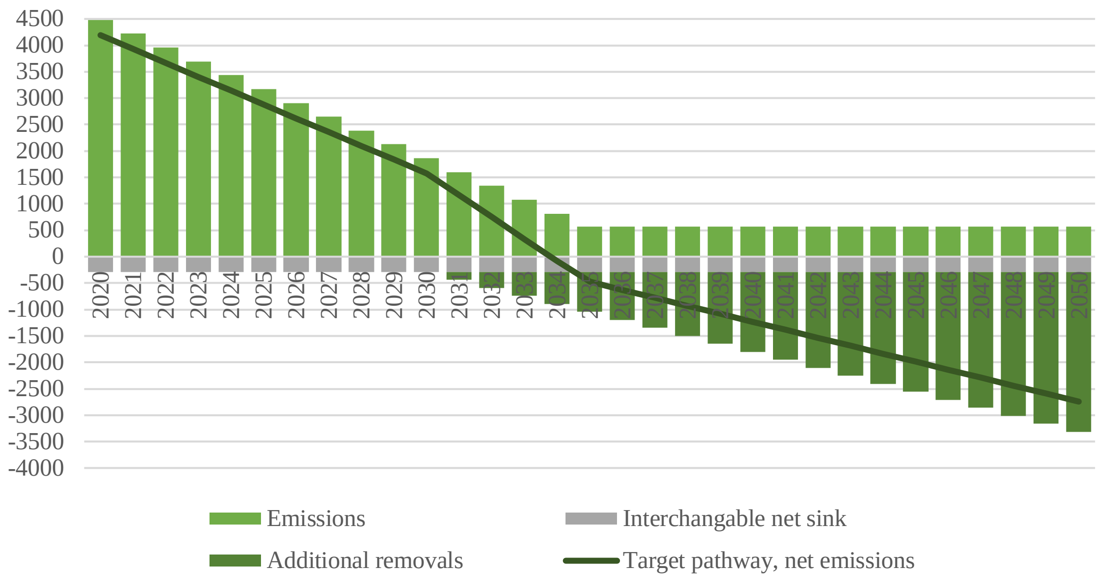

Figure 10b. The global carbon budget divided according to Ability to Pay, linear emissions reduction and increased removals, and a net land-use sector sink of -290 Mt for the EU.

Figure 10b demonstrates the case of Ability to Pay for the EU. Emissions are reduced by 262 Mt each year until 2036 and removals are increased from 2031 onwards by -151 Mt each year. GHG neutrality occurs in 2034 and the reduction in 2050 compared to 1990 is 143% when considering remaining emissions of 572 Mt and additional removals of -3026 Mt. The net effect of emissions, additional removals and the land-use sector of the EU in 2050 is -2 743 Mt.

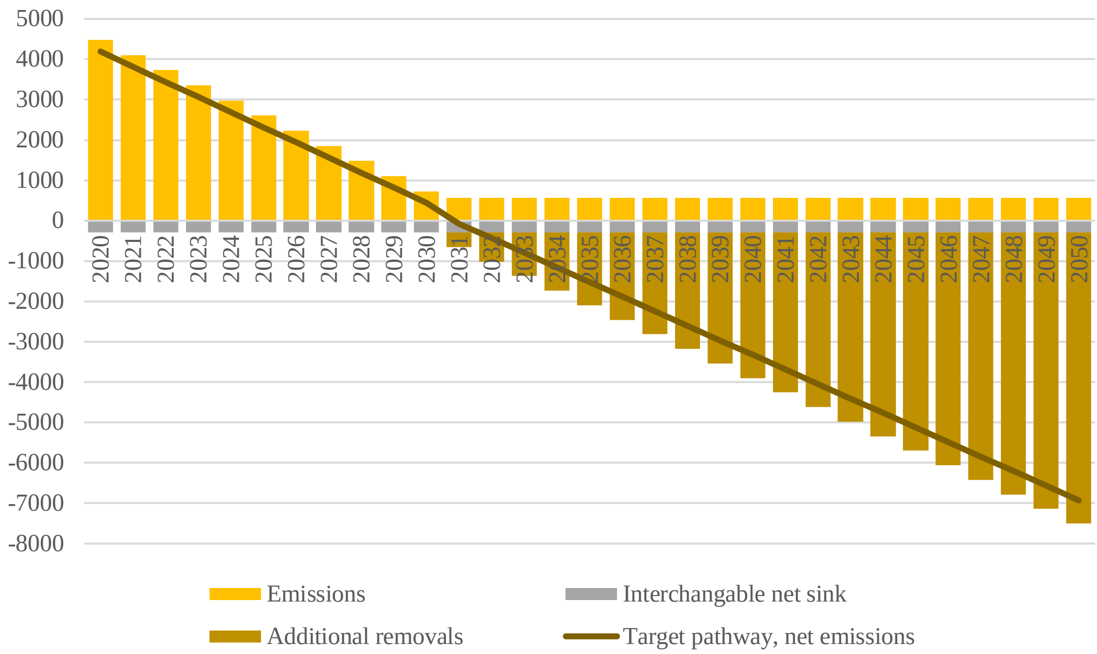

Figure 10c. The global carbon budget divided according to Historic Responsibility, linear emissions reduction and increased removals, and a net land-use sector sink of -290 Mt for the EU.

In the case of Historic Responsibility, the EU should decrease emission by 90% compared to 1990 in just 10 years, which means a mitigation rate of 375 Mt. GHG neutrality occurs in 2031, which is the same year from which additional removals begin to increase by -361 Mt per year. In 2050, additional removals add up to -7 211 Mt. The reduction target in 2050 is thus 216% and the net effect on the atmosphere by the EU including all emissions, sinks and removals is -6 929 Mt.

5.2.Sweden

The case of Sweden differs from the previous cases of Finland and the EU. Sweden has the same emission levels as Finland but double the population. The net land-use sector sinks also compensated for approximately 80% of fossil and process-based emissions which results in current net emissions of 1 t per capita (See Chapter 3). We can thus expect the framework to work in a distinctive way for a special case like this. The GHG quotas for Sweden in each case of equity are as follows:

	Equality	Ability to Pay	Historic Responsibility
Total	410 Mt	139 Mt	1201 Mt
Per capita	38 t	13 t	111 t

The same pattern as previously can be seen in the cases of Equality and Ability to Pay, but counterintuitively Historic Responsibility provides the biggest quota, despite Sweden being a highly developed country. The following three graphs present the results of the equity framework analysis in more detail.

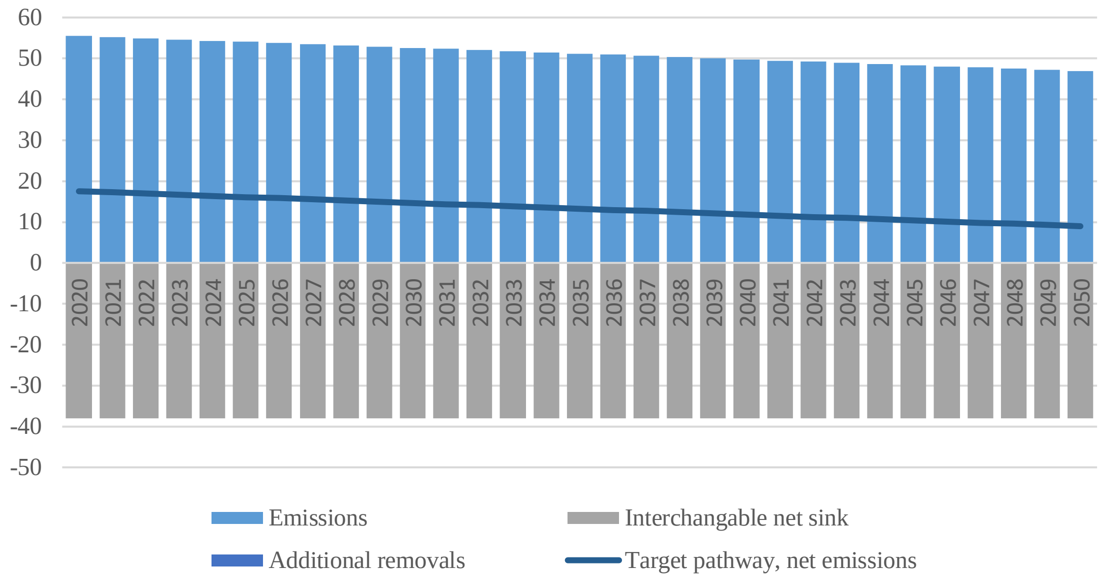

Figure 11a. The global carbon budget divided according to Equality, linear emissions reduction and increased removals, and a net land-use sector sink of -38 Mt for Sweden.

In the case of Sweden staying within its allocated GHG quota according to Equality, emissions barely need to be reduced; a meagre 0.3 Mt per year reduction would suffice, and no additional removals would be needed. GHG neutrality does not occur, and in 2050 emissions are 35% lower than in 2050; only 11 percentage point more than what the current emissions level is.

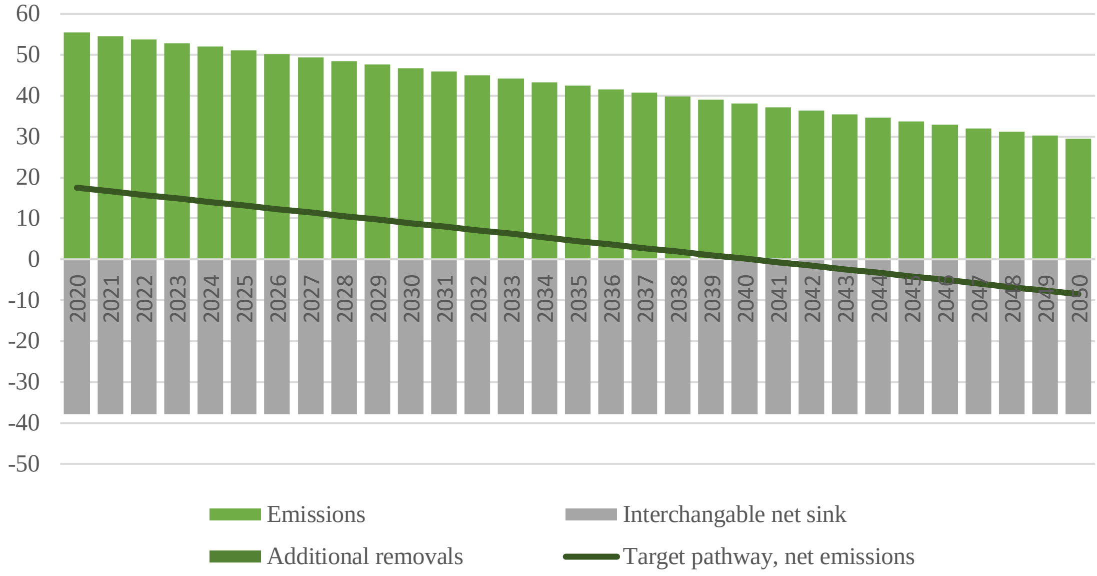

Figure 11b. The global carbon budget divided according to Ability to Pay, linear emissions reduction and increased removals, and a net land-use sector sink of -38 Mt for Sweden.

The case of Ability to Pay alters the scenario slightly, but not dramatically; again, no additional emissions removals are needed. The mitigation rate is 0.9 Mt per year leading to an emissions level of 29 Mt in 2050. However, GHG neutrality does occur in 2040 and emissions are reduced by 59% in 2050 compared to 1990 levels. GHG neutrality occurs mainly due to the high level of net land-use sector sinks rather than mitigation efforts.

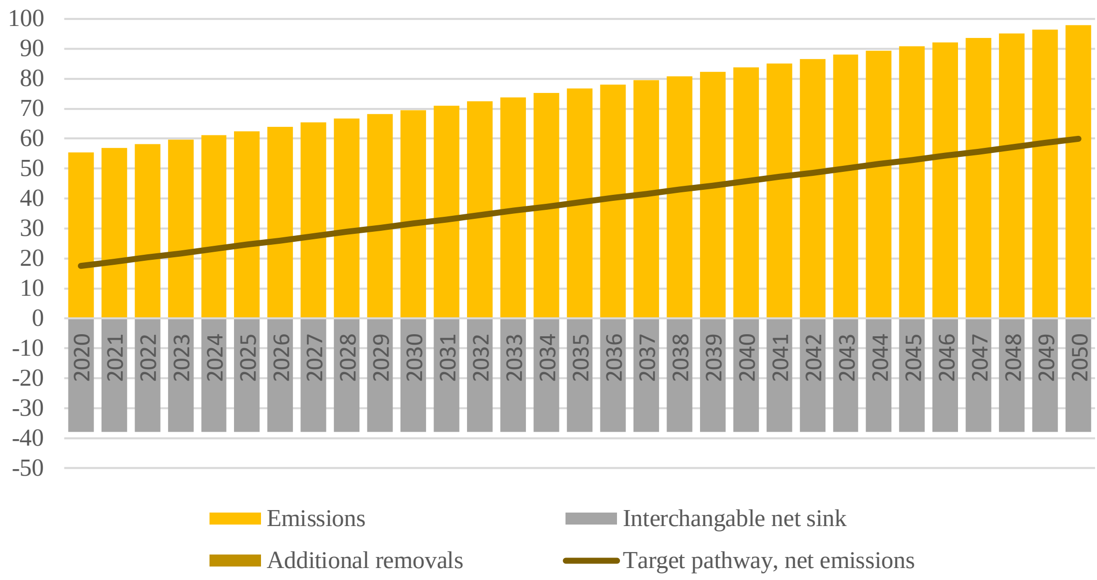

Figure 11c. The global carbon budget divided according to Historic Responsibility, linear emissions reduction and increased removals, and a net land-use sector sink of -38 Mt for Sweden.

This last case, presented in Figure 11c above, is the most dramatic so far. Since Sweden's historic per capita net emissions for 1990-2019 are 80 t while the global average is 153 t, Sweden has no emissions debt, unlike Finland and the EU. This means that the quota according to Historic Responsibility is larger than the quota according to Equality, since unused emissions space from 1990-2019 can be used during the 2020-2050 period according to this framework. Remarkably, Sweden would be allowed to increase its emissions by 1.4 Mt per year; at a rate which is larger than the mitigation rates of the previous equity calculations. In the case of Historic Responsibility, Sweden would remain within its GHG quota by increasing its fossil and process-based emissions to the level of 98 Mt in 2050, an increase of 35% compared to 1990 levels and a 75% increase compared to current levels.

5.3. Germany

Germany has decreased it emissions from 1990 by 26%, so more than the EU, Sweden or Finland had. Its current per capita emissions are 11.4 t and net per capita emissions are 11.1 t, which are the highest in all of the case studies in this thesis, despite the larger reduction percent reached in 2019 compared to 1990 than e.g. Finland. However, Germany had higher than average per capita emissions in 1990, which is perhaps why emissions reduction have been easier to achieve. For this reason, in the analysis of GHG quotas according to equity, Germany's emissions plateau at 95% instead of 90% as in the other case studies. Another point worth noting is that Germany's emissions are 21% of the EU's emissions, so we are looking at a significant part of the climate change driving emissions of Europe. The results of the GHG quota according to different equity measures are shown below:

	Equality	**Ability to Pay**	**Historic Responsibility**
Total	3 131 Mt	1 044 Mt	-14 837 Mt
Per capita	38 t	13 t	-180 t

The now familiar division is visible here too: Equality provides the largest quota, while Ability to Pay is smaller, but still positive; Historic Responsibility however is negative and, in this case, very much so. Next, I will show how these are applied to emissions reduction pathways and long-term targets in demonstrative graphs.

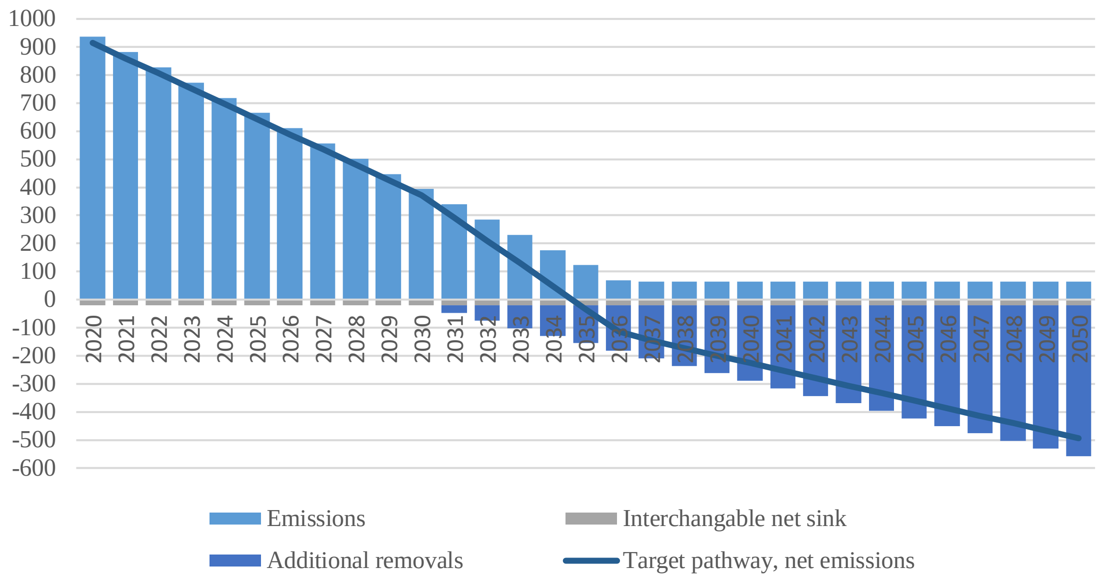

Figure 12a. The global carbon budget divided according to Equality, linear emissions reduction and increased removals, and a net land-use sector sink of -21 Mt for Germany.

In the case of Equality, as Figure 12a above shows, additional emissions removals are required for remaining within the calculated GHG quota. Additional removals grow by -27 Mt per year leading to 536 Mt in 2050, which together with remaining emissions add up to a 137% reduction target compared to 1990 levels. Emissions are decreased by 54 Mt per year up to 2036 after which they plateau at 63 Mt for the remainder of the time period. GHG neutrality occurs in 2035.

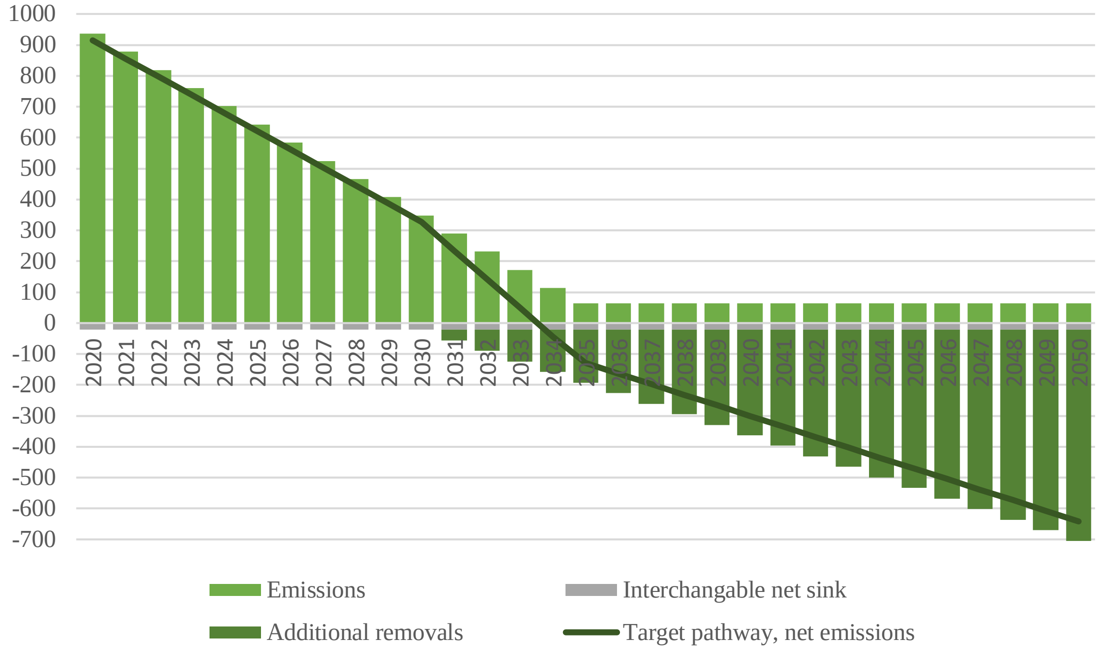

Figure 12b. The global carbon budget divided according to Ability to Pay, linear emissions reduction and increased removals, and a net land-use sector sink of -21 Mt for Germany.

Ability to Pay looks broadly similar to the case of Equality, since even Equality required immense emissions reductions, but is slightly more stringent in its mitigation needs. Emissions are reduced by 59 Mt per year until 2035, and additional removals increase by -34 Mt each year. GHG neutrality occurs in 2034 and the effect of remaining emission and additional removals of -684 Mt in 2050 translate into a reduction target of 149%.

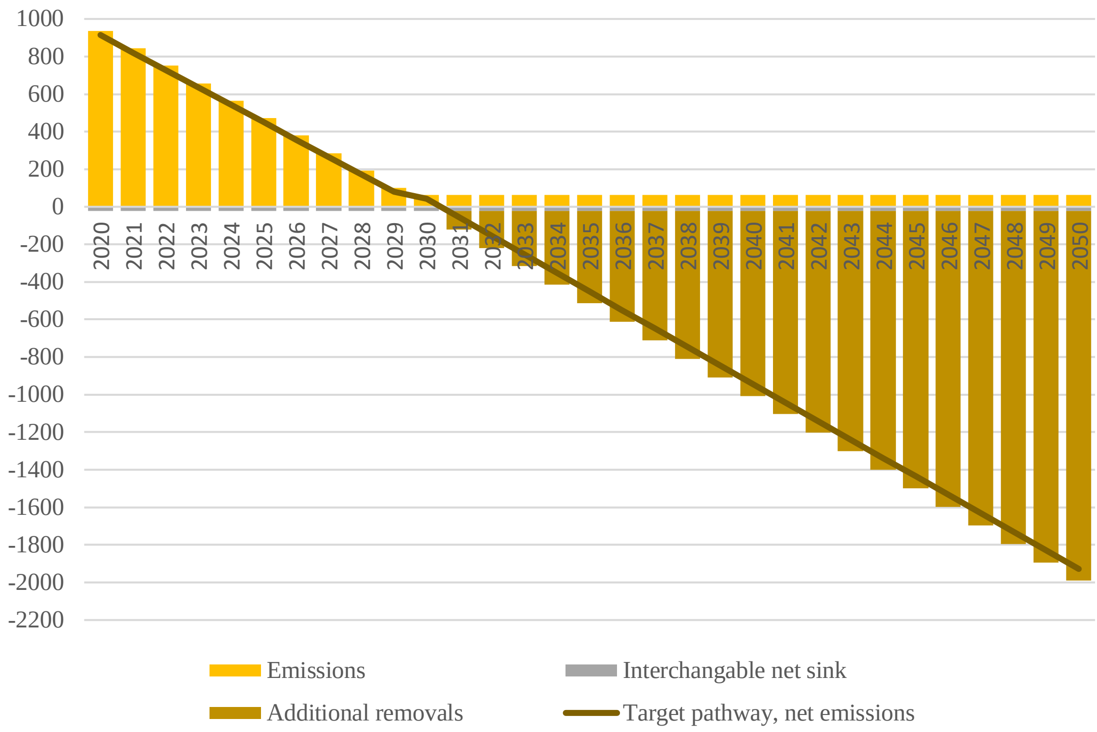

Figure 12c. The global carbon budget divided according to Historic Responsibility, linear emissions reduction and increased removals, and a net land-use sector sink of -21 Mt for Germany.

The case of Historic Responsibility is again dramatic, like in the case of Sweden, but for opposite reasons: the amount of actual fossil and process-based emissions allowed is dwarfed by the required cumulative amount of emissions removals for remaining within the GHG quota. The 2050 target in this case is 251% with -1970 Mt or 1.97 Gt of additional emissions removals. Emissions are reduced by 93 Mt per year to 2030, with GHG neutrality occurring the following year when additional emissions removals commence.

5.4. United Kingdom

The UK was one of the first countries in the world to set binding climate framework legislation and the only to my knowledge and to date who has successfully applied five-year emissions quotas as the tool for keeping on track with climate change mitigation (Fankhauser et al. 2018). The UK has also managed to already decrease its emissions by 38% compared to 1990, which is by far the largest decrease in all of the case studies in this thesis. The results for the UK in this equity framework are as follows:

	Equality	Ability to Pay	Historic Responsibility
Total	2711	1068	-6718
Per capita	38	15	-94

The burden of Historic Responsibility shows up again and Equality provides the largest quota. The per capita Ability to Pay and Historic Responsibility quotas are larger than for Germany and approximately the same as for Finland. The following graphs will demonstrate what these quotas mean for emissions pathways, required additional emissions removals and key targets.

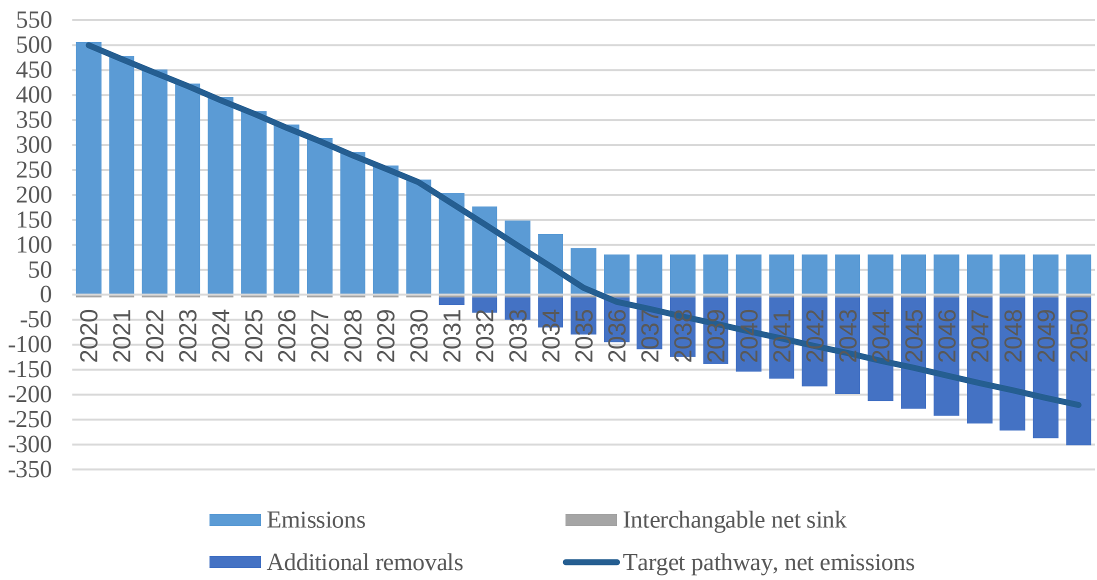

Figure 13a. The global carbon budget divided according to Equality, linear emissions reduction and increased removals, and a net land-use sector sink of -6 Mt for the UK.

The case of Equality in Figure 13a shows the pathway for the UK for remaining within the set GHG quota. The land-use sector net sink of -6 Mt per year is included in these calculations, but it is barely visible due to its small size compared to emissions and required additional removals. Due to the small size of the land-use sector net sink GHG neutrality occurs only after additional removals have been increased for five to six years at an annual rate of -15 Mt. After a mitigation rate of 27 Mt from 2020 onwards, emissions plateau at 81 Mt in 2036. The remaining emissions and additional removals of -296 Mt in 2050 in total translate into a reduction target of 127% compared to 1990. The full effect of all emissions, sinks and additional removals of the UK in 2050 adds up to -221 Mt.

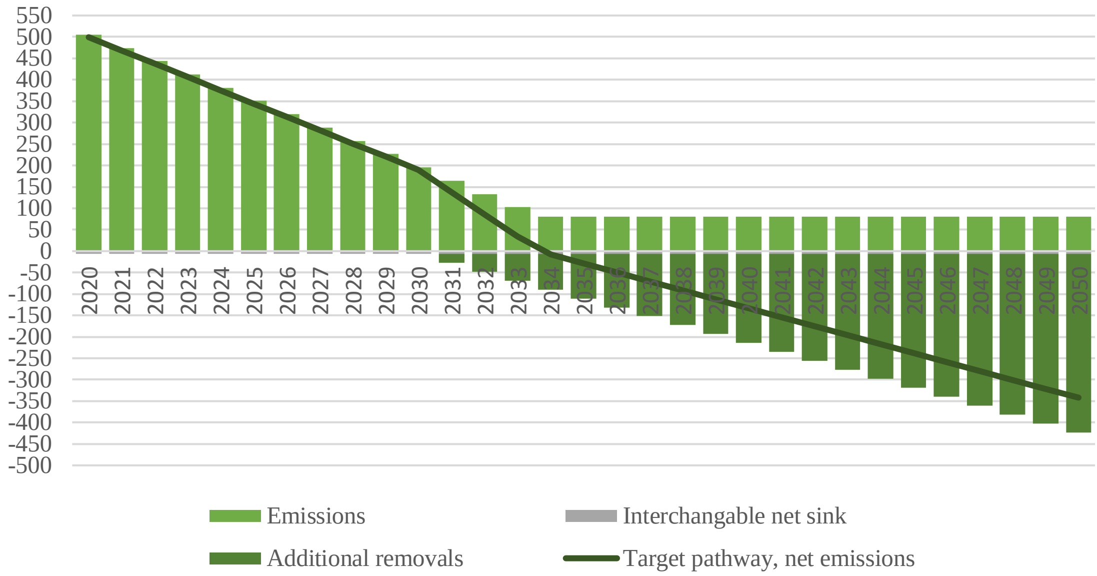

Figure 13b. The global carbon budget divided according to Ability to Pay, linear emissions reduction and increased removals, and a net land-use sector sink of -6 Mt for the UK.

In the case of Ability to Pay shown in Figure 13b, conditions are again similar to Equality due to the volume of emissions reductions required. Emissions are decreased by 31 Mt per year up 2034, when emissions plateau for the rest of the period. Additional removals form 2031 onwards are -21 Mt per year adding up to -417 Mt in 2050. Additional removals and remaining emissions in total in 2050 result in a 141% reduction target

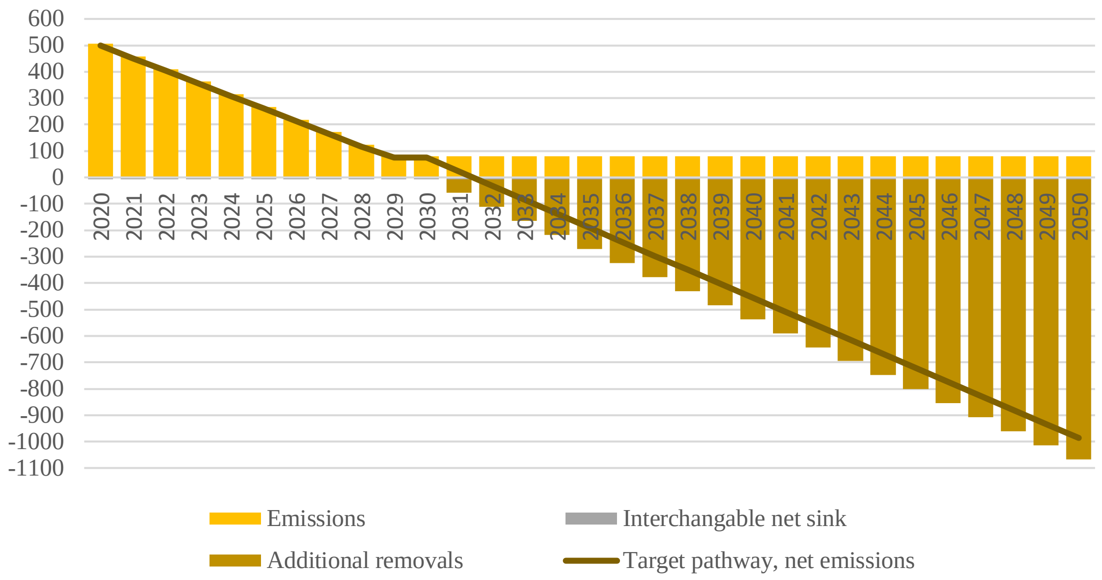

Figure 13c. The global carbon budget divided according to Historic Responsibility, linear emissions reduction and increased removals, and a net land-use sector sink of -6 Mt for the UK.

In the case of Historic Responsibility, the UK should decrease its emission by 90% compared to 1990 in just 9 years, which means a mitigation rate of 48 Mt per year up to 2029 after which emissions plateau. GHG neutrality occurs in 2031, which is the same year from which additional removals begin to increase by -53 Mt per year. In 2050, additional removals add up to -1 061 Mt or 1 Gt. The reduction target in 2050 including remaining emissions and additional removals is thus 221% and the net effect on the atmosphere by the UK of all emissions, sinks and removals is -986 Mt.

6. Discussion

The equity criteria and calculations I have presented can give food for thought on how to look at a potential fair share of climate mitigation efforts and a way of evaluating countries' existing climate targets. Table 6 below combines some of the results from the calculations in Chapter 4. From this table, we can again see that Sweden differs completely from the other case studies. Finland differs slightly from the EU, Germany and the UK, which all have broadly similar targets. The difference between Sweden and Finland is interesting, since even though national emissions are currently at the same level, per capita emissions are double in Finland compared to Sweden. The mitigation targets in Ability to Pay reflect this quite well - 100% versus 59%, or approximately 2 Mt mitigation rate versus 1 Mt mitigation rate for Finland and Sweden, respectively.

Table 6. Targets for 2050, mitigation rates, and GHG neutrality in all case studies.

	EU	Finland	Sweden	Germany	UK
Equality	129 % 236.9 Mt 2036	93 % 2.0 Mt 2038	35 % 0.3 Mt -	137 % 54.2 Mt 2035	127 % 27.5 Mt 2036
Ability to Pay	143 % 262.1 Mt 2034	100 % 2.3 Mt 2036	59 % 0.9 Mt 2041	149 % 58.7 Mt 2034	141 % 31.0 Mt 2034
Historic Responsibility	216 % 375.5 Mt 2031	144 % 3.4 Mt 2031	- - -	251 % 92.9 Mt 2031	221 % 47.7 Mt 2032

To see how reliable my results are, I will compare them to other published results. I can only compare results for the European Union, since country-based approaches have not been developed. Most often either Europe or Western Europe are regions that are considered in allocation approaches, which are reasonably close to the EU. Also, since the framework presented in this thesis is unique, I cannot compare my results directly with others available. Neither have there been studies published on the allocation of the 1.5 degree budget, to my knowledge. This is why examining the results of the sensitivity analysis on larger GHG budgets of Finland can provide some direction to how well the developed framework functions, since the largest GHG budget in the sensitivity analysis is close to the 2 degree budget.

In Raupach et al. (2014) mitigation rates for the European Union were calculated to be 2% to 6% compared to 2012 emissions. In my calculations, the mitigation rates are higher, since they are 5 to 8 percent compared to 2012 emissions levels. In Raupach et al. (2014) the method for calculating the carbon budget is not the same as mine, and they are looking at the 2 degree budget instead of the 1.5 degree budget, Thus, it makes sense that the mitigation rate is higher in my results, since the GHG budget is more strict for 1.5 degrees than 2 degrees.

In Wang et al. (2017) allowances range from 151 t to 332 t per capita for Annex I countries or 50 Gt to 80 Gt for Western Europe for 2011-2100. My per capita results across all case studies range from -218 t to 73 t. The total amount of emissions in my assessment for 2020 to 2050 for the EU ranges from -40 Gt to 20 Gt. When examining all these figures, it is clear there is substantial deviation, even though the equity measures applied in Wang et al. are in part very similar to mine. My conclusion is that deviation is mainly due to the fact that Wang et al. are dealing with the 2 degree budget, while I am looking at the 1.5 degree budget. Another key point is that the Wang et al. calculations are for 2011 onwards. In my calculations the actual recorded increase in emissions between 2011 and 2019 (Global Carbon Project 2018), is accounted for, decreasing the GHG budget available further, compared to Wang et al. If looking at the section on sensitivity analysis, the Finnish GHG quota in the last row of Table 4 is close to the 2 degree estimation in SR15 (IPCC 2018). The per capita allocations in this case would be -8 t to 109 t for 2020 to 2050. If I add to these figures the net emissions from 2011 to 2019, the range would be 57 t to 175 t, which brings it closer to the Annex I estimation by Wang et al. (2017). Examining the larger GHG budget shortens the gap to Wang et al. calculations, but a difference still remains. Since Wang et al. use a different, more conservative approach focusing on fossil fuel emissions (omitting non-CO_2 and the land-use sector) unlike my adjusted framework, this may explain the different quotas too.

In Peters et al. (2015), the share of the remaining carbon quota for the EU from 2015 onwards is 53 Gt or 73 Gt, depending on the equity measure. Peters et al. use the inertia (grandfathering) principle for the 73 Gt budget and a combined equity approach for the 53 Gt budget. Again, these results are calculated based on and for the purpose of fossil fuels, resulting in larger quotas than the ones produced in this thesis. However, they do note that this is the limitation of the method for policy relevancy. Peters et al. decided to omit non-CO_2 emissions from their calculations, since translating non-CO_2 emission into

CO_2 equivalents requires the use of global warming potential calculations, which is complicated when applied in a specific timeframe and a limit of global warming according to Shine et al. (2007). They also discuss the issue of the land-use sector and decide to leave it out due to uncertainty in measurement. Since I consider that the EU has reliable measurement, reporting and verifying in the land-use sector, I am in favour of including the land-use sector in my case studies, but I do agree with Peters et al. that this may be a problem in some other countries. It is commendable that they include in their article comparison of their results to NDCs and current pledges; next, I will attempt at this too.

The resulting targets for Finland presented in this thesis are in part more ambitious than current climate policy. Based on my analysis, Finland should reduce its emissions to over a 100% by 2050 and be clearly net negative for most of the 2030s and 2040s; the minimum reduction of 80% compared to 1990 of the Climate Change Act (Finlex 2015) is thus not in line with the results of framework analysis on equity and science-based targets as the basis for NDCs and long-term targets. The 80% target in the Act can be adjusted though, and the Finnish government is at the moment of writing reviewing the Climate Act. The government has set a target of carbon neutrality for 2035 meaning GHG neutrality, which may appear in the revised Climate Act. This GHG neutrality target is in line with the results of this thesis, and hopefully will get set in legislation soon. Especially the case of Ability to Pay proved a good measure, since it was the least sensitive to changes in the size of the global GHG budget or national let land-use sector sink. Ability to Pay and a net land-use sector sink of -14 Mt results in GHG neutrality occurring in 2035 and emissions reduction of 116% in 2050 compared to 1990. These results are the ones I think should be the targets for Finland – the net sink in the calculation is slightly lower than historical average, but this counts towards uncertainty and the decrease in double counting sinks inherent to the global GHG budget estimation. The climate targets of the other case studies are presented in Table 7 below.

Table 7. Current climate targets for the EU, Finland, Sweden, Germany, and the UK.

EU	'Climate neutrality by 2050' - net-zero greenhouse gas emissions by 2050 including the land-use sector[10]
Finland	'Carbon neutrality by 2035' - net-zero greenhouse gas emissions by 2035 including the land-use sector[11]
Sweden	'Carbon neutrality by 2045' - minimum 85% reduction of GHGs, remaining emissions compensated by international offsets and additional removals while only additional land-use sector sinks are used [12]
Germany	Reduction of 80% to 95% in 2050 while striving for 'carbon neutrality' [13]
UK	Legislation for net zero emissions from all greenhouse gas emissions by 2050[14]

The EU, Germany, and the UK can be bunched together for assessment, since their targets are the same in practice: GHG neutrality by 2050. A difference in commitment to these targets exists between these nations, though. The UK is very committed to its target, since it is now established in legislation. The EU is in the process of proposing a climate act, and it seems climate neutrality will be included in it. Germany has the vaguest target, with the target range quite wide and carbon neutrality only 'strived for'.

According to the framework analysis of this thesis, none of these targets are sufficient for the EU, the UK or Germany as a long-term target or NDC. Even with the largest GHG quota, which is the Equality quota, the reduction target should be approximately 130% compared to 1990 emissions levels for all three nations. An appropriate NDC would have a long-term target of significantly net negative emissions in 2050 and a GHG neutrality target for early to mid-2030s, with perhaps some statement on how emission removals will be addressed to ensure their delivery.

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[10] https://ec.europa.eu/clima/policies/strategies/2050_en Retrieved: 1.1.2020
[11] https://valtioneuvosto.fi/marinin-hallitus/hallitusohjelma/hiilineutraali-ja-luonnon-monimuotoisuuden-turvaava-suomi Retrieved: 1.1.2020
[12] (Seppälä et al. 2019)
[13] https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/fortschrittsbericht-monitoring-energiewende.pdf?__blob=publicationFile&v=8 Retrieved: 28.2.2020
[14] https://greengb.campaign.gov.uk/ Retrieved: 1.1.2020

From Table 7, it is striking how different Sweden's target is to all others; Sweden does not include the land-use sector automatically in its GHG neutrality target. Instead, Sweden has committed to an 85% reduction by 2045 and plans to offset the remaining emissions by utilising CCS technologies, additional emissions removals by natural sinks, and international offsetting. It would be interesting to know precisely what is meant by additional emissions removals by natural sinks, since it is not clear how this would be measured in practice. It would be helpful to learn more of the Swedish target, since it would provide a new and alternative way for looking at net emissions and especially additional emission removals as part of climate policy targets.

The equity framework of this thesis did not provide instructive results in line with the spirit of the Paris Agreement for Sweden, since the land-use sector net sink compensates for most of the fossil and process-based emissions already. However, when considering the Swedish set target for 2045, it seems that in forming this target, they have gone through a similar though process as I have in this equity analysis; Sweden can't look at climate policy targets in the same way as other. GHG neutrality in the conventional sense is not a sufficient, ambitious or justifiable target for Sweden. Instead, I would argue that a commitment to reduce fossil and process-based emissions to the same extent as other countries, i.e. 90% by 2050, and offsetting the residue, would be a sufficiently ambitious target. The current Swedish target of 85% for 2045 is thus close to this, but not quite.

As the previous paragraphs show, carbon neutrality is a trend in climate policy targets. Proof of this is the Net Zero Tracker (Energy & Climate Intelligence Unit 2019), which contains all suggested, confirmed and achieved GHG neutrality targets, which in total cover half of the global GDP. Despite the popularity, there are different definitions for GHG neutrality. Most often the term used is carbon neutrality or 'net zero emissions', but what is often meant is in fact GHG neutrality, such as discussed in this thesis (Seppälä et al. 2019). Not just terminologically, but in methodology there are differences, which would affect comparing national targets to the framework of this thesis. One of the differences is the case of how the land-use sector is approached, as discussed above. Another instance is the use of international offsets or tradeable GHG quota allocations. Lastly, even if the world on the whole reached GHG neutrality, global warming would continue due to the long-lasting lives of GHG gases in the atmosphere (Partanen 2018).

A problem in addition to the ambiguousness of GHG neutrality targets is that GHG neutrality targets do not consider cumulative emissions. One of the strengths of the framework analysis in this thesis is that GHG neutrality is not a target in itself, instead it just occurs at some point in the 2020-2050 timeframe; since cumulative emissions is the thing that matters in climate change, in theory it is irrelevant at a country-level when GHG neutrality occurs. However, due to the popularity of GHG neutrality targets, it is one of the important results of this thesis. The popularity of the term may be due to how ambitious it sounds; but, as the results of this thesis show, GHG neutrality depends on numerous factors. For example, Sweden may be GHG neutral soon, with modest, unambitious mitigation rates, while Germany requires extremely steep and ambitious mitigation and emissions removal to reach GHG neutrality.

One other weakness in this framework in addition to issues regarding the methodology of emissions and sinks, is perhaps the linear reduction pathway for demonstrating the GHG quota. I chose linear, since it is commonly applied in the EU, but it leads to two problems. Firstly, in cases where emissions could be decreased easily in larger blocks to begin with, for example by eliminating coal from energy production, this linear pathway is not suitable. The linear pathway, instead of a stepped or inward curving pathway, causes the need for greater emissions removals later. In other words, mitigating more emissions than the linear pathway demands lessens the amount of emission removals required later. Secondly, in some of the cases presented, the mitigation rate was extremely steep and could not be sustained in real life conditions. The only way to fix this would be to apply a segmented pathway, e.g. for buying time for fossil-based power plants to run their lifespan and switching directly and simultaneously to carbon free technology. Again, this might not be enough or suitable for remaining within the quota; if the mitigation rate is very steep, it means the quota overall is so small that early action is worth looking into, since cumulative emissions are at the core of GHG quotas.

The cumulative approach for developing climate targets is based strongly in science, since it is the cumulative amount of carbon in the atmosphere which causes global warming. Thus, including cumulative emissions, such as in the method of this thesis, as part of a climate policy target is well founded. Despite this, national climate policy targets are primarily targets for emissions reductions or GHG neutrality in a certain year rather than specifically targeting cumulative emissions. Some targets appear cumulative though, but the basis for them is usually that a certain reduction percentage by a certain year is aimed for. They may be demonstrated as emissions allocations for specific years leading towards that target, such as in the EU Effort Sharing Decision, and higher or lower emissions than the allocated amount in one year affect the following years' allocations. However, I expect that these kinds of policies are not designed with a cumulative emissions target in mind, instead they are steppingstones towards a set target, which I think is key to understand when assessing them. Cumulative targets would be most appropriate in line with science, but there are many problems in setting them.

Timing is one of the issues with cumulative targets. Outcome targets, once set, can be left unaltered, since if no other restrictions are in place, it is not relevant how the target is reached. In the case of a cumulative quota which is then mapped out, as I have done in the figures demonstrating the results of the GHG quota allocation, the pathway in which the subsequent reduction target is met is the whole point of the set policy guideline. If emissions do not decrease at the required rate, future allocations need to be adjusted to reflect this. This may not turn out to be one of the more serious concerns – in some of the case studies of this thesis emission removals close to 2050 were so extensive that actually cutting emission quicker and thus requiring less emission removals for remaining within the GHG quota may turn out to be the easier mitigation strategy.

Another consideration regarding timing is the selection of 2050 as the end year of this analysis. But how about after 2050? If applying the idea on what the framework is based on, it would be sufficient that countries are GHG neutral from then on. This would be counterintuitive, since it would mean that in most of my case studies emissions could suddenly be increased from significantly net negative GHG emissions to just GHG neutrality. However, as discussed previously, many of the targets calculated required astounding amounts of emissions removals. So, perhaps some of the emission removal activity could be postponed to the post-2050 period to decrease the pressure on achieving them; this would also postpone limiting global warming, though.

Since timing issues for the cumulative emissions target makes it complicated, perhaps that is why outcome targets are so widely used. The issue with the framework presented in this thesis is that I have looked at equity in allocation, not outcome. Therefore, if climate targets are outcome-based, should not the equity framework applied also be concerned with equity in outcome? Convergence of per capita emissions to a certain level, perhaps weighted if e.g. Ability to Pay was to be considered, would be equity in outcome rather than initial allocation. Equity in outcome seems initially appealing, since it seems fair that similar low-carbon lifestyles would be required for all. This is an interesting idea, but perhaps more suited to cases where individual carbon footprints are examined, rather than a summed up figure for a country-level approach. Also, using equity in outcome and simultaneously allocating a global GHG quota requires looking at all countries in the world at the same time, and is thus not perhaps a good tool for evaluating individual NDCs. However, looking at what results in per capita emissions we get for 2050, there are some interesting points for and against convergence, since even though fossil-and process based emissions converge in the results of this framework, required additional emissions removals do not. I have gathered the results in Table 8 below, but left Sweden out, since the framework did not produce viable mitigation targets for it.

Table 8. Remaining emissions, additional removals and net per capita in 2050 (t CO_2e).

		EU, 90%	Finland 90%	Germany 95%	UK 90%
Equality	Emissions	1.1	1.3	0.8	1.1
	Add. removals	-4.2	-0.4	-6.5	-4.1
	Net, with sinks	-3.7	-2.9	-6.0	-3.1
Ability to Pay	Emissions	1.1	1.3	0.8	1.1
	Add. removals	-5.8	-1.3	-8.3	-5.8
	Net, with sinks	-5.3	-3.8	-7.8	-4.8
Historic Responsibility	Emissions	1.1	1.3	0.8	1.1
	Add. removals	-13.8	-7.1	-23.9	-14.9
	Net, with sinks	-13.3	-9.6	-23.4	-13.8

When emissions plateau at either 90% or 95% reductions, they do so resulting in similar, approximately 1 t, per capita emissions in all cases; this is conceivable, since towards the base year 1990 economic development had resulted in similar technological conditions leading to similar per capita emissions in 1990: EU 11.0 t, Finland 13.0 t, Germany 15.3 t, and the UK 11.3 t. Germany's per capita emissions were much higher, which is why a 95% reduction target was selected for Germany instead of 90% like in other cases in this framework, as discussed previously. In additional removals the pattern discussed in the results section is visible; for Germany, the UK and the EU the level of additional removals is much higher than for Finland and especially so for Germany. This is due to Finland having a high level of net land-use sector sink per capita; it compensates already for approximately a third of fossil-and process based emissions. But is it equitable to calculate the land-use sector fully for the benefit of Finland, which as a country is sparsely populated[15] and thus has the space for vast forests?

Forgoing the problem of equity in regard to inevitable and unmodifiable national conditions for natural land-use sector sinks, i.e. the physical space available for forests, other problems arise in the land-use sector too. Even though measurement and reporting are done according to best available methods, their uncertainty levels are very high compared to fossil and process-based emissions and technological emissions removals, since we are measuring natural, biological processes (carbon sequestration, emissions from soil) rather than mechanical processes (carbon capture and storage (CCS), fossil-fuel carbon content). Therefore, one of the weaknesses of the framework developed in this thesis is relying on one tonne of net land-use sector sink being the correct quantity for compensating for on tonne of fossil and process-based emissions, despite uncertainty. Also, fossil and process-based emissions should be decreased according to all basic knowledge on climate change despite having high net land-use sector sinks. This is not accounted for in the framework, as the framework analysis of Sweden clearly shows. Since the approach is a purely algebraic calculation of emissions, sinks and emissions removals within a GHG budget constraint.

The problem of the land-use sector and some of the differences in the results compared to published papers in the field of carbon budget allocation can be overcome, if the approach presented in the sensitivity analysis section of this thesis is applied. The mitigation targets including decreasing non-CO_2 emissions were 130%, 144%, and 257%, when the land-use sector was completely left out and the equity framework applied to purely CO_2 emissions. The need for emissions removals becomes heightened and my assumption of non-CO_2 was purely speculative, while an important sector regarding climate change is left out, making the approach not fit for a comprehensive, economy-wide approach in my opinion. It was interesting to see though that GHG neutrality occurred virtually in the same year, when comparing the CO_2-only and -14 Mt sink results within each equity framework.

[15] The EU average in 2018 was 118 per km^2, while in Finland the same figure is merely 18 per km^2. Source: Eurostat, Population Density database. Available online: https://ec.europa.eu/eurostat/web/products-datasets/product?code=tps00003 Retrieved 1.1.2020.

As it remains expensive and improbable all emissions can be eliminated, this heightens the need for emissions removals, or 'negative emissions'. In this thesis, the consequence of all over 100% reduction targets for 2050 is the need for additional removals. In the case of Finland, this would be achieved easiest by increasing the net sink of the LULUCF sector. Measures, which would enhance either forest sinks or decrease land-use sector emissions, contain inherent uncertainty when looking to the future due to conditions guiding biological processes, such as extreme weather, increased logging, pests or soil degradation. Utilising CCS technologies would eliminate this issue, since it is a measurable mechanical process. However, relying on negative emissions technology for sorting out mitigation needs is not enough, as large-scale bioenergy with CCS (BECCS) faces biophysical, technical and social challenges and other CCS technology has not been widely developed (Fuss et al. 2014; Anderson & Peters 2016). Also, the effect of emissions removals may be smaller tonne for tonne than the effect of emissions, since global warming would continue even if all emissions end today, as mentioned before, meaning that halting climate change would require net negative emissions. The results for all but Sweden in this thesis did lead to net negative emissions, which adds to the relevancy of these results as climate policy guidelines.

Finally, there is a strong basis for the argument that responsibility for emissions should be with those who consume and gain the benefits from products and services rather than responsibility lying on those who produce them, if equity and fairness were to be considered (Davis & Caldeira 2010). However, since this is a framework for looking at NDCs, which are based on territorial emissions, I will not delve into equity in consumption-based emissions. Other studies, such as the 1.5 Degree Lifestyles report (Lettenmeier et al. 2019), are more suited for assessing it than this framework, since the idea of consumption-based emissions reductions depends highly on individual action rather than producing a climate policy target according to the Paris Agreement. Most of the results of this thesis do however show the need for extensive changes in current production and consumption, but unlike consumption-based emissions, the keys are in each nation's own hands whether to act or not.

7. Conclusions

In this thesis I introduced the changed paradigm of international climate policy from negotiated top-down targets of the Kyoto era to the new, Paris Agreement bottom-up mitigation contributions, NDCs. NDCs are submitted to the UNFCCC on the basis of what countries consider as their fair share of efforts in line with temperature targets, equity considerations and national circumstances. This means that normative decisions on fairness need to be made when selecting a long-term target required by the Paris Agreement.

For this purpose, I developed a framework for considering some of the key issues that crop up in examining long-term climate policy. Different equity measures exist for assessing fairness, of which I selected Equality, Ability to Pay and Historic Responsibility as the ones to consider, since they are the most unambiguous as formulas and are the most prevalent in carbon budget allocation studies. The Paris Agreement temperature targets can be calculated into carbon budgets, of which I selected the most recent IPCC estimation for the 1.5 degree budget and subtracted subsequent global emissions from. To be able to consider all sources and sinks of GHGs, I applied the carbon budgets as GHG budgets instead of purely carbon budgets and included all emissions and sinks reported in national GHG inventories, which are reported in line with IPCC 2006 guidelines. While not a completely accurate utilisation of the carbon budget, I deemed this approach sufficient for examining climate policy ambition.

The equity calculations for allocating the GHG budget to countries for the period of 2020-2050 produced an emissions reduction pathway while the land-use sector net sink was kept fixed according to the historical average with an illustrative pathway for required additional emissions removals. These results were presented in graphs, and key figures pointed out, such as the mitigation rate, the year GHG neutrality occurs, what the 2050 end result is as a reduction of emissions compared to 1990, and at what rate emissions removals are required to increase.

My goal of suggesting a long-term climate policy target in line with climate science, equity and 1.5 global carbon budget was successful in part; I was able to apply all the set conditions and produce a calculation alongside a demonstrative graph with specific key targets. However, some of the results were unrealistic for applying to real life conditions, such as the amount of emissions removals required for Germany. Mitigation rates, which

I had fixed as linear, were very drastic in some cases, which might not be possible in present conditions. Contrary to what I had initially set to find out, GHG neutrality targets to be achieved in the 2030s for most cases transpire as the most significant result. GHG neutrality is however only a milestone toward a long-term target, which I would argue based on these case studies is a significantly over 100% target.

I would also argue that despite the uncertainty factors in this framework analysis, to remain within 1.5 degree global warming the conclusion is roughly the same for developed countries – emissions need to be reduced at a perhaps previously unforeseen speed and that emissions removals and land-use sector sinks also carry significant weight, since current high emissions levels need to be compensated for. The results in this thesis for Finland, the EU, Germany and the UK speak on behalf of this. The exception in this thesis was Sweden, since due to already low per capita emissions and high land-use sector sinks, its net effect on the climate per capita is very small. However, the land-use sector sink may not be fully usable for offsetting emissions due to the nature of the carbon budget, and as part of the EU, Sweden's net sinks also count towards compensating emission for those countries who due to geographic and climate conditions do not have efficient forests for capturing carbon. Thus, developed countries should strive for GHG neutrality in the 2030s, instead of 2050, as many are now currently doing.

Future research has much to focus on. According to the results of the framework analysis of this thesis, emissions removals are key for staying within a set 1.5 degree compatible GHG quota. Especially since the mitigation rates required in this thesis may prove impossible, leading to additional cumulative emissions that need to be compensated for towards 2050. There is much hope in this field as several pilot projects are ongoing, but none at the scale needed – at least yet. However, relying on emissions removals should not water down the need for reducing fossil and process-based emissions to the bare minimum while looking after the sustainability of the land-use sector and related other biodiversity benefits. Realistic information on different emissions removal technology scenarios in different countries ranging from limited technology availability to fully scalable technology would be an interesting angle for research in emissions removal technologies and would feed in well to the NDC process.

To provide countries with a scientific base for their NDCs, future research could advance in developing robust, country-based approaches for dividing the carbon budget. This would require demonstrating how much of the land-use sector is included or excluded in the carbon budget itself. In addition, some instruction or signal for what to do with non-CO_2 emissions would need to be provided too. Also, instead or a qualitative analysis of results, a quantitative statistical approach for determining significance across equity scenarios should be used. In this way, NDCs can be truly assessed to be in line the Paris Agreement commitments.

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