FINNISH CLIMATE CHANGE PANEL REPORT 2/2024

Review of Finland's emissions reduction pathway, taking into account the role of non-CO_2 greenhouse gases and indirect sink effects

ANTTI-ILARI PARTANEN, SALLY WEAVER, TOMMI EKHOLM, TARU PALOSUO, TIMO VESALA, JYRI SEPPÄLÄ, HANNELE KORHONEN, MARKKU OLLIKAINEN

SUOMEN ILMASTOPANEELI

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Authors: Antti-Ilari Partanen, Sally Weaver, Tommi Ekholm, Taru Palosuo, Timo Vesala, Jyri Seppälä, Hannele Korhonen, Markku Ollikainen

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The Finnish Climate Change Panel promotes dialogue between science and policy on issues to do with climate change. It provides recommendations for government decision making on climate policy and strengthens the multidisciplinary approach to climate science. The Panel's reports and statements are based on scientific evidence.

Ilmastopaneeli.fi
LinkedIn | Bluesky
info@ilmastopaneeli.fi

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FOREWORD AND KEY MESSAGES FROM THE FINNISH CLIMATE CHANGE PANEL

The target of carbon neutrality by 2035, as set out in the Finnish Climate Act (423/2022), is one of the first science-based national climate targets in the world. The carbon neutrality target and the net emissions reduction pathway leading up to it serve as an answer to the question: in the global context, how much is Finland's globally fair share of the remaining global carbon budget if we are to remain within the 1.5 °C limit set by the IPCC? The target is derived from inventory accounting used in climate policy and the ability to pay as a global principle of fairness, and implements the Paris Agreement.

Approaches to reviewing global carbon sinks and climate modelling have evolved since the Panel's earlier review and recommendation (Ollikainen et al. 2019, Climate Panel 2021). As a result, the Panel has carried out a methodological review in this report, comparing the methodology based on the greenhouse gas inventory accounting, which underpins climate policy, with climate science modelling. The fundamental question is: in the global context, what is Finland's fair share of the remaining greenhouse gas budget.

Applying the IPCC's estimate of the remaining carbon budget at national level requires projecting the evolution of non-CO_2 emissions based on climate science modelling and quantifying the so-called indirect sink effects. Non-CO_2 emissions in this context are methane (CH_4), nitrous oxide (N_2O) and fluorinated greenhouse gases (F gases). Indirect sink effects include, for example, the change in forest growth due to global warming and increased CO_2 concentrations, and the effects of global warming on soil emissions compared to the pre-industrial climate. Both factors (non-CO_2 emissions and the indirect sink effect) can be included in the accounting at national or global level, or as a combination of both. The choices made will affect the national outcome, i.e. the net emissions pathway derived from the emission budget. Depending on the approach chosen, the report's calculations indicate that an equitable target year for achieving carbon neutrality, where greenhouse gas emissions are, at most, equal to removals, is around 2029–2037. Based on this review, the Finnish Climate Change Panel highlights the following points.

Carbon neutrality by 2035 is a legitimate target and its implementation must be ensured

The Finnish Climate Change Panel emphasises that carbon neutrality by 2035, as set out in the Finnish Climate Act, is a justified target for Finland's climate policy, in light of the principle of fairness based on ability to pay, as the review shows that carbon neutrality will be achieved between 2029 and 2037. This view is also supported by the Panel's estimates regarding feasible climate actions to achieve carbon neutrality by 2035. In addition to this, the Panel believes that achieving carbon neutrality by 2035 is important for Finland in terms of reaping the benefits of the clean transition.

In the emissions trading sector, the reduction in fossil fuel emissions in Finland is progressing even faster than expected. This could allow the carbon neutrality target to be achieved at a lower net sink level than the historical average for the land-use (LULUCF) sector. Emissions reductions can be accelerated further, and the net sink, i.e. the sum of carbon dioxide removals and soil emissions, must be strengthened. Cost-effective, emissions-reducing and sink-boosting measures must be put in place immediately in the land-use sector. Technological sinks are also needed to support an increase in the net sink of the land-use sector. There is sufficient time to achieve the carbon neutrality target, provided we speed up the process of reinforcing the natural and technological sinks and make rapid enough progress on emissions reductions.

Speeding up the process of reinforcing sinks

In the report we used a level corresponding to the historical average of the net sink, as in the previous analysis of the Finnish Climate Change Panel, to ensure consistency in the comparison of methodologies. The net sink level for the LULUCF sector in the early 2020s has been significantly lower, even in terms of emissions, than the average for the time series starting in 1990. The deterioration of the net sink is due to a lack of action to maintain an adequate net sink level and an increase of over 20% in annual logging compared to the early 2010s, with soil emissions from peatlands having grown due to global warming.

The LULUCF sector's net sink can be increased by reducing soil emissions in peatlands used for agricultural purposes, old peat extraction areas, and swamp forests. Cost-effective measures are feasible for these areas. A level of economic use of forests that is compatible with the objectives of sinks and biodiversity can also be outlined.

The potential for increasing the technological sink is good, as Finland produces about 28 Mt of biogenic carbon per year in large-scale plants (plants emitting more than 0.1 Mt CO_2/year). Investments in biogenic carbon capture and storage could be launched, for example through a public tender. At the same time, this would force the use of biogenic carbon dioxide, in addition to its storage, in new products to replace fossil fuels.

Global climate policy needs harmonisation

The methodological review carried out shows that the Paris Agreement can be applied differently from country to country, even when done in a way that is justified by climate science. The target of keeping global warming to no more than 1.5 °C may not be met even if countries apply the same principle of fairness, as the indirect sink effect and non-CO_2 emissions should also be accounted for based on the same principles. Making the accounting principles of national targets visible when countries define their national contributions to the Paris Agreement, and later harmonising accounting practices between countries, may be necessary in the development of UN climate policy.

Tackling methane, with its high global warming potential, in climate policy

When comparing the differences between the greenhouse gas inventory and climate science methods, the effects of non-CO_2 emissions are prominent. Methane, in particular, is a short-lived greenhouse gas that has very high global warming potential. With the current accounting approach based on a 100-year radiative forcing, the impact is 30 times that of CO_2, but over a 20-year time scale the impact is more than 80 times that of CO_2. The current accounting method does not guide the targeting of actions to reduce methane emissions effectively enough, so a shorter time horizon may be necessary in the accounting method based on radiative forcing, in order to effectively target climate actions to avoid exceeding the 1.5 °C limit.

Further research

There are uncertainties in the projection of non-CO_2 emissions, in the modelling of indirect sink effects and, to some extent, in the climate modelling itself. Furthermore, different modelling criteria and methodological choices will produce different results, as always when using different approaches.

Strengthening the scientific basis for climate policy, in particular the assessment of national and global indirect sinks, will be an important task for the scientific community in the future.

Helsinki, 9 October 2024

The Finnish Climate Change Panel

SUMMARY

The report examines how much a fair share would be for Finland to shoulder when it comes to climate actions, and the consequent emissions reduction pathway. The inventory accounting approach used by the Finnish Climate Change Panel in previous assessments is compared with approaches that are more consistent with climate science modelling and the definitions used in the Intergovernmental Panel on Climate Change's (IPCC) scientific reports. The report takes into consideration non-CO_2 greenhouse gases and indirect sink effects as part of climate modelling. The review covers the period 2020–2050. In addition to the direct application of inventory accounting as previously used by the Panel, the report proposes two emissions reduction pathways for Finland (Method 1 and Method 2), which are both in line with the aim of a 1.5 °C limit as set out in the Paris Agreement. The results of the analysis are compared with the Panel's earlier recommendations on the national emissions reduction pathway and carbon neutrality target. The emissions reduction pathways presented are based on linear emissions reductions, distributed evenly over the period 2020–2050.

The report looks at the impact of Finland's greenhouse gas emissions on global warming. The starting point is an approach that follows the climate policy of the parties to the Paris Agreement: direct application of the inventory accounting approach. Following this approach, the emissions reduction pathway is calculated using net CO_2 emissions from the LULUCF sector according to the greenhouse gas inventory and non-CO_2 greenhouse gas emissions are reconciled to align with the remaining carbon budget in accordance with the greenhouse gas inventory. Finland's fair share of global climate change mitigation efforts based on net emissions as detailed in the greenhouse gas inventory can be explored by looking at its fair share of the remaining carbon budget or the proportion of global warming it is responsible for. The latter approach used in the report allows non-CO_2 greenhouse gases to be more accurately accounted for. Indirect sink effects, i.e. the impact of climate change and increased CO_2 concentrations on managed land, are estimated based on two studies that involved forest growth on managed forest land being modelled both taking into account climate change and on the basis of the pre-industrial climate, and the difference between these simulations being used to calculate indirect sink effects.

With Method 1, indirect sink effects and non-CO_2 greenhouse gas emissions are reconciled at global level. With Method 2, the same reconciliations are done at national level. In both cases, the calculation results in a lower emission budget than with the Panel's previous method. In particular, the interpretations and results following Method 2 would require Finland to adopt a significantly more stringent climate policy in the period under consideration. Following Method 1, Finland would be carbon neutral by 2037 and following Method 2, by 2029. The primary reason for Method 1 resulting in a later date for achieving carbon neutrality than the current carbon neutrality target is the IPCC's updated remaining carbon budget estimate. The effects of non-CO_2 emissions are particularly prominent when comparing the differences between the direct application of the greenhouse gas inventory and methods more compatible with climate science.

The conclusion of the review is that, in light of the principle of fairness based on the ability to pay, Finland's 2035 carbon neutrality target is, at the very least, not too ambitious as a fair contribution to remaining under the 1.5 °C limit set out in the Paris Agreement. The report provides preliminary results for examining how to bring the inventory accounting approach that underpins climate policy more in line with a climate science approach.

TIIVISTELMÄ

Raportissa tarkastellaan Suomen reilua osuutta ilmastotoimista ja siitä seuraavaa päästövähennyspolkua. Ilmastopaneelin aiemmissa arvioissa käyttämää inventaariolaskentaan perustuvaa lähestymistapaa verrataan ilmastotieteellistä mallinnusta ja IPCC:n tieteellisten raporttien määritelmiä paremmin vastaaviin lähestymistapoihin. Raportin tarkastelussa otetaan huomioon muut kuin CO_2-kasvihuonekaasut sekä epäsuorat nieluvaikutukset osana ilmastonmallinnusta. Tarkasteluvälinä on vuodet 2020–2050. Raportti esittää Suomelle Ilmastopaneelin aiemmin käyttämän inventaariolaskennan suoran sovelluksen lisäksi kaksi päästövähennyspolkua (tapa 1 ja tapa 2), jotka ovat linjassa Pariisin sopimuksen 1,5 asteen tavoitteen kanssa. Analyysin tuloksia verrataan Ilmastopaneelin aiemmin antamiin suosituksiin kansallisesta päästövähennyspolusta ja hiilineutraaliustavoitteesta. Esitetyt päästövähennyspolut perustuvat lineaarisiin päästövähennyksiin, jotka jakautuvat tasaisesti vuosille 2020–2050.

Raportti käsittelee Suomen kasvihuonekaasupäästöjen vaikutusta globaaliin ilmaston lämpenemiseen. Lähtökohtana on Pariisin sopimuksen osapuolien ilmastopolitiikan mukainen lähestymistapa, inventaariolaskennan suora sovellus. Siinä päästövähennyspolku lasketaan käyttämällä kasvihuonekaasuinventaarion mukaisia LULUCF-sektorin nettopäästöjä ja hiilibudjettiin sovitetaan kasvihuonekaasuinventaarion mukaisesti muut kuin CO_2-kasvihuonekaasupäästöt. Kasvihuonekaasuinventaarion nettopäästöihin pohjaavaa reilua osuutta globaaleista ilmastonmuutoksen hillintätoimista voidaan käsitellä tarkastelemalla reilua hiilibudjettiosuutta tai osuutta ilmakehän lämmittämisestä. Raportissa käytetyllä jälkimmäisellä tarkastelutavalla muut kuin CO_2-kasvihuonekaasut voidaan huomioida laskennassa tarkemmin. Epäsuorien nieluvaikutusten, eli ilmastonmuutoksen ja kasvaneen CO_2-pitoisuuden vaikutus ihmiskäytössä olevilla mailla, arvioidaan perustuen kahteen tutkimukseen, joiden menetelmässä metsien kasvua hoidetulla metsämaalla mallinnettiin ilmastonmuutoksen kanssa ja esiteollisella ilmastolla, ja näiden simulaatioiden erotuksesta laskettiin epäsuorat nieluvaikutukset.

Tavassa 1 epäsuorat nieluvaikutukset ja muut kuin CO_2-kasvihuonekaasupäästöt sovitetaan globaalilla tasolla. Tavassa 2 samat sovitukset tehdään kansallisella tasolla. Laskennan tulokset johtavat kummassakin tavassa pienempään päästöbudjettiin kuin Ilmastopaneelin aiemmalla menetelmällä. Erityisesti tavan 2 mukaiset tulkinnat ja tulokset vaatisivat Suomelta selkeästi tiukempaa ilmastopolitiikkaa tarkasteltavana ajanjaksona. Tavan 1 mukaan Suomen tulisi olla hiilineutraali vuonna 2037 ja tavan 2 mukaan jo vuonna 2029. Tavan 1 nykyistä hiilineutraaliustavoitetta myöhäisempi ajankohta johtuu pääosin päivitetystä IPCC:n hiilibudjettiarviosta. Muiden kuin CO_2-päästöjen vaikutukset korostuvat kasvihuonekaasuinventaarion suoran sovelluksen ja ilmastotieteen kanssa yhteensopivampien menetelmien eroja vertailtaessa.

Tarkastelun lopputuloksena voidaan todeta, että maksukykyyn perustuvan oikeudenmukaisuusperiaatteen valossa Suomen vuoden 2035 hiilineutraaliustavoite ei ole ainakaan liian kunnianhimoinen Suomen reiluksi panokseksi Pariisin sopimuksen 1,5 asteen tavoitteen saavuttamiseen. Raportti tarjoaa alustavia tuloksia sen tarkasteluun, kuinka ilmastopolitiikan perustana oleva inventaariolaskennan mukainen lähestymistapa saataisiin paremmin vastaamaan ilmastotieteen mukaista lähestymistapaa.

SAMMANDRAG

Rapporten granskar vilken Finlands rättvisa andel av klimatåtgärderna och den därav följande utsläppsminskningsbanan skulle kunna vara. Klimatpanelens tidigare bedömningar som utgått från ett inventeringsbaserat perspektiv jämförs med sådana perspektiv som är mer förenliga med klimatvetenskaplig modellering och definitionerna i IPCC:s vetenskapliga rapporter. I granskningen beaktas icke-CO_2-relaterade växthusgaser och indirekta sänkeffekter som en del av klimatmodelleringen. Granskningen omfattar åren 2020–2050. Rapporten lägger fram en direkt tillämpning av den inventeringsberäkning som Klimatpanelen tidigare använt för Finland, samt två utsläppsminskningsbanor (sätt 1 och sätt 2), som följer Parisavtalets 1,5-gradersmål. Analysens resultat jämförs med Klimatpanelens tidigare rekommendationer om den nationella utsläppsminskningsbanan och målet om koldioxidneutralitet. Utsläppsminskningsbanorna grundar sig på linjära utsläppsminskningar, som fördelar sig jämnt över 2020–2050.

Rapporten behandlar effekterna av Finlands växthusgasutsläpp på den globala uppvärmningen. Utgångspunkten är det klimatpolitiska perspektiv som omfattas av parterna i Parisavtalet, det vill säga en direkt tillämpning av inventeringsberäkning. Där beräknas utsläppsminskningsbanan utifrån de inventerade nettoutsläppen av växthusgaser från LULUCF-sektorn. Icke-CO_2-relaterade växthusgaser anpassas till koldioxidbudgeten enligt inventeringen. Den rättvisa andelen av de globala klimatförändringsbegränsande åtgärderna som grundar sig på de inventerade nettoutsläppen kan klarläggas genom att undersöka vilken andel av koldioxidbudgeten eller den globala uppvärmningen som vore rättvis. Det senare perspektivet som används i rapporten gör det möjligt att noggrannare beakta icke-CO_2-relaterade växthusgaser i beräkningarna. De indirekta sänkeffekterna, dvs. effekterna av klimatförändringarna och ökade CO_2-koncentrationer på mark i mänsklig användning, beräknas utifrån skillnaden mellan två studier där skogstillväxten på brukad skogsmark har modellerats med beaktande av klimatförändringar och ett förindustriellt klimat.

I sätt 1 anpassas de indirekta sänkeffekterna och utsläppen av icke-CO_2-relaterade växthusgaser på global nivå. I sätt 2 sker anpassningarna på nationell nivå. Beräkningsresultaten för de båda sätten ger en mindre utsläppsbudget än Klimatpanelens tidigare metod. I synnerhet skulle tolkningarna och resultaten av sätt 2 kräva att Finland antar en klart strängare klimatpolitik under den aktuella perioden. Enligt sätt 1 blir Finland koldioxidneutralt år 2037 och enligt sätt 2 redan år 2029. Att tidpunkten för koldioxidneutralitet i sätt 1 infaller senare än det nuvarande målet för klodioxidneutralitet beror främst på IPCC:s uppdatering av den beräknade koldioxidbudgeten. Effekterna av icke-CO_2-relaterade utsläpp framhävs vid en jämförelse av skillnaderna mellan en direkt tillämpning av växthusgasinventering och klimatvetenskapligt mer förenliga metoder.

I ljuset av principen om betalningsförmåga är granskningens slutsats att Finlands mål om koldioxidneutralitet 2035 åtminstone inte är för ambitiöst för att Finland ska kunna uppnå Parisavtalets 1,5-gradersmål på ett rättvist sätt. Rapporten erbjuder preliminära resultat för en granskning av hur det inventeringsbaserade perspektivet som ligger till grund för klimatpolitiken bättre skulle kunna motsvara det klimatvetenskapliga perspektivet.

GLOSSARY

Non-LULUCF sectors. Sectors outside the land use sector (LULUCF), i.e. the emissions trading and effort sharing sectors according to the EU emissions classification.

Indirect sink effects. Changes in net emissions from the LULUCF sector due to climate change and increased CO_2concentrations on managed land compared to pre-industrial reference levels.

Net CO_2 emissions of the LULUCF sector according to the accounting method for global carbon cycle models. Net greenhouse gas emissions from the LULUCF sector, including only direct impacts caused by humans, related to logging, land-use changes or reforestation, for example. Does not include indirect sink effects.

Remaining carbon budget. The maximum cumulative amount of carbon dioxide emissions that is compatible with, for example, a 1.5 °C limit at either global or national level. Includes assumptions on future emissions of non-CO_2 greenhouse gases and particulate matter.

Carbon neutrality. This report uses an approach that is well-established in Finnish climate policy discourse to understand carbon neutrality as a balance of sinks and emissions of all greenhouse gases, using the greenhouse gas inventory accounting method. The IPCC defines carbon neutrality differently, i.e. as when directly anthropogenic CO_2 emissions and sinks are balanced according to the accounting method for global carbon cycle models.

Net CO_2 emissions of the LULUCF sector according to greenhouse gas inventories. The sum of emissions and removals in the LULUCF sector for managed land, including indirect sink effects, as specified in the greenhouse gas inventory instructions.

LULUCF. Land use, land use change and forestry.

Emission budget. The maximum allowable cumulative amount of greenhouse gases made commensurate with carbon dioxide, that is compatible with a limit such as 1.5 degrees at either global or national level. Includes assumptions on future global emissions of particulate matter.

Allowable warming contribution. The maximum allowable future warming contribution of greenhouse gas emissions that would raise the global average temperature by no more than 1.5 degrees Celsius from the 1850–1900 average. Can be defined either at global level or by calculating the national share.

WAM-CN scenario (With additional measures carbon neutrality). Scenario for Finland's greenhouse gas emissions and sinks based on both the carbon neutrality target under the Finnish Climate Act and the HIISI project. This report has used the non-CO_2 greenhouse gas emissions (CH4, N_2O, F gases) from all sectors from the scenario. See Annex 5.

1. INTRODUCTION

The Paris Agreement (UN 2015) was signed in 2015. The objective the parties to the agreement committed to is to limit the global average temperature increase to well below 2 °C above pre-industrial levels and to aim to limit it to 1.5 °C. The parties to the Paris Agreement subsequently agreed to focus on working towards remaining under the 1.5 °C limit (UNFCCC 2021, 2023). The agreement requires countries to offer time-bound emission reduction pledges to meet this objective. Whether emission reductions will be sufficient to meet the common objective is jointly assessed every five years, and the assessment is used as a basis for improving the effectiveness of climate action.[1] The Intergovernmental Panel on Climate Change's (IPCC) special report entitled Global Warming of 1.5 °C (2019) showed that if temperatures are allowed to rise by 2 °C, the damage caused by climate change will increase significantly compared to a 1.5 °C limit. Since the report was published, several countries and the European Union (EU) have updated their climate targets to better reflect the 1.5 °C limit objective.

However, setting national targets for individual countries to remain under the 1.5 °C limit is inherently challenging. The task is to decide what share a country can consider its fair share of the 1.5 °C remaining carbon budget if we are to meet the shared objective. The term remaining carbon budget refers to the maximum total amount of CO_2 emissions within a given timeframe that would keep global warming below a limit level, such as the 1.5 °C limit objective (Rogelj et al. 2016). Setting a national remaining carbon budget combines a scientifically defined remaining carbon budget calculation with each country's view on what is its fair share of the global climate effort.

The call for global fairness arises from both the 1992 United Nations Framework Convention on Climate Change (UN 1992) and the Paris Agreement. Article 2 of the Paris Agreement states that the Agreement shall be implemented in accordance with the principle of equity and, inter alia, the principle of common but differentiated responsibilities. Equity, or fairness, is also expected to guide the setting of national emission reduction targets (Art. 4.1). According to the principle of common but differentiated responsibilities, developed countries should take the lead in global climate action and emission reductions (Art. 4.1, 4.3, 4.4). The definition of an equitable national emission reduction target for the implementation of the common objectives of the Paris Agreement is left to national determination in the Paris Agreement. Global fairness or equity is therefore a normative concept, and there is no unequivocally correct criterion. Climate research has analysed and operationalised a number of criteria for determining fairness, such as the principles of equal and historical responsibility, as well as various definitions that emphasise the greater responsibility of developed countries (see, for example, Ollikainen et al. 2019).

When it comes to European countries, the UK was the first to unilaterally outline its emission reduction target well before the Paris Agreement, committing to an 80% reduction by 2050 (see e.g. Climate Change Committee 2020). Following the Paris Agreement, the UK, the Netherlands, Finland, Sweden and Denmark led efforts to outline long-term, national climate targets that would be in line with the Paris Agreement's aim of a 1.5 °C limit. At the request of Finland’s Minister of Climate and the Environment, the Finnish Climate Change Panel prepared a review and recommendation for a globally fair net emissions reduction pathway for Finland, consistent with the objective of a global warming limit of 1.5 °C (Ollikainen et al 2019, Finnish Climate Change Panel 2021). The national emissions reduction

[1] The first assessment of the state of mitigation work was carried out COP28 UAE – United Nations Climate Change Conference held in Dubai in 2023, which concluded that countries need to step up their climate actions significantly. For the first time, the COP agreement included a commitment to divest from fossil fuels.

objectives set out in the Finnish Climate Act overhauled in 2022 (423/2022) and the target of achieving carbon neutrality by 2035 are in line with the Panel's recommendation. Like the EU's climate neutrality objective, the emissions pathway and Finland's carbon neutrality target also include anthropogenic greenhouse gases other than CO_2 and emissions and sinks from the LULUCF sector in accordance with the greenhouse gas inventory.

The globally fair emissions pathway defined by Finland and the countries mentioned above is based on two key assumptions: The remaining carbon budget limits the total amount of greenhouse gas emissions, and a greenhouse gas inventory in line with IPCC guidelines (IPCC 2006) can be used to monitor emissions and compliance with the remaining carbon budget. Inventory accounting also serves, for example, as a basis for EU climate policy planning and as a guideline for the annual monitoring of the Paris Agreement. However, it should be noted that the remaining global carbon budgets calculated by the IPCC and the internationally agreed greenhouse gas inventories used to monitor climate policy differ methodologically in three respects.

First, EU and UN climate policy is based on a greenhouse gas inventory that includes CO_2, CH_4, N_2O and F gases. The remaining carbon budget calculated by the IPCC, on the other hand, is defined for carbon dioxide alone, but the size of the remaining carbon budget is affected by assumptions about future emissions of non-CO_2 greenhouse gases and aerosols (Lamboll et al. 2023, Rogeli et al. 2018). The warming contribution of non-CO_2 greenhouse gases is taken into account when considering the temperature limit, but no single limit value corresponding to the remaining carbon budget can be set for their emission levels.

The second difference relates to the commensuration of different greenhouse gas emissions. In climate policy, different emissions are commensurated into CO_2 equivalents using GWP100 factors (average global warming potential over 100 years) from the IPCC assessment reports (Pierrehumbert 2014). In this case, the warming contribution of a tonne of emissions of different greenhouse gases has been converted to the warming contribution of a tonne of CO_2 over 100 years. However, these multipliers are not used in the remaining carbon budget calculations of the IPCC assessment reports, instead, the warming contribution of CO_2 emissions, non-CO_2 greenhouse gases and aerosols is based on more precise physical simulations. The weakness of the GWP100 factors is that they do not accurately indicate the warming contribution of different gases on different time scales. From a climate policy perspective, it is important to note that they underestimate the warming contribution of methane on a short (decades) timescale and overestimate it on a timescale of more than 100 years.

The third difference between climate modelling and the application of inventory accounting concerns emission and sink accounting in the LULUCF sector. In the net emissions calculated using the greenhouse gas inventory accounting approach, which underpin climate policy for the LULUCF sector, all emissions and sinks from or on managed land are counted as anthropogenic. This accounting approach is based on IPCC guidance (IPCC 2006). In contrast, for example, the remaining carbon budgets in IPCC assessment reports use net CO_2 emissions of the LULUCF sector according to the accounting method for global carbon cycle models, where only changes in carbon storage or emissions caused directly by human activities, such as land use change or deforestation, are counted as anthropogenic (Friedlingstein et al. 2022). So-called indirect sink effects are not counted as anthropogenic in this accounting model (see Annex 3). Indirect sink effects include, for example, the change in forest growth due to global warming and increased CO_2 concentrations, or the effects of global warming on soil emissions compared to the pre-industrial climate (Grassi et al. 2021). In remaining carbon budget accounting, these impacts are classified as part of the underlying ‘natural sink’, including for managed areas. For example, halting the rise in the average global temperature requires net zero CO_2 emissions based on the accounting method for global carbon cycle models, where indirect sink effects are not included in net emissions. Due to differences in accounting for net emissions from the LULUCF sector, countries should collectively set more stringent emission objectives, in order to be in line with global temperature targets (Gidden et al. 2023).

The report and recommendation for the EU 2040 climate objectives, as set by the ESABCC (The European Scientific Advisory Board on Climate Change 2023) constitute the first report on EU climate policy that takes into account the indirect sink effects of climate change in accounting for net emissions from the LULUCF sector. The ESABCC's recommendations for the EU emission budget are based on feasible scenarios for both CO_2 and non-CO_2 greenhouse gas emissions, which at global level are almost compatible with the 1.5 °C limit. In assessing feasibility, the report rejected scenarios where, for example, an increase in carbon dioxide capture in the near future or a decrease in final energy demand were considered unrealistic. Taking feasibility as a starting point differs from, for example, the Finnish Climate Change Panel's analysis based on principles of fairness.

Emission budgets derived from principles of fairness (including, for example, taking into account population, ability to pay or historical responsibility) were also considered in the ESABCC report, but were significantly lower than emission budgets based on scenarios assessed as feasible. The approach of the ESABCC report and the first scientific estimates of indirect sink effects (Grassi et al. 2021 and 2023) provide a new knowledge base for assessing climate policy in the EU and its Member States. They also provide a good starting point for reconsidering how well the net emissions pathway based on inventory accounting and the resulting climate policy corresponds with the climate science approach, where, for example, the determination of emission reduction targets to remain under the 1.5 °C limit is based on carbon cycle models, indirect sink effects and assumptions on the development of non-CO_2 emissions.

In light of new information, this report assesses Finland's emissions pathway towards its carbon neutrality target by refining the inventory accounting approach to better reflect climate science modelling. The implementation of the assessment will require addressing how to account for the difference between inventory accounting and global carbon cycle models in the calculation of net anthropogenic emissions and how to model non-CO_2 emissions in policy planning based on inventory accounting. The report therefore seeks an approach that is methodologically compatible with the global remaining carbon budgets set out in the IPCC reports. This will be used to produce two alternative emission reduction pathways for Finland that would be compatible with the global 1.5 °C limit. The resulting pathways are compared to the inventory accounting pathway produced by the Panel (Finnish Climate Change Panel 2021).

2. METHODOLOGY FOR ACCOUNTING FOR INDIRECT SINK EFFECTS AND NON-CO_2 EMISSIONS IN DETERMINING A GLOBALLY FAIR EMISSION BUDGET AND NET EMISSIONS PATHWAY

Finland's fair share of global climate change mitigation efforts based on net emissions as detailed in the greenhouse gas inventory can be approached by looking at its fair share of global warming instead of its fair share of the remaining carbon budget. This approach also allows the climate impacts of non-CO_2 greenhouse gases, which vary over time, to be taken into account through modelling. In this context, the term ‘emission budget’ is used in this report to describe the maximum level of future emissions of all greenhouse gases allowed if we are to keep warming to no more than 1.5 °C higher than the pre-industrial climate. The remaining carbon budget covering only CO_2 is the proportion that results from subtracting future non-CO_2 greenhouse gas emissions from the emission budget. The emission budget is based on an estimate of the maximum allowed warming contribution of future greenhouse gas emissions if we are to avoid exceeding the 1.5 °C limit. It takes into account the diminishing warming contribution of greenhouse gases already emitted over time. The theory behind the allowable warming contribution and emission budget and the calculations in this report are presented in Annex 1.

The starting point for the analysis is the current climate policy approach of the EU and other parties to the Paris Agreement: a direct application of inventory accounting. It calculates the emission reduction pathway based on the remaining carbon budget, using net CO_2 emissions of the LULUCF sector according to the greenhouse gas inventory, while also reconciling non-CO_2 greenhouse gas emissions with the remaining carbon budget using GWP100 factors. This accounting approach does not, therefore, take into account the definitional difference in net CO_2 emissions from the LULUCF sector between the greenhouse gas inventory and global carbon cycle models approaches, or the problems associated with the use of GWP100. On the other hand, accounting for all greenhouse gases within the remaining carbon budget is a stricter interpretation of the original idea of the remaining carbon budget.

Changing the direct application of inventory accounting to correspond to a climate science approach requires indirect sink effects to be taken into account. This can be implemented at either global or national level. To estimate the remaining carbon budget, assumptions must also be made about the development of non-CO_2 emissions at global and national level, as non-CO_2 greenhouse gas emissions make up part of the emission budget and the assumed future aerosol emissions will affect the size of the emission budget. In order to develop alternative accounting methods, the role of non-CO_2 greenhouse gas emissions and indirect sink effects should be investigated.

2.1 NON-CO_2 EMISSIONS

Non-CO_2 emissions pose a major challenge in defining emission budgets and remaining carbon budgets. The total non-CO_2 emissions of scenarios with the same temperature effect depend on the mutual distribution of different greenhouse gases and aerosol types and their temporal distribution (including, in the case of aerosols, their geographical distribution). For example, methane emitted close to 2050 will have a much greater temperature impact in 2050 than methane emitted in 2020. Therefore, the national share of future non-CO_2 greenhouse gas emissions cannot be determined in an unequivocal and straightforward way, as in the case of the remaining carbon budget, because for non-CO_2 greenhouse gas emissions, the time of emission is relevant. In order to calculate the allowable warming contribution of future greenhouse gas emissions, a global estimate of the decrease in the warming contribution of past emissions and the change in the cooling contribution of aerosol emissions is needed. Unlike for CO_2, the warming contribution of non-CO_2 emissions emitted before 2020 will change over time, because methane and in particular aerosols are short-lived in the atmosphere.

In climate policy, emissions of non-CO_2 greenhouse gases are usually commensurated with CO_2 using GWP100 factors (Pierrehumbert 2014). A GWP100 factor shows how many times over, compared to one tonne of CO_2, one tonne of greenhouse gas emissions will warm the climate over 100 years. The GWP factor is defined separately for each greenhouse gas. The use of the GWP100 factors has many advantages. It allows all greenhouse gases to be considered simultaneously and promotes the cost-effective allocation of efforts to reduce emissions across these gases. The time horizon of 100 years is, however, unnecessarily long for climate policy purposes and will slow down the reduction of methane emissions in particular.

Furthermore, GWP100 does not represent the relationship between emissions and temperature impact in 100 years' time. Over this time, some of the additional global warming will have had time to be sequestered in the oceans, and the amount of heat bound will depend on the lifetime and warming contribution of the gases in different ways to the cumulative warming contribution measured by GWP. Therefore, a much more accurate estimate of the climate impact of different non-CO_2 emission scenarios can be obtained by modelling the climate impact of different greenhouse gases and aerosols by considering their lifetime and radiative properties explicitly instead of using GWP100.

In the future, the HIISI calculations' (Koljonen et al. 2022) policy, or WAM (with additional measures), scenario adaptation i.e. WAM-CN (with additional measures carbon neutrality) will be used for non-LULUCF sectors' (i.e. effort sharing and emissions trading sectors according to the EU's emission classification) non-CO_2 greenhouse gas emissions, and the WAM scenario for the non-CO_2 greenhouse gas emissions of the Finnish LULUCF sector (Annex 5). In this report, this combination of the WAM-CN and WAM scenarios will be referred to as WAM-CN for the sake of clarity. In the WAM-CN scenario, the non-CO_2 greenhouse gas emissions of all sectors are calculated for each year in the period 2020–2050. This total amount of non-CO_2 greenhouse gas emissions over time is used in this report's analysis. Figure 1 shows the combined non-CO_2 greenhouse gas emissions of all sectors used in the calculation as CO_2 equivalents, using GWP100 factors.

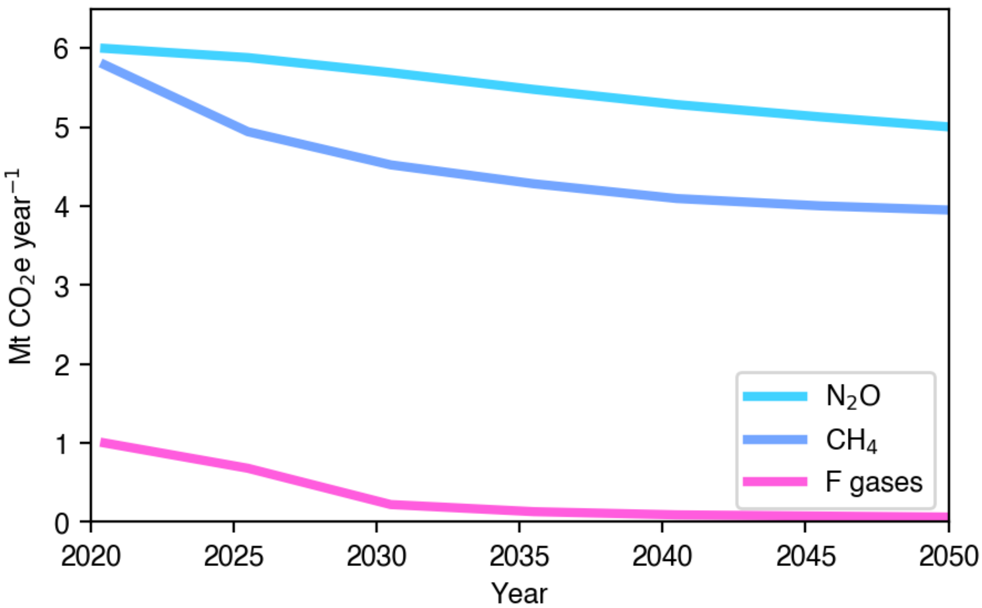

Figure 1: Finland's non-CO_2 greenhouse gas emissions converted to CO_2 equivalents (CO_2e) using GWP100 factors in the WAM-CN scenario.

Figure 2 illustrates how converting non-CO_2 greenhouse gases into CO_2 equivalents using GWP100 factors significantly underestimates their warming contribution compared to modelling each greenhouse gas separately in terms of radiative forcing and lifetime.

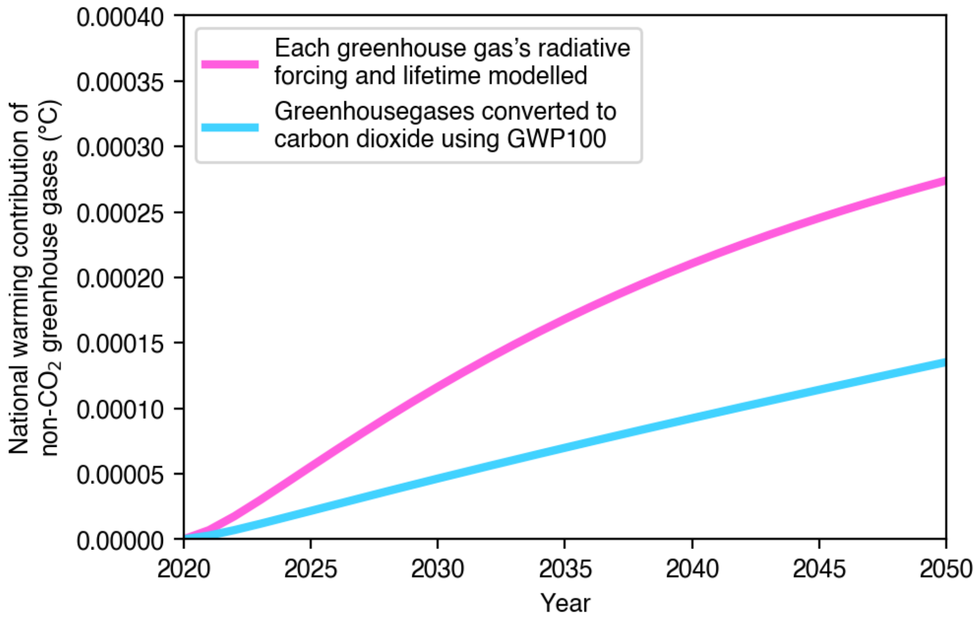

Figure 2: The warming contribution of non-CO_2 greenhouse gases (CH_4, N_2O, F gases) in the WAM-CN scenario, modelled with the FaIR 2.1 model (Leach et al, 2021), taking into account the radiative forcing and lifetime of each greenhouse gas, and 2) by first converting the gases to CO_2 equivalents using GWP100 factors. The coloured areas represent 95% error margins.

2.2 INDIRECT SINK EFFECTS

The remaining carbon budget sets a cap on future carbon dioxide emissions for a given global average temperature increase, such as 1.5 °C, compared to the pre-industrial temperature. Bio-based CO_2 emissions and sinks from the LULUCF sector consume or add to the remaining carbon budget in the same way as fossil-based CO_2 emissions or technical sinks, so the evolution of net emissions from the LULUCF sector is relevant for achieving the objectives of the Paris Agreement. However, a problem in monitoring the remaining carbon budget and climate objectives is that, at global level, the annual net carbon dioxide emissions from the LULUCF sector according to national greenhouse gas inventories are estimated to be about 7 Gt CO_2 y^{-1} lower than with the methodologies underlying the remaining carbon budget (Grassi et al. 2023)[2]. The difference is significant, as fossil-based CO_2 emissions, for example, were estimated to be 37 Gt CO_2 y^{-1} in 2022.

Possibly the main reason for this 7 Gt difference is the difference in the definitions of anthropogenic emissions and sinks in the different calculation methods. In the greenhouse gas inventory, all emissions and sinks from managed land are counted as anthropogenic. The accounting method for global carbon cycle models, on the other hand, only counts direct effects, such as land use change, deforestation and

[2] y^{-1} =1/year

regrowth, as anthropogenic, but not the indirect sink effects of increased CO_2 concentrations and climate change (Friedlingstein et al. 2022).

This difference is of great practical importance. If all countries were to pursue a 1.5 °C remaining carbon budget based on the greenhouse gas inventory methodology, their combined emissions would exceed the amount allowed by the global remaining carbon budget (Grassi et al. 2021). Therefore, differences in calculation methods should be reconciled so that the global remaining carbon budget can be used as a basis for inventory accounting-based climate policy. The calculation of the global emission budget for 2020–2050 is described in Annex 1.

Indirect sink effects, i.e. the impact of climate change and increased CO_2 concentrations on managed land, were estimated based on the results of two studies (Grassi et al. 2021, 2023). The methodology used in these studies modelled forest growth on managed forest land with climate change and with the pre-industrial climate. The difference between these simulations was used to calculate the indirect sink effects, assuming that the indirect sink effects are equal for natural and managed forests, and that the sum of the anthropogenic indirect sink effect and the direct effect equals the measurable net emissions. According to the analysis described above, indirect sink effects in Finland averaged -26 Mt CO_2 y^{-1} between 2000 and 2020 and -14 Mt CO_2 y^{-1} between 2020 and 2050 (see Annex 3 for details).

That said, the indirect sink effects and the warming contribution of non-CO_2 greenhouse gas emissions can be reconciled with emission budget accounting and remaining carbon budget accounting in several ways. The four boxes in Table 1 illustrate the options for the reconciliation methods.

Table 1: The options in the grid reconcile the conflicts between inventory accounting and the emission targets defined by climate science in terms of non-CO_2 greenhouse gas emissions and indirect sinks, at either national or global level.

Method 1) Global reconciliation of indirect sink effects and global reconciliation of non-CO_2 greenhouse gas emissions	Method 3) National reconciliation of indirect sink effects and global reconciliation of non-CO_2 greenhouse gas emissions.
Method 4) Global reconciliation of indirect sink effects and national reconciliation of non-CO_2 greenhouse gas emissions.	Method 2) National reconciliation of indirect sink effects and national reconciliation of non-CO_2 greenhouse gas emissions.

The top left box (Method 1) reconciles the global emission budget for both indirect sink effects and non-CO_2 greenhouse gases to make it compatible with greenhouse gas inventory accounting. The box in the bottom right (Method 2) reconciles the emission budget on a purely national basis. This report mainly deals with the methods in these two boxes. The bottom left box (Method 4) and the top right box (Method 3) represent combinations of global and national reconciliation. The main results of these methods are presented in Annex 2.

2.3 SELECTED METHODS FOR RECONCILING INVENTORY ACCOUNTING METHODOLOGY WITH A CLIMATE SCIENCE-BASED EMISSION BUDGET

The EU and other parties to the Paris Agreement have based their climate policies on inventory accounting. It provides a relatively straightforward way to determine each country's emission budget and pathway to net emission reductions.

> DIRECT APPLICATION OF INVENTORY ACCOUNTING
>
> The net emissions pathway is determined by apportioning a nationally fair share of the remaining global carbon budget, which is done by combining the net emissions of the national LULUCF sector with the national non-LULUCF CO_2 emissions and the non-CO_2 emissions of all sectors to determine the pathway.

In this report, the direct application of inventory accounting is reconciled with the definitions of global carbon cycle models and IPCC scientific reports using two different methods. The methodology involves subtracting an estimate of indirect sink effects, either at global or national level, from the emission budget based on global carbon cycle models and IPCC scientific reports. This would provide an emission budget estimate that would be compatible with the CO_2 emissions according to the greenhouse gas inventory. Similarly, in both methods, a correction term is added to either the global or the national emission budget to make the greenhouse gas inventory emission budget compatible with the explicitly modelled non-CO_2 greenhouse gas emissions' warming contribution in 2050[3] (see Annex 1).

> METHOD 1: RECONCILING THE EMISSION BUDGET AT GLOBAL LEVEL
>
> The different definitions of net CO_2 emissions from the LULUCF sector in global carbon cycle models and the greenhouse gas inventory approach are reconciled using indirect sink effects (Grassi et al. 2021). The reconciliation is done by adding the sum of global indirect sink effects for 2020–2050 to the global emission budget before calculating the national fair share. This reconciliation will reduce the global emission budget. A (negative) adjustment term based on the assumed global-level non-CO_2 greenhouse gas scenario and more accurate climate modelling is also added to the global emission budget, to allow for the direct use at national level of the CO_2 equivalent of non-CO_2 greenhouse gas emissions calculated with GWP100 factors.

[3] An interesting feature of modelling non-CO_2 emissions is that their estimated emission trends over the period under consideration actually depend on the climate policy pursued. Thus, policy is used in this respect to produce a remaining carbon budget for policy formulation. This introduces policy uncertainty, in addition to scientific uncertainty, into the calculation of emissions and remaining carbon budgets.

METHOD 2: RECONCILING THE EMISSION BUDGET AT NATIONAL LEVEL

With this accounting method, no reconciliation is done at global level, and instead the national emission budget allocated to Finland is reconciled with the net CO_2 emissions of the LULUCF sector at national level according to inventory accounting. The reconciliation is done by adding the sum of national indirect sink effects for 2020–2050 to the national emission budget. As at global level, this reconciliation reduces the emission budget. The adjustment term for non-CO_2 greenhouse gases is calculated similarly to Method 1, but using the assumed national non-CO_2 greenhouse gas scenario.

Methods 1 and 2 resolve the inconsistency caused by the difference in the way the greenhouse gas inventory and global carbon cycle models treat net CO_2 emissions from the LULUCF sector. Method 1 does this at global level and Method 2 at national level, as shown in Table 1. Taking into account indirect sink effects is a simplification and does not take into account, for example, the sink change resulting from the interaction between direct and indirect sink effects (Pongratz et al. 2014). There are also substantial scientific uncertainties about indirect sink effects. However, there is currently no better method for taking them into account.

Calculated with Method 1, indirect sink effects are included in Finland's carbon sink, while Method 2 only considers direct effects as Finland's part of carbon sink. Regarding the LULUCF sector and indirect sink effects, Method 2 is similar to the method used in the ESABCC report (2023), where the indirect sink effects' share was subtracted from the emission budget estimates to make them consistent with the greenhouse gas inventories. The ESABCC report did not limit non-CO_2 greenhouse gas emissions based on principles of fairness, as this report does.

2.3.1 Uncertainty related to calculation methods

There are significant uncertainties associated with the quantification of indirect sink effects and the projection of non-CO_2 emissions trends and climate modelling (see Annex 2 for a more detailed uncertainty analysis), which it is important to be aware of. Determining indirect sink effects is a challenging task, as it is difficult to distinguish, for example, the growth-enhancing effect of climate change on forest growth from the intensification of forest management and the growth-enhancing effect of processing and fertilisation. Furthermore, different models give very different results on indirect sink effects. The determination of indirect sink effects also has to take into account future developments in land use change, and in particular, deforestation. Presumably, however, the scenario uncertainty associated with deforestation is minor compared to the model uncertainty. At the same time, it should be remembered that inventory accounting of net LULUCF emissions itself is also subject to a high degree of uncertainty, as the numerous corrections made in recent years show. However, uncertainty does not undermine the usefulness of inventory accounting in monitoring climate actions.[4]

[4] The Finnish Climate Change Panel examined the uncertainty associated with inventory accounting by performing a sensitivity analysis on the remaining carbon budget and the size of the LULUCF sector's net sink. However, the remaining carbon budget calculation and the fixed time horizon mean that the uncertainty did not have a decisive impact on the results.

Forecasting the trends in non-CO_2 emissions and modelling their climate impact is another source of uncertainty. The trends in these emissions will depend on climate policy in the near future. For example, the EU has a strategy to reduce methane emissions (EU 2020) and in 2024 it adopted the Methane Regulation (EU 2024) in an effort to cut methane emissions from the energy sector. Additionally, the EU will include methane emissions from maritime transport in the Emissions Trading Scheme (ETS) in 2026, according to current plans (Traficom 2023). The European Commission has also explored the possibility of emissions trading for agricultural emissions, where methane and nitrous oxide play a major role.

The warming contribution of non-CO_2 greenhouse gas emissions is also subject to scientific uncertainty in addition to scenario uncertainty. This uncertainty can be modelled by using probability distributions of parameters related to non-CO_2 greenhouse gases and the climate in general. It should be noted that there is also uncertainty associated with the commonly used GWP100 factors (Derwent 2020), but this is not considered in this report as part of the uncertainty analysis of the direct application of inventory accounting. Because of the uncertainties, it is worth looking not only at the best predictions but also at the distribution of the results to understand the magnitude and direction of the uncertainties in Methods 1 and 2.

3. DEFINING FINLAND'S EMISSION BUDGET AND REMAINING CARBON BUDGET IN THE CONTEXT OF FINLAND'S FAIR SHARE OF THE 1.5 °C LIMIT

The period 2020–2050 has been chosen to align with the message of the IPCC assessment reports that the 1.5 °C limit requires net zero CO_2 emissions to be achieved by the early 2050s (Calvin et al. 2023). The remaining carbon budget and the emission reduction pathways derived from it are based on the WAM-CN scenario (with additional measures carbon neutrality, see Annex 5) of the HIISI project (Koljonen et al. 2022), which also includes the non-CO_2 greenhouse gas emissions for 2020–2050 as referred to above. LULUCF net emissions using the greenhouse gas inventory definition (including both direct and indirect anthropogenic sink effects) were assumed to be −21 Mt CO_2e y^{-1}, as in previous reports of the Finnish Climate Change Panel, of which an average of 2.7 Mt CO_2e y^{-1} was interpreted to be non-CO_2 greenhouse gas emissions under the WAM-CN scenario. The net CO_2 emissions from the LULUCF sector were calculated to be −23.7 Mt CO_2 y^{-1} (negative values represent sinks) and cumulatively for the period 2020–2050 −735 Mt CO_2.

In Table 2, the emission budget and the remaining carbon budget for all sectors and non-LULUCF sectors for 2020–2050, reconciled to be compatible with the Finnish greenhouse gas inventory, are determined for each intermediate step for each calculation method (direct application of inventory accounting, Method 1 and Method 2). For the direct application of inventory accounting, the remaining global carbon budget was updated to reflect the latest remaining carbon budget of 500 Gt CO_2 from 2020 as presented in the IPCC's Sixth Assessment Report (IPCC 2023), while the previous accounting by the Finnish Climate Change Panel was based on the remaining carbon budget presented in the IPCC's special report entitled Global Warming of 1.5 °C (Rogelj et al. 2018), of which 336 Gt CO_2 remained at the beginning of 2020. The direct application of inventory accounting is based on the solution of the Panel's previous reports to use the global remaining carbon budget for CO_2 to limit the total amount of greenhouse gas emissions, i.e. the emission budget. The global emission budget based on Methods 1 and 2 was calculated based on the IPCC's Sixth Assessment Report's estimate of remaining warming (0.43 °C), a reduction in the warming contribution of greenhouse gases emitted before 2020, and an assumed change in future aerosol emissions (see Annex 1 for details). This resulted in a global emission budget of 875 Gt CO_2e. The difference between this and the global emission budget with the direct application of inventory accounting roughly reflects the proportion non-CO_2 greenhouse gases account for of the global emission budget. Under Method 1, the global emission budget is reconciled with inventory accounting by adding adjustment terms for the LULUCF sector and non-CO_2 greenhouse gases. The adjustment term for the LULUCF sector is the sum of the global indirect sink effects for 2020–2050, i.e. −151 Gt CO_2 (calculation, see Annex 3). The adjustment term for non-CO_2 greenhouse gases is −362 Gt CO_2e. The adjustment term for non-CO_2 greenhouse gases reconciles the emission budget to be compatible with the GWP100 conversion factor used by greenhouse gas inventories, based on the difference in their warming contribution in 2050 between a simple climate model that takes into account the characteristics of each gas and the GWP100 conversion factor. In contrast, with Method 2, the emission budget for both the LULUCF sector and non-CO_2 greenhouse gases will be adjusted at a later stage at national level. With the direct application of inventory accounting, no reconciliation is done at all. As a result, in Table 2, all three global emission budgets used as a basis for the accounting differ: 500 Gt CO_2e, 363 Gt CO_2e and 875 Gt CO_2e.

Each remaining global carbon budget is allocated to Finland with the same ratio as in the Finnish Climate Change Panel's (2021) report (79 Mt CO_2 / 336,000 Mt CO_2 ≈ 0.235 ‰). The direct application of inventory accounting results in an emission budget for Finland before national adjustments of

118 Mt CO_2e, with Method 1: 85 Mt CO_2e, and with Method 2: 206 Mt CO_2e.[5] The adjustment term for non-CO_2 greenhouse gases with Method 2 at national level is −292 Mt CO_2e. The correction term is almost equal to the total of the non-CO_2 greenhouse gases (318 Mt CO_2e) Calculated using GWP100, so a more accurate approach based on climate modelling gives them almost twice the warming contribution as was calculated using GWP100. Furthermore, with Method 2, an adjustment term of −438 Mt CO_2e is added to account for the indirect sink effects at national level. This gives an adjusted emission budget for Finland of 118 Mt CO_2e using the direct application of inventory accounting, or 85 Mt CO_2e with Method 1 and −523 Mt CO_2e with Method 2. The negative value of the emission budget with Method 2 means that this amount of net greenhouse gas emissions, commensurated with GWP100 factors, should be removed from the atmosphere between 2020 and 2050.

The remaining carbon budgets are established by deducting from the emission budgets the total for the non-CO_2 greenhouse gases (318 Mt CO_2e).Since the emission budgets are reconciled in Methods 1 and 2 to be compatible with GWP100-based emissions, and no adjustment is made in the direct application of inventory accounting, the totals for non-CO_2 greenhouse gases are calculated using GWP100 in all methods. Thus, the reconciled remaining carbon budget for Finland (including only CO_2) is −200 Mt CO_2e with the direct application of inventory accounting, −233 Mt CO_2e with Method 1 and −841 Mt CO_2e with Method 2.

For non-LULUCF sectors, the remaining carbon budget can be calculated by subtracting the net CO_2 emissions of the LULUCF sector (−735 Mt CO_2e) from the remaining carbon budget in accordance with inventory accounting.

The direct application of inventory accounting gives Finland the largest remaining carbon budget for non-LULUCF sectors for 2020–2050 (535 Mt CO_2). This amount corresponds to just over 14 years of fossil-based CO_2 emissions at 2020 levels (37.6 Mt CO_2 y^{-1}) and would allow an average of 17.3 Mt CO_2 y^{-1} in emissions over the period under consideration. This is only slightly higher than the remaining carbon budget determined with Method 1 (503 Mt CO_2), which would allow for an average of 16.2 Mt CO_2 y^{-1} in emissions. It is noteworthy that Method 2 leads to a negative remaining carbon budget for non-LULUCF sectors (−106 Mt CO_2). In climate policy language, this means that over the period 2020–2050, fossil-based emissions would have to be cut very sharply to stay within the remaining carbon budget of Method 2. In addition to this, (technological and natural) sinks should be increased so that Finland is at a significantly negative emission level over the period under review, i.e. it should transition to solutions that make a major contribution to removing carbon dioxide from the atmosphere, with the net amount within the remaining carbon budgets for the non-LULUCF sectors. This would mean that Finland would have to produce net negative emissions averaging −3.4 Mt CO_2 y^{-1} outside the LULUCF sector. It is worth noting that the accounting is based on the assumption that at the same time the net CO_2 emissions from the LULUCF sector would be −23.7 Mt CO_2 v^{-1} using the greenhouse gas inventory accounting method, so overall Finland's net CO_2 emissions would average

[5] The emission budget of the inventory accounting approach is slightly higher than the 79 Mt remaining carbon budget of the Finnish Climate Change Panel report (2021) (which in the terminology of this report corresponds to the emission budget). There are two reasons for this. Firstly, the calculation in this report is based on IPCC AR6's remaining carbon budget, which is slightly higher than the estimate of the IPCC's special report Global Warming of 1.5 °C, on which the Panel's previous reports were based. Secondly, this report focuses primarily on budgets that limit warming to below 1.5 °C with a 50% probability, while the previous report's emission budget was based on a 66% probability.

–27.1 Mt CO_2 y^{-1}. Accounting Methods 3 and 4 as set out in Annex 2 produce remaining carbon budgets that fall between the two (Method 1 and Method 2).

Table 2: Intermediate steps in the calculation of Finland's emission budget and remaining carbon budget (Mt CO_2e) for 2020–2050, calculated in three different ways. The upper part of the table shows the global level calculation and the lower part shows the national level calculation. The figures are expressed in Mt CO_2e.

	Direct application of inventory accounting	**Method 1**	**Method 2**
Global emission budget	500,000	875,000	875,000
Reconciliation of LULUCF accounting at global level		−151,000	
Reconciliation of non-CO_2 greenhouse gases at global level		−362,000	
Reconciled global emission budget	**500,000**	**363,000**	**875,000**
Finland's share of the global emission budget (0.235‰)	118	85	206
Reconciliation of LULUCF accounting at national level			−438
Non-CO_2 greenhouse gas reconciliation at national level			−292
Finland's reconciled emission budget	**118**	**85**	**−523**
Finland's non-CO_2 greenhouse gas emissions (all sectors)	318	318	318
Finland's remaining carbon budget (all sectors)	**−200**	**−233**	**−841**
Finland's CO_2 emissions (LULUCF)	−735	−735	−735
Finland's remaining carbon budget (non-LULUCF)	**535**	**503**	**−106**

4. REVIEW OF FINLAND'S EMISSION REDUCTION PATHWAY FOR 2020–2050

After calculating cumulative emissions, the emission reduction pathways were outlined so that the cumulative CO_2 emissions of the non-LULUCF sectors did not exceed the remaining carbon budget calculated for them for 2020–2050. There is no limit to the number of different ways to allocate emissions to different years, but in line with the approach taken in the Panel's previous reports, a linear reduction in CO_2 emissions from non-LULUCF sectors from 2020 was chosen. As part of the solution, net emissions from the LULUCF sector were kept constant. The annual CO_2 emissions for both the LULUCF sector and the other sectors calculated using the methodology described above are shown in Figure 3.Figure 3 Net CO_2 emissions from the LULUCF sector (−23.7 Mt CO_2 y^{-1}) are reported according to the greenhouse gas inventory accounting method for all three methods.[6] The 2020 CO_2 emissions are 37.6 Mt CO_2 y^{-1} in accordance with the recorded emissions (Statistics Finland 2023b) , but the non-CO_2 greenhouse gas emissions are from the WAM-CN scenario (the scenario emissions for 2020 are very close to the recorded emissions). Calculated with the direct application of inventory accounting (left panel of Figure 3), the total annual CO_2 emission reduction need for non-LULUCF sectors is 1.4 Mt CO_2 y^{-1}. The annual emission reductions needed are 1.4 Mt CO_2 y^{-1} when calculated with Method 1 and 2.7 Mt CO_2 y^{-1} when calculated with Method 2, i.e. twice as much as with the direct application of inventory accounting.

Within the net CO_2 emissions of the non-LULUCF sectors, this report did not distinguish between fossil-based emissions and additional removals (technological sinks). The net CO_2 emissions from non-LULUCF sectors, calculated using the direct application of inventory accounting, are in 2050 –3.2 Mt CO_2 y^{-1}. So if gross CO_2 emissions from other sectors were zero, this is the amount of additional removals – in practice, technological sinks – that would be needed. For comparison, the additional removals under the 95% emission reduction pathway in the Panel's report (2021) were –2.6 Mt CO_2 y^{-1} in 2050. The 2050 net CO_2 emissions from other sectors for Methods 1 and 2 were –5.2 Mt CO_2 y^{-1} and –44.5 Mt CO_2 y^{-1}, i.e. additional removals would need to be at least as large or even larger if gross emissions from other sectors do not fall to zero. Achieving such high levels of additional removals would be very challenging economically. To stay within the emission budget, it would very likely be cheaper to reduce non-CO_2 greenhouse gas emissions by more than in the WAM-CN scenario and possibly increase the LULUCF sink even more than assumed.

In addition to annual emission reductions, the different accounting methods can be compared by looking at the years in which either net zero greenhouse gas emissions or net zero CO_2 emissions are achieved. In the 95% emission reduction pathway outlined in the Panel's report (2021) and in the Finnish Climate Act, carbon neutrality (i.e. net zero emissions of greenhouse gases) will be achieved by 2035. In this report, the corresponding year with the direct application of inventory accounting is 2038 (see the red line in the left panel of Figure 3). This is due to a larger emission budget (118 Mt CO_2 vs. 79 Mt CO_2) and relatively smaller reductions in non-CO_2 greenhouse gas emissions in the WAM-CN scenario compared to the reductions of all greenhouse gases in previous Panel reports (non-CO_2 greenhouse gases were not specified in previous reports). The years by which net zero greenhouse gas emissions will be achieved, when calculated using Methods 1 and 2, are 2037 and 2029 respectively. Net zero CO_2 emissions (dark blue lines in Figure 3) are achieved before net zero greenhouse gas emissions.

[6] Figure 8 in Annex 4 shows the corresponding figure for the accounting method for global carbon cycle models.

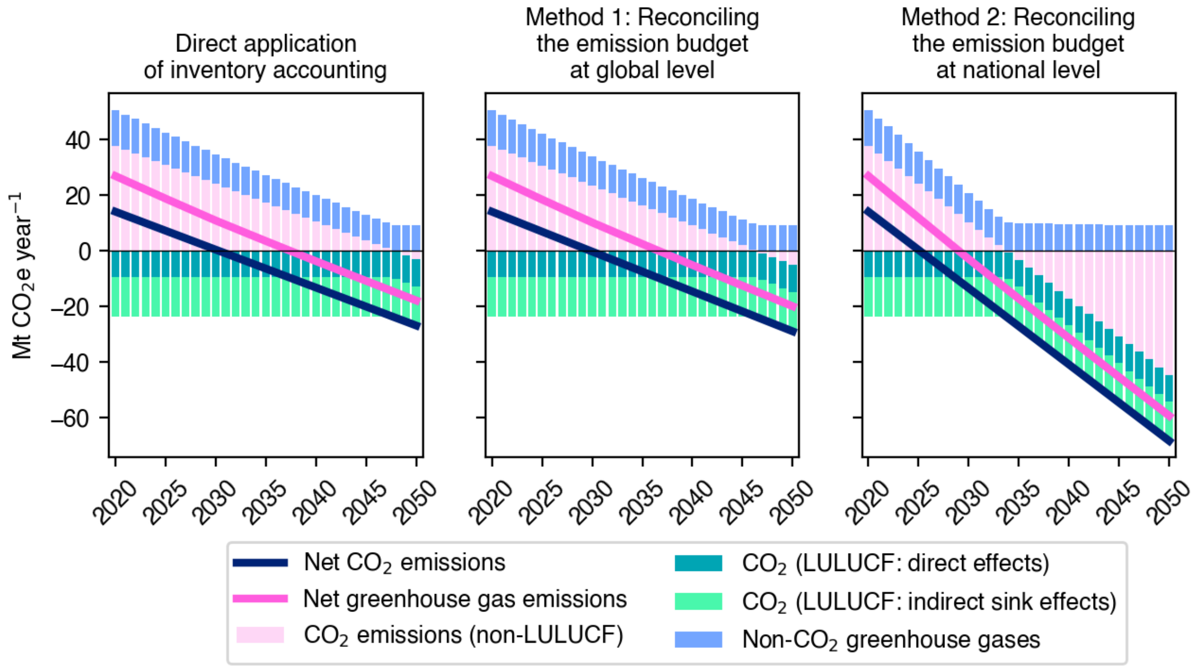

Figure 3: Linear emission reduction pathways calculated so that the cumulative emissions from non-LULUCF sectors correspond with the results presented in Chapter 3. LULUCF sector CO_2 remains at a constant average level of –23.7 Mt CO_2 y^{-1} for the period 2020–2050. Sinks and net emissions and non-CO_2 greenhouse gas emissions are presented according to the greenhouse gas inventory definition, with direct effects and indirect sink effects in the LULUCF sector included in net emissions.

The years stated above for when net zero will be achieved were based on net emissions from the LULUCF sector and total greenhouse gas emissions as accounted for using the greenhouse gas inventory. The IPCC assessment reports use net CO_2 emissions from the LULUCF sector according to the accounting method for global carbon cycle models, so the years calculated using this method are more comparable with the years given by the IPCC. For example, according to the IPCC's AR6 Synthesis Report (Calvin et al. 2023), emission reduction pathways that almost keep to the 1.5 °C limit at global level will achieve net zero greenhouse gas emissions[7] at the global average level after 2070 and net zero CO_2 emissions after 2050 (Calvin et al. 2023). Using net CO_2 emissions of the LULUCF sector according to the accounting method for global carbon cycle models, as reported by the IPCC, net zero greenhouse gas emissions will be reached later than stated by the inventory accounting method: in 2048 with direct application of inventory accounting, in 2047 with Method 1 and in 2034 with Method 2. Similarly, net zero CO_2 emissions would be achieved with these three methods in 2041, 2040 and 2031 (see the red and dark blue lines in Figure 8 in Annex 4).

Finally, it should be noted that the emission reduction pathways identified are based on best estimates for the emission budget and remaining carbon budget, calculated in each of the three ways. The uncertainties surrounding these have been discussed above. These uncertainties also introduce uncertainty in the pathways to emission reductions, in particular in their steepness and hence, for example, in when carbon neutrality will be achieved with each accounting method. In addition to this,

[7] This differs from the established concept of carbon neutrality in Finland in that the IPCC reports net CO_2 emissions from the LULUCF sector according to the accounting method for global carbon cycle models. In IPCC terminology, this is 'greenhouse gas neutrality', while 'carbon neutrality' in IPCC reports refers only to net zero CO_2 emissions.

the assumption of the HIISI project's WAM-CN scenario on the emission pathway of non-CO_2 greenhouse gases has a crucial impact on the results. It is possible to specify the magnitude or uncertainty of all variables, but the level of precision chosen here allows for a comparative discussion of emission reduction targets, as the uncertainty is generally the same for all accounting options.

4.1 THE CLIMATE IMPACT OF FINLAND'S GREENHOUSE GAS EMISSIONS

4.1.1 The warming contribution of non-CO_2 greenhouse gases

The WAM-CN scenario used in this report (see Annex 5) has relatively high emissions of non-CO_2 greenhouse gases compared to the 1.5° C limit level. The SSP1-RCP1.9 scenario with a near 1.5 °C limit objective, used as a baseline scenario, shows a 53% and 25% reduction in methane and nitrous oxide emissions respectively between 2020 and 2050. In the WAM-CN scenario used, the corresponding emission reduction percentages for Finland are only 32% and 17%. If Finland's share of methane and nitrous oxide emissions in the SSP1-RCP1.9 scenario is calculated to be the same as the fair share of the global emission budget (0.235 ‰), emissions in 2020 would be only 41% and 11% of the corresponding methane and nitrous oxide emissions in the WAM-CN scenario. In scenarios more generally consistent with the 1.5 °C limit, the median reduction between 2020 and 2050 is 50% for methane and 25% for nitrous oxide (Forster et al. 2023). In summary, the 2020 non-CO_2 greenhouse gas emissions in the WAM-CN scenario are higher and their relative emission reductions in 2020–2050 are lower than Finland's fair share of global non-CO_2 greenhouse gas emissions in the 1.5 °C scenarios.

The relatively high level of non-CO_2 greenhouse gas emissions in the WAM-CN scenario can also be illustrated by comparing their warming contribution to Finland's fair share of the warming contribution of non-CO_2 greenhouse gases in the SSP1-RCP1.9 scenario.

At global level, in the SSP1-RCP1.9 scenario, the warming contribution of non-CO_2 greenhouse gases emitted from 2020 onwards increases by about 0.3 °C by 2050 (Figure 4a). The grey dashed line represents the allowable warming contribution of all greenhouse gases to keep global warming below 1.5 °C, which is the basis for the global emission budget. Finland's fair share of this is indicated by the red line in Figure 4b. Finland's non-CO_2 greenhouse gas warming contribution (the light blue line in Figure 4bFigure 4), on the other hand, rises much faster and higher than Finland's fair share and also exceeds Finland's share of the limit for the warming contribution of all greenhouse gases (grey dashed line in Figure 4b). Because of this excess, Finland's remaining carbon budget is negative, i.e. the warming contribution of non-CO_2 greenhouse gases must be offset by negative CO_2 emissions (see Chapter 3).

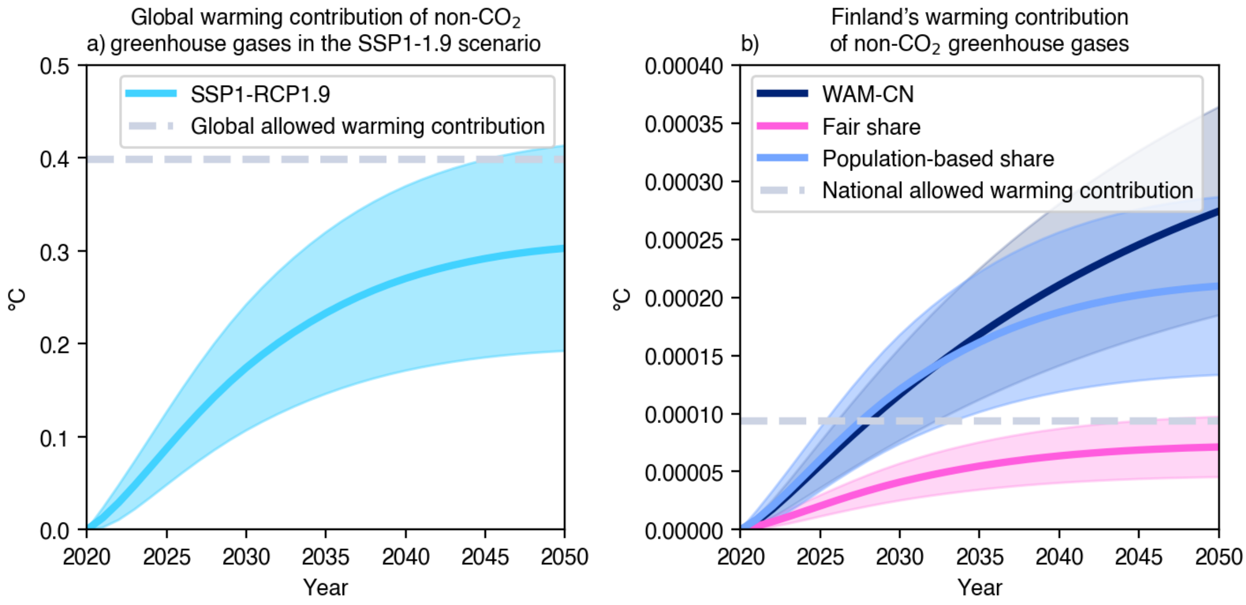

Figure 4: The warming contribution of non-CO_2 greenhouse gases at a) global and b) Finnish level. Coloured areas represent 95% confidence intervals based on the FaIR model simulation cluster. The grey dashed line shows the maximum allowable future greenhouse gas warming contribution in 2050 at Finnish level to still remain under the 1.5 °C limit. The fair and population-based shares refer to the share of the global warming contribution for non-CO_2 greenhouse gases.

Furthermore, the relatively large amounts of non-CO_2 greenhouse gases in the WAM-CN scenario illustrate the fact that their warming contribution is larger than the population share of global non-CO_2 emissions in the SSP1-RCP1.9 scenario (dark blue line in Figure 4b). That is, the per capita warming contribution of non-CO_2 greenhouse gases in the WAM-CN scenario would be larger than the per capita warming contribution at global level in the SSP1-RCP1.9 scenario (using current population figures). This shows that the WAM-CN scenario used as the basis for the calculation is potentially unrealistically high if the aim is emission reductions to remain under the 1.5 °C limit, and that non-CO_2 greenhouse gases reduce the remaining carbon budget unnecessarily in Methods 1 and 2. Although no cost-benefit analysis was carried out in this project, it would presumably be cheaper to reduce non-CO_2 greenhouse gases beyond the WAM-CN scenario than to achieve the CO_2 emission reductions and technological sinks required by the remaining carbon budgets of Methods 1 and 2.

4.1.2 Overall impact of emission reduction pathways on the average global temperature

The remaining carbon budgets and emission reduction pathways presented above are based on Finland's fair share of the warming contribution of greenhouse gas emissions. This chapter illustrates how the warming contribution evolves under different emission reduction pathways calculated in different ways.

For all three methods, Finland's net emissions were calculated based on the net CO_2 emissions of the LULUCF sector according to the accounting method for global carbon cycle models, as this accounting method best reflects the magnitude of their climate impact. Net CO_2 emissions of the LULUCF sector according to the greenhouse gas inventory do not have such a straightforward relationship with temperature change. The results are presented in Figure 5. The left-hand y-axis shows the impact of Finland's greenhouse gas emissions on the average global temperature. The right-hand y-axis shows the average global temperature relative to pre-industrial times, if each country's contribution were in proportion to their fair share of warming, as for Finland. In practice, this would mean global warming if all other countries were to meet their obligations as well as Finland does.

As Finland's remaining emission budget will be fully depleted in a few years at current emission levels, all three emission reduction pathways (direct application of inventory accounting, Method 1 and Method 2) will lead to it emissions exceeding the budget in the 2020s. The emission reduction objectives in this report are based on the global temperature target for 2050 and the derived maximum allowable warming contribution for Finland in 2050 (see Annex 1). Thus, exceeding the emission budget does not necessarily conflict with this global target, provided that the warming contribution is sufficiently reduced by 2050. Scaled up to global level, this overshoot would correspond in a best-case scenario (Method 2) to warming of about 2 °C by around 2040. The large overshoot of the allowed warming contribution and the subsequent cooling effect with all three methods is due to the significant role of sinks in emission reduction pathways. At global level, it would not be possible in practice to achieve such high sinks in relative terms before 2050.

Only Method 2 would reduce Finland's warming contribution sufficiently by 2050 to meet the 1.5 °C limit obligations, which in this report are determined by what is considered the normative fair share. The impact of the emissions reduction pathway with the direct application of inventory accounting on global warming in 2050 is 0.38 mK[8], while the maximum allowed warming compatible with the 1.5 °C limit is 0.09 mK. Finland's contribution to warming would therefore be four times this limit level. The best estimate of the allowed global greenhouse gas warming contribution in 2050 globally is 0.40 K. If all countries were to similarly exceed their allowed greenhouse gas warming contribution, this would lead to global warming of almost 3 °C compared to pre-industrial times. This illustrates how the required emission reductions are estimated if non-CO_2 greenhouse gases are converted into CO_2 equivalents using GWP100 factors and net CO_2 emissions of the LULUCF sector according to greenhouse gas inventories are used directly without considering the conflict with the accounting method for global carbon cycle models. For Finland, the role of indirect sink effects is particularly pronounced.

Interpreting the results of Method 1 is more complex and prone to misinterpretation than the other two methods. The results in Figure 5 show a national warming contribution of 0.37 mK in 2050 and global warming of 2.7 °C if other countries were to similarly exceed their own allowable warming contributions. However, Method 1 takes into account and adjusts for the problems of direct application of inventory accounting for non-CO_2 greenhouse gases and indirect sink effects, so if all countries were to follow its principle, global warming would be limited to 1.5 °C as in Method 2. In short, the reason for this apparent contradiction is that in Method 1, countries' inventory-based emissions in accordance with international climate policy practice do not directly reflect their warming contribution at national level. Although Finland's fair share of the allowed warming contribution and thus of the global emission budget is the starting point of Method 1, counting indirect sink effects as anthropogenic and converting non-CO_2 greenhouse gas emissions using GWP100 factors will increase Finland's warming contribution beyond the fair level. Accounting for the indirect sink effects and GWP100 conversion errors in Method 1 at global level by reducing the emission budget means that all countries must collectively compensate for the underestimation of Finland's warming contribution in Method 1 by reducing their emissions even more. In addition to this, if indirect sink effects were to reduce a country's sink, for example due to increased drought conditions or soil becoming an emission source, the principle of Method 1 would make it the responsibility of the country concerned to compensate with greater emission reductions or sink increases. Thus, if implemented consistently, Method 1 would also limit global warming to 1.5 °C,

[8] Millikelvin, or one thousandth of a degree Celsius.

but the uneven geographical distribution of proportions of indirect sink effects and shares of non-CO_2 greenhouse gas emissions would have an upward or downward effect on the target level for individual countries.

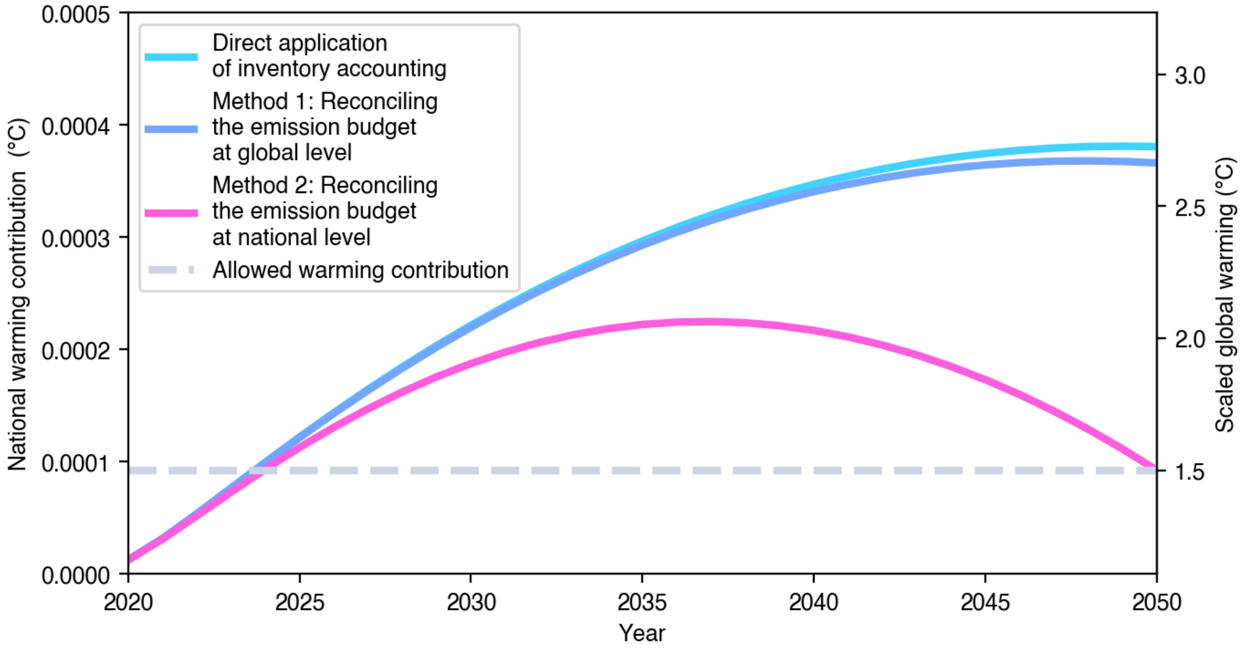

Figure 5: The warming contribution of three differently calculated emission reduction pathways. The horizontal dashed line shows the maximum allowable warming impact for Finland's greenhouse gases in 2050, which was the starting point for the emission budget calculations. The left-hand Y-axis shows the impact of Finland's warming contribution on global temperature and the right-hand side shows the global effect if all countries were to have the same effect in proportion to their fair share of warming.

5. SUMMARY AND CONCLUSIONS

This report outlined approaches to determining a national emission budget for Finland that is justified by climate science and consistent with the Paris Agreement's 1.5 °C warming limit, and compared the results with the Finnish Climate Change Panel's previous recommendations (Ollikainen et al. 2019, Finnish Climate Change Panel 2021). The analysis takes into account in detail the warming contribution of non-CO_2 greenhouse gas emissions and indirect sink effects.

The report analysed in more detail two different ways to reconcile the net CO_2 emissions of the LULUCF sector according to greenhouse gas inventories with the accounting method for global carbon cycle models. These two approaches were compared with the direct application of inventory accounting used in the Panel's previous assessments. For Methods 1 and 2, the warming contribution of non-CO_2 greenhouse gas emissions was estimated using a simple climate model and the indirect sink effects were estimated based on studies by Grassi et al. (2021, 2023). With Method 1, the reconciliation of the emission budget for indirect sink effects and non-CO_2 greenhouse gas emissions is done at global level. With Method 2, the same reconciliations are done at national level. The direct application of inventory accounting is based on the Panel's (Ollikainen et al. 2019, Finnish Climate Change Panel 2021) method, where Finland's share of the global remaining carbon budget is defined as including all greenhouse gas emissions by converting different greenhouse gases into carbon dioxide equivalents using GWP100 factors[9] and assuming that the LULUCF sink in its entirety according to the greenhouse gas inventory is anthropogenic.

The main finding from the report's analysis is that the more climate-science-compatible Methods 1 and 2 lead to a lower national emission budget for Finland than calculated by the Panel. In particular, the interpretations and results following Method 2 would require Finland to adopt a significantly more stringent climate policy in the period 2020–2050. Following Method 2, Finland would be carbon neutral by 2029 instead of 2035 and following Method 1, by 2037. The primary reason for Method 1 resulting in a date later than 2035 for achieving carbon neutrality is the updated IPCC remaining carbon budget estimate. The difference between the years when carbon neutrality will be achieved is not very large, and although the results are affected by various uncertainties, the main conclusion of the analysis is that Finland's carbon neutrality target of 2035, as recommended by the Panel (2021), and the emissions pathway in the Climate Act are not too ambitious for Finland to make a fair contribution to the 1.5 °C warming limit of the Paris Agreement, when the fairness criterion is national ability to pay.

The analysis in this project shows that emissions and remaining carbon budgets and the resulting emission reduction pathways differ depending on the method chosen to make the calculation compatible with climate science. The results derived are preliminary in nature and do not allow for a well-founded recommendation as to which calculation method would be most preferable. Each calculation method has its uncertainties (such as the non-CO_2 greenhouse gas emissions scenario chosen, the estimation of indirect sink effects, and uncertainties in climate modelling) and other accounting challenges. Thus, the second conclusion of the report is that the analysis has outlined consistent approaches and provided preliminary results for examining how to bring the inventory accounting approach, which is prevalent in climate policy, more in line with the climate science approach.

[9] The GWP100 factors have been used to convert the warming contribution of a tonne of emissions of each different greenhouse gas into the warming contribution of a tonne of CO_2 over 100 years. The weakness of the GWP100 factors is that they do not accurately capture the warming contribution of different gases on different time scales.

The report also shines a spotlight on perspectives for refining international climate policy. As the Paris Agreement is a so-called bottom-up agreement, it is up to its parties to determine their own national fair contribution to its implementation. It would be worthwhile analysing which of the calculation methods outlined would best reflect the spirit of the Paris Agreement, and in particular ensure that different countries' choices between different adaptation methods lead to an outcome that would limit global warming to 1.5 °C.

The discrepancy between the net CO_2 emissions of the LULUCF sector according to the accounting method for global carbon cycle models and greenhouse gas inventories poses challenges for science-based climate policy. Grassi et al (2021) have suggested that countries add an estimate of indirect sink effects to the greenhouse gas inventory. This would make it easier to use the greenhouse gas inventory to monitor the impact of climate policy at national and global level, for example in the context of the Paris Agreement, assuming that other countries improve their reporting. This would require separate additions, but not changes, to the current way of reporting emissions and sinks in the greenhouse gas inventory. Similarly, global carbon cycle models could be developed to calculate anthropogenic carbon sinks from land use according to the LULUCF sink of the greenhouse gas inventory.

Finally, it is worth stating that aggregating greenhouse gas emissions according to the GWP100 principle significantly underestimates the warming contribution of non-CO_2 greenhouse gas emissions over the next few decades, which are pivotal for remaining within the 1.5°C limit. It would be useful to see whether, over a 20–30 year time horizon, the assessment of the warming contribution would bring the direct application of inventory accounting closer to climate science modelling, and provide a straightforward way of looking at climate targets while also improving the effectiveness of current policies for reducing non-CO_2 greenhouse gas emissions.

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ANNEXES

ANNEX 1: SCIENTIFIC BACKGROUND AND METHODOLOGY FOR CALCULATING EMISSION BUDGETS AND REMAINING CARBON BUDGETS

The science behind the global remaining carbon budget

The almost linear dependence between the change in average global temperature and cumulative CO_2 emissions (Transient Climate Response to cumulative CO_2 Emissions, TCRE) makes it possible to determine the remaining carbon budget without taking into account the temporal distribution of emissions (Allen et al. 2009, Herrington & Zickfeld 2014, Matthews et al. 2009). The IPCC's methodology for calculating the 1.5 °C remaining carbon budget (RCB) in its most recent reports is based on the warming still remaining from the 1.5 °C global warming limit (T_l), the impact of non-CO_2 forcing $^{CO2}{}_{non\text{-}CO2}$ and the TCRE (Rogelj et al., 2018). The rationale behind the remaining carbon budget is that T_l can be expressed as the sum of CO_2 emissions and the impact of non-CO_2 forcing:

$$T_r = T_{CO_2} + T_{non-CO_2} \quad (1)$$

The warming caused by CO_2, T_{CO2}, can be expressed as the product of cumulative CO_2 emissions (i.e. the remaining carbon budget (RCB)) and the TCRE:

$$T_{CO_2} = TCRE \times HB \quad (2)$$

Combining the formulas gives

$$T_r = TCRE \times HB + T_{non-CO_2} \quad (3)$$

From this, a remaining carbon budget can be derived according to the methodology used by the IPCC:

$$HB = \frac{T_r - T_{non-CO_2}}{TCRE} \quad (4)$$

The assessment of the impact of non-CO_2 forcing is based on a pair of simulations using simple climate models, one considering only CO_2 and the other all forcing. From the temperature difference between these simulations, first we can calculate the effect of non-CO_2 forcing on temperature as a function of time (e.g. for the period 1850–2100). The term $T_{non\text{-}CO2}$ can be calculated as the change in the difference between the previous two simulations from the present to the time when CO_2 emissions reach net zero. The term $T_{non\text{-}CO2}$ is therefore not the direct effect of non-CO_2 forcing on temperature in a net zero year, but rather how much the effect has changed from the present situation, i.e. how much of the remaining warming to 1.5 °C is due to non-CO_2 forcing. The IPCC's calculations are based on the average temperature impact of non-CO_2 forcing – $T_{non\text{-}CO2}$ – in scenarios consistent with the 1.5 °C limit.

Challenges in accounting for national non-CO_2 emissions in the remaining carbon budget framework

Splitting the global remaining carbon budget into national remaining carbon budgets, so that non-CO_2 emissions are also allocated on a country-by-country basis, is a challenge. Non-CO_2 emissions pose a bigger problem from a scientific perspective, because the remaining carbon budget is defined only for CO_2 emissions and no simple emission budget can be defined for other emissions. The term non-CO_2

in the remaining carbon budget formula is the temperature change caused by non-CO_2 greenhouse gases and aerosols and does not include direct information on emissions. The total non-CO_2 emissions of scenarios leading to the same temperature impact depend on the distribution of different greenhouse gases and aerosol types and their temporal (and, in the case of aerosols, geographic) distribution. For example, methane emitted close to 2050 will have a much larger temperature impact in 2050 than methane emitted in 2020.

The warming contribution of CO_2 emissions at a selected time point can be estimated well as the product of cumulative CO_2 emissions and the TCRE from the pre-industrial period to the time point in question (Allen et al. 2009, Matthews et al. 2009). Thus, the warming contribution of CO_2 emissions that have occurred (in this case before 2020) remains roughly unchanged over the century-long timescale (MacDougall et al. 2020, Palazzo Corner et al. 2023). The warming contribution of non-CO_2 emissions emitted before 2020 will change over time because methane and aerosols are short-lived in the atmosphere. The term $T_{non\text{-}CO2}$ includes both the negative change in the warming contribution of past emissions and the warming contribution of future emissions. Therefore, the national share of future non-CO_2 emissions cannot be determined in a straightforward way as in the case of the remaining carbon budget.

In climate policy, emissions of non-CO_2 greenhouse gases are usually commensurated with CO_2 using the GWP100 factors (Pierrehumbert 2014). A GWP100 factor shows how many times over, compared to one tonne of CO_2, one tonne of greenhouse gas emissions will warm the climate over 100 years. The GWP factor is defined separately for each greenhouse gas. However, GWP100 does not reflect the relationship between emissions and the temperature effect 100 years from now, as over this time, some of the additional global warming will have had time to be sequestered in the oceans, and the amount of heat bound depends on the lifetime and warming contribution of the gases differently to the cumulative warming contribution measured by GWP. Therefore, a much more accurate estimate of the climate impact of different non-CO_2 emission scenarios can be obtained by modelling the climate impact of different greenhouse gases and aerosols by considering their lifetime and radiative properties explicitly instead of using GWP100.

National emission and remaining carbon budgets based on maximum allowable warming

The challenges listed above can be tackled in more than one way. This project has developed a framework for calculating a national remaining carbon budget based on a national non-CO_2 greenhouse gas emissions scenario. These non-CO_2 greenhouse gas emissions comply with the WAM-CN scenario, which is compatible with the carbon neutrality pathway set out by the Finnish Climate Change Panel (see Annex 5).

The methodology presented is based on an extension of the IPCC's remaining carbon budget method. The first challenge is to calculate how much net warming future greenhouse gas and aerosol emissions are likely to cause. Put simply, greenhouse gases warm the climate and aerosol particles, on average, cool it. Due to the high uncertainty in modelling the climate impacts of national aerosol emissions and the significant negative health impacts of aerosol particles, this project limits the discussion of aerosols to global level before considering them at the national level, and national emission budgets are therefore limited to greenhouse gases. If aerosols were to be considered at national level, increasing cooling aerosol emissions and thus their negative health impacts could offset greenhouse gas emission reductions in order to stay within the emission budget.

After these choices, formula (1), which describes the remaining warming, can be expressed as:

$$T_r = T_{CO_2} + (T_{non-CO_2-ghg,t\geq 2020} + T_{non-CO_2-ghg,t<2020} + T_{aero}) \quad (5)$$

The above warming caused by the change in non-CO_2 forcing is first split into the effect of non-CO_2 greenhouse gases emitted before and after 2020 and the effect of the change in the aerosol forcing.

Reordering gives the maximum possible *future* greenhouse gas warming T_{ghg} that will not exceed the 1.5 °C limit:

$$T_{ghg} = T_{CO_2} + T_{non-CO_2-ghg,t\geq 2020} = T_r - T_{non-CO_2-ghg,t<2020} - T_{aero} \quad (6)$$

Finland's remaining carbon budget can be calculated using essentially the same principle as in the global remaining carbon budget formula (4) by multiplying T_{ghg} by Finland's share F_{Fi} in the allocation of the remaining carbon budget, as per the Panel's (2019) report:

$$HB_{Fi} = \frac{F_{Fi}(T_r - T_{non-CO_2-ghg,t<2020} - T_{aero}) - T_{non-CO_2-ghg,t\geq 2020,Fi}}{TCRE} \quad (7)$$

Of the terms in the formula, $T_{non-CO_2-ghg,t<2020}$ is negative (the warming contribution of past emissions is reduced), T_{aero} is positive (the future cooling effect of aerosols is reduced in 1.5 °C scenarios) and the term indicating the warming contribution of Finland's future non-CO_2 greenhouse gas emissions, $T_{non-CO_2-ghg,t\geq 2020,Fi}$, is positive. The differences in this formula compared to the original remaining carbon budget formula are that the warming contribution of aerosol emissions, future non-CO_2 greenhouse gas emissions, and the removal of the warming contribution of past greenhouse gas emissions are specified. Since the reference years in this report, as in the IPCC's Sixth Assessment Report, are 2010–2019, the warming terms are calculated relative to the average of these years. Furthermore, Finland's fair share for 2015–2019 of CO_2 emissions $E_{2015–2019}$ (210 Gt CO_2) must be deducted from the remaining carbon budget (not actual Finnish emissions, as the fair share is only calculated from 2020 onwards):

$$HB_{Fi} = \frac{F_{Fi}(T_r - T_{non-CO_2-ghg,t<2020} - T_{aero}) - T_{non-CO_2-ghg,t\geq 2020,Fi}}{TCRE} - F_{Fi}E_{2015-2019} \quad (8)$$

If the remaining carbon budget is adjusted in accordance with Method 1 with the global addition of global indirect sink effects $E_{is,ga}$ and the correction term for the global non-CO_2 greenhouse gases' warming contribution is $E_{non\text{-}CO2\text{-}ghg,ga}$, the remaining carbon budget formula is:

$$HB_{Fi} = \frac{F_{Fi}(T_r - T_{non-CO_2-ghg,t<2020} - T_{aero}) - T_{non-CO_2-ghg,t\geq 2020,Fi}}{TCRE} - F_{Fi}(E_{2015-2019} - E_{is,ga} - E_{non-CO_2-ghg,ga}) \quad (9)$$

The correction term for the warming contribution of non-CO_2greenhouse gases, $E_{non\text{-}CO2\text{-}ghg,ga}$, is calculated as the difference between the modelled global 2050 warming contribution and the TCRE, divided by the CO_2 equivalent calculated using GWP100 E_{non-CO_2-ghg}:

$$E_{non-CO_2-ghg} = E_{GWP100} - \frac{T_{non-CO_2-ghg,t\geq 2020,ga}}{TCRE} \quad (9)$$

If the term $T_{non-CO_2-ghg,t\geq 2020,Fi}$ is set to zero, formula 8 gives Finland's emission budget as per Method 1:

$$PB_{Fi} = \frac{F_{Fi}(T_r - T_{non-CO_2-ghg,t<2020} - T_{aero})}{TCRE} - F_{Fi}(E_{2015-2019} - E_{is,ga} - E_{non-CO_2-ghg,ga}) \quad (10)$$

Under Method 2, the adjustments are made at national level, resulting in an emission budget as follows:

$$PB_{Fi} = \frac{F_{Fi}(T_r - T_{non-CO_2-ghg,t<2020} - T_{aero})}{TCRE} - F_{Fi}E_{2015-2019} + E_{is,fi} + E_{non-CO_2-ghg,fi} \quad (11)$$

Calculation of emission budget terms and remaining carbon budget terms

The terms for non-CO_2 greenhouse gases and aerosols as described above were calculated using the FaIR 2.1 model (Leach et al. 2021, Smith 2022) using the Finnish non-CO_2 greenhouse gas scenario (Annex 5) and the SSP1-RCP1.9 scenario at global level. The TCRE describing the global average temperature increase and the cumulative emissions were assumed to follow the normal distribution of the IPCC's Sixth Assessment Report (μ=1.65 °C / 1000 Gt CO_2, σ=0.68 °C / 1000 Gt CO_2). The figures presented in Chapters 2 and 3 of the report are based on the best estimate for each term. The TCRE followed the IPCC's best estimate and the average of the simulation pair was used for the values of the terms calculated with the FaIR model. Table 3 summarises the best estimates of the variables needed to calculate emission budgets and remaining carbon budgets.

Table 3: Best estimates for the variables needed for remaining carbon budget and emission budget estimates.

Variable	Description	Best estimate	Source
F_{Fi}	Finland's fair share of the global allowable warming contribution	0.235‰	(Finnish Climate Change Panel 2021)
T_r	Remaining warming of 1.5 °C, compared to the 1850–1900 average	0.43 °C	(Calvin et al. 2023)
$T_{non-CO_2-ghg,t<2020}$	Change in the warming contribution of non-CO_2 greenhouse gases emitted before 2020 from 2010–2019 to 2050.	–0.319 °C	FaIR 2.1 simulations
T_{aero}	Change in the temperature impact of aerosol emissions from 2010–2019 to 2050.	0.262 °C	FaIR 2.1 simulations
$T_{non-CO_2-ghg,t\geq2020,Fi}$	Warming contribution of non-CO_2 greenhouse gases emitted in Finland in 2020–2050 in 2050.	0.000274 °C	FaIR 2.1 simulations
$T_{non-CO_2-ghg,t\geq2020,ga}$	Warming contribution of non-CO_2 greenhouse gases emitted globally in 2020–2050 in 2050.	0.30 °C	FaIR 2.1 simulations
$TCRE$	Average global temperature rise in relation to cumulative CO_2 emissions (Transient Climate Response to cumulative CO_2 emissions)	0.450 °C / 1000 Gt CO_2	(Calvin et al. 2023)
$E_{2015-2019}$	Realised global CO_2 emissions in 2015–2019	210 Gt CO_2	(Calvin et al. 2023)
$E_{is,ga}$	Global indirect sink effects on net CO_2 emissions from the LULUCF sector 2020–2050	–151 Gt CO_2	(Grassi et al. 2021, 2023) (see Annex 3)
$E_{is,fi}$	National indirect sink effects on net CO_2 emissions from the LULUCF sector 2020–2050	–438 Mt CO_2	(Grassi et al. 2021, 2023) (see Annex 3)

ANNEX 2: UNCERTAINTY ESTIMATES FOR EMISSION BUDGET AND REMAINING CARBON BUDGET CALCULATIONS

In addition to the best estimate, an uncertainty estimate was calculated by combining the multivariate distribution calculated from the FaIR results with the probability distribution of the TCRE. By randomly selecting values from each distribution to form 10 million combinations, 10 million different realisations of Finland's emission budget and remaining carbon budget (Figure 6) were calculated accordingly. A random sample of indirect sink effects at national and global level was also taken to calculate emission reduction pathways. A similar methodology was used to estimate the size and uncertainty of the remaining global carbon budget (Lamboll et al. 2023, Matthews et al. 2021). Table 3 shows the medians and 95% confidence intervals for the emission budgets and remaining carbon budgets and the impact of non-CO_2 greenhouse gases. The uncertainty analysis of the direct application of inventory accounting was based only on the uncertainty of the TCRE and the global non-$CO2_2$ term ($T_{non\text{-}CO2}$). The distribution of the latter was obtained by scaling the distribution calculated from the FaIR results so that the expected value of the global remaining carbon budget calculated using the TCRE median corresponded with the IPCC estimate of 500 Gt CO_2. A more detailed analysis would have been possible if the background calculations and simulations of the IPCC report had been available.

Table 4: Intermediate steps in the calculation of Finland's emission budgets and remaining carbon budgets (Mt CO_2e) for 2020–2050 calculated in five different ways. The upper part of the table shows the global level calculation and the lower part shows the national level calculation. The figures are expressed in Mt CO_2e. The first figure in each section gives the best estimate and the figures in brackets give the 95% confidence interval based on combining 10,000,000 realisations and probability distributions of the different factors.

	Direct application of inventory accounting	**Method 1 Global reconciliation of indirect sink effects and global reconciliation of non-CO_2 greenhouse gas emissions.**	**Method 2 National reconciliation of indirect sink effects and national reconciliation of non-CO_2 greenhouse gas emissions.**	**Method 3 National reconciliation of indirect sink effects and global reconciliation of non-CO_2 greenhouse gas emissions.**	**Method 4 Global reconciliation of indirect sink effects and national reconciliation of non-CO_2 greenhouse gas emissions.**
Global emission budget	**500,000 (56,000, 2,830,000)**	**875,000 (182,000, 4,450,000)**	**875,000 (182,000, 4,450,000)**	**875,000 (182,000, 4,450,000)**	**875,000 (182,000, 4,450,000)**
Reconciliation of LULUCF accounting at global level		−151,000 (−259,000, −43,000)			−151,000 (−259,000, −43,000)
Reconciliation of non-CO_2 greenhouse gases at global level		−362,000 (−2,550,000, 6,000)		−362,000 (−2,550,000.6 000)	
Reconciled global	**500,000 (56,000,**	**363,000 (−521,000,**	**875,000 (182,000,**	**514,000 (−364,000,**	**724,000 (18,500,**

emission budget	**2,830,000)**	**2,150,000)**	**4,450,000)**	**2,300,000)**	**4,300,000)**
Finland's share of the global emission budget (0.235‰)	118 (13, 666)	85 (−123, 507)	206 (43, 1,050)	121 (−86, 541)	170 (4, 1,010)
Reconciliation of LULUCF accounting at national level			−438 (−1,480, 604)	−438 (−1,480, 604)	
Non-CO_2 greenhouse gas reconciliation at national level			−292 (−2,270, 31)		−292 (−2,270, 31)
Finland's reconciled emission budget	**118 (13, 666)**	**85 (−123, 507)**	**−523 (−2,110, 621)**	**−317 (−1,400, 846)**	**−121 (−1,370, 160)**
Finland's non-CO_2 greenhouse gas emissions (all sectors)	318	318	318	318	318
Finland's remaining carbon budget (all sectors)	**−200 (−305, 348)**	**−233 (−440, 189)**	**−841 (–2,430, 303)**	**−635 (−1,720, 528)**	**−439 (−1,690, −157)**
Finland's CO_2 emissions (LULUCF)	−735	−735	−735	−735	−735
Finland's remaining carbon budget (non-LULUCF)	**535 (430, 1,080)**	**503 (295, 924)**	**−106 (−690, 1,040)**	**100 (−987, 1,260)**	**296 (−952, 578)**

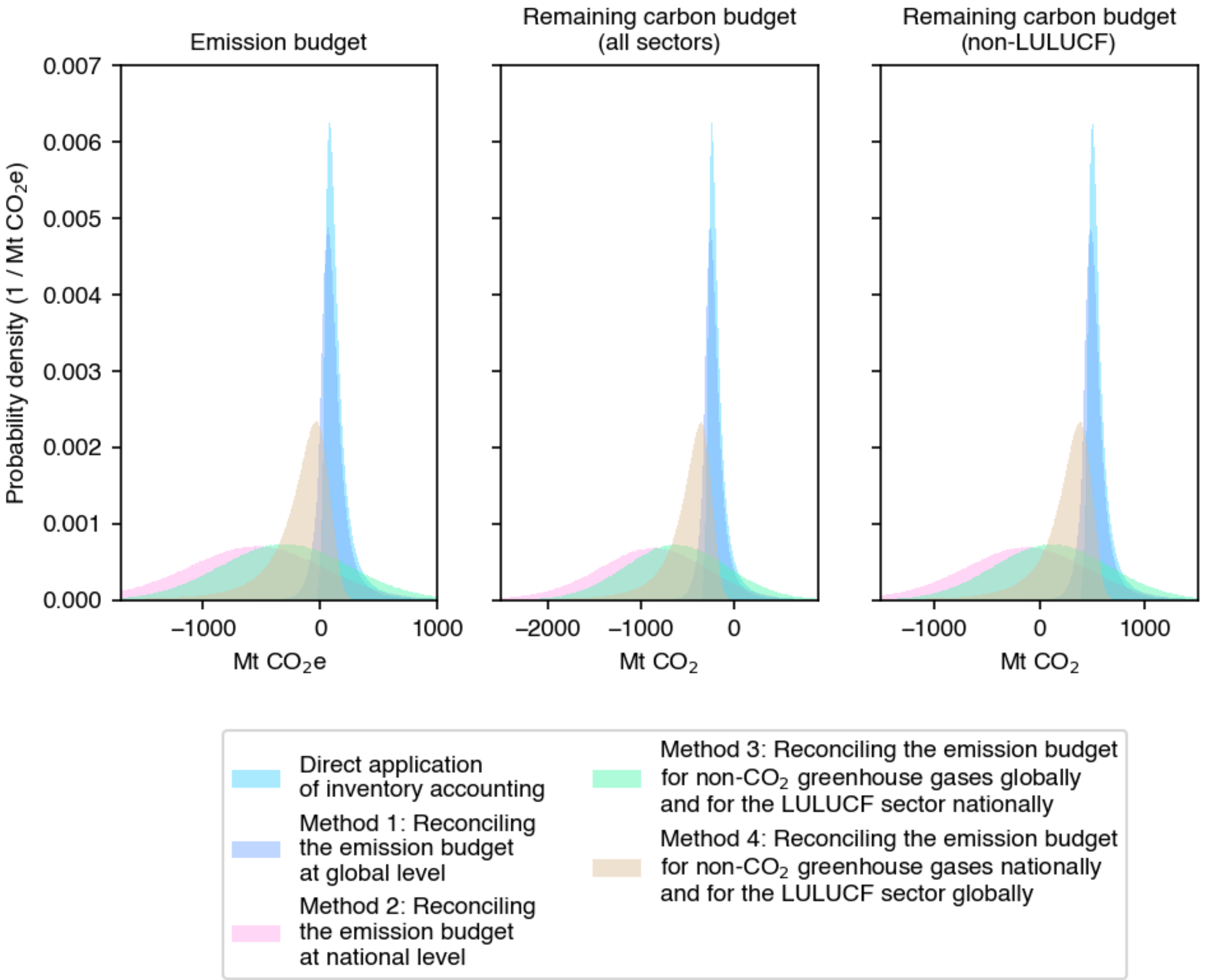

Figure 6: Probability distributions for Finland's a) emission budgets and b) remaining carbon budgets for all sectors and c) remaining carbon budgets for non-LULUCF sectors based on 10,000,000 realisations.

ANNEX 3: INDIRECT SINK EFFECTS

The remaining carbon budget sets a cap on future carbon dioxide emissions for a given global average temperature increase, such as 1.5 °C, compared to the pre-industrial climate. Emissions and sinks from the LULUCF sector consume or add notionally to the remaining carbon budget in the same way as fossil-based CO_2 emissions or technological sinks, so the evolution of net emissions from the LULUCF sector is key for achieving the objectives of the Paris Agreement. However, a problem for monitoring the remaining carbon budget and climate targets is that at the global level, the annual net carbon emissions from the LULUCF sector according to national greenhouse gas inventories are estimated to be about 7 Gt CO_2 y^{-1} lower than according to the methodology underlying the remaining carbon budget (Grassi et al. 2023). The difference is significant, as fossil-based CO_2 emissions, for example, were estimated at 37 Gt CO_2 y^{-1} in 2022. The main reason for this difference may be the difference in the definitions of anthropogenic emissions and sinks with the following accounting methods. In the greenhouse gas inventories, all emissions and sinks from managed land are counted as anthropogenic. The global carbon cycle models' definition, on the other hand, only counts direct effects, such as deforestation and regrowth, as anthropogenic, but not the indirect sink effects of increased CO_2 and climate change (Friedlingstein et al. 2022).

One difference of practical significance is the following: if all countries were to pursue a 1.5 °C remaining carbon budget based on the greenhouse gas inventory methodology developed by the Finnish Climate Change Panel, their combined emissions would exceed the amount allowed by the global remaining carbon budget (Grassi et al. 2021). Therefore, differences in calculation methods should be reconciled so that the global remaining carbon budget can be used as a basis for inventory accounting-based climate policy. This report uses a simple methodology of subtracting the estimate of indirect sink effects from the net emissions in the greenhouse gas inventory to produce a net emissions estimate that is consistent with the net anthropogenic emissions from global carbon cycle models. The method is a simplification and does not take into account factors such as the sink change resulting from the interaction between direct and indirect sink effects (Pongratz et al. 2014). However, there is currently no better method available.

Anthropogenic climate change and increased atmospheric carbon dioxide concentrations are affecting carbon balances in northern regions. The net effect depends on the responses of vegetation carbon fixation and organic matter decomposition to rising temperatures and longer growing seasons (Heikkinen et al. 2022, Ise et al. 2008), rising CO_2 concentrations (Tagesson et al. 2020), and the increase in extreme weather events (Schlesinger et al. 2016). In this report, indirect sink effects, i.e. the impacts of climate change and increased CO_2 concentrations on managed land, were estimated based on the results of two studies (Grassi et al. 2021, 2023). In the methodology used by these studies, forest growth in managed forests was modelled with climate change and with the pre-industrial climate, and the difference between these simulations was used to calculate the indirect sink effects, assuming that the indirect sink effects are equal for natural and managed forests, and that the sum of the indirect sink effect and the direct effects equals the measurable sink.

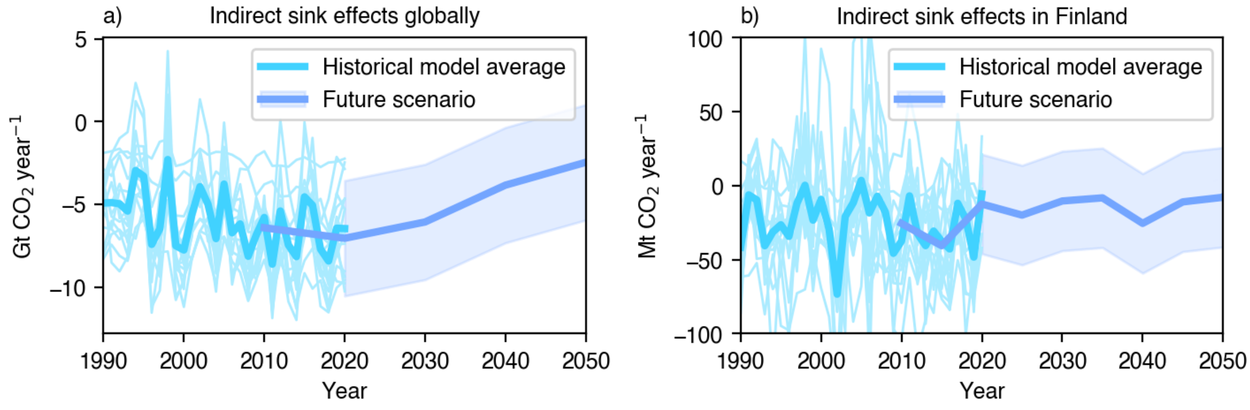

Figure 7: Indirect sink effects (impact of climate change and increased CO_2 concentration on the carbon sink of managed land) in the historical period 1990–2020 and in the future scenario (SSP2-1.9) a) at global level and b) in Finland. The thin blue lines show the results of the individual models and the light blue area shows the 95% confidence interval for the future scenario calculated from the historical dispersion of the models.

In this report, we first calculated the indirect sink effects for both Finland and globally for the period 1990–2020 (Grassi et al. 2023) based on the results of 16 global ecosystem models (Figure 7). The future scenario was based on the indirect sink effects modelled by (Grassi et al. 2021) in the SSP2-RCP1.9 scenario for the period 2010–2100. Since the latter study was based on only one model and the average result of several models was considered more reliable, its result was adjusted both globally and for Finland uniformly for each year so that the average for 2010–2020 was equal to the average of the 16 models (Grassi et al. 2023) (Figure 7). The uncertainty of the future scenario was modelled using a normal distribution with a single year standard deviation based on the standard deviation of the average of the 16 ecosystem models for the years 1990–2020 between the models (green shaded area in Figure 7). The SSP2-RCP1.9 scenario was chosen because in terms of its climate impacts, it is consistent with the SSP1-RCP1.9 scenario selected as the global background scenario in this report due to its underlying RCP scenario.

According to the analysis described above, indirect sink effects averaged –26 Mt CO_2 y^{-1} between 2000 and 2020 and –14 Mt CO_2 y^{-1} between 2020 and 2050. For comparison, the net carbon dioxide emissions from the LULUCF sector according to the Finnish greenhouse gas inventory averaged –25 Mt CO_2 y^{-1} between 2010 and 2020 (Statistics Finland, 2023a), so according to this analysis the indirect sink effects were in practice equal to the net sink of the LULUCF sector between 2000 and 2020. Thus, with the reconciliation method used in this report, which subtracts indirect sink effects from net emissions as defined in the greenhouse gas inventory, the net anthropogenic carbon dioxide emissions as per global carbon cycle models would have been 1 Mt CO_2 y^{-1}, i.e. the LULUCF sector would have been a small source of carbon dioxide emissions. However, this net emission estimate is lower than the independent estimate of 11 Mt CO_2 y^{-1} created using bookkeeping models (Grassi et al. 2023).

Estimates by (Grassi et al. 2021, 2023) of indirect sink effects cover only forest land. They justified this by the fact that greenhouse gas inventories show that most (>95%) of the estimated sinks are in forests, and also by the fact that sinks in non-forest land are not reported in greenhouse gas inventories in all countries.

In the Finnish greenhouse gas inventory, the CO_2 sink of forests has varied between 37.9 and 17.2 Mt CO_2 y^{-1} in the 2010s. In 2021, the CO_2 sink provided by forests was only 7.4 Mt CO_2 y^{-1}, making the LULUCF sector a net CO_2 emitter for the first time. The carbon storage of arable land, grasslands, wetlands and built-up land in Finland varied less in the 2010s and these land use categories have been sources of carbon dioxide emissions, i.e. on average they have together reduced the net CO_2 sink of the LULUCF sector by about 12 Mt CO_2 y^{-1} (Statistics Finland, 2023a). CO_2 emissions from arable land on mineral soils were around 0.5–1 Mt CO_2 in the 2010s, i.e. quite low compared to total emissions and sinks. The contribution of indirect sink effects to CO_2 emissions from arable land on mineral soils is expected to be small. Additionally, the share of land use categories other than arable land in the emission balance of the LULUCF sector is relatively small, so overall in the Finnish greenhouse gas inventory for LULUCF emission categories other than forests, it can be concluded that the reported indirect sink effects will be small and their exclusion from the accounting in this report will not significantly affect the results.

ANNEX 4: EMISSION REDUCTION PATHWAYS PRESENTED USING THE ACCOUNTING METHOD FOR NET EMISSIONS FROM THE LULUCF SECTOR, IN ACCORDANCE WITH GLOBAL CARBON CYCLE MODELS

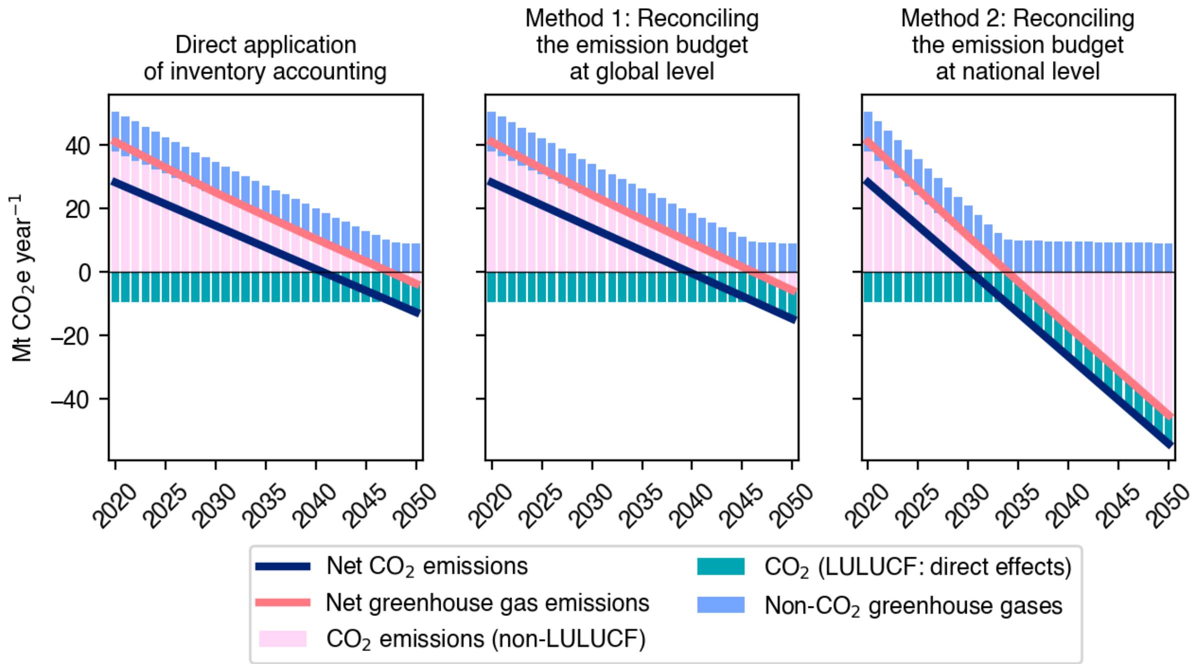

Figure 8: Linear emission reduction pathways calculated so that the cumulative CO_2 emissions from non-LULUCF sectors minus the technical sinks match the results presented in Table 2. Net LULUCF sector CO_2 emissions remain at a constant average level of –23.7 Mt CO_2 y^{-1} for the period 2020–2050. Sinks and net emissions are presented according to the accounting method for global carbon cycle models.

ANNEX 5: WAM-CN SCENARIO

The calculations of the 2020–2100 impact of non-CO_2 greenhouse gases in this report are based on the HIISI project's WAM scenario for the LULUCF sector (Maanavilja et al. 2021) and for non-LULUCF sectors they are based on the WAM-CN scenario (Lehtilä et al. 2021, Antti Lehtilä, personal correspondence), which in 2050 shows greenhouse emission reductions of at least 90% compared to 1990. In this scenario, carbon neutrality (based on GWP100 factors) would be achieved in 2035, assuming −21 Mt CO_2e y^{-1} in net emissions from the LULUCF sector. Subtracting from the above net emissions the non-CO_2 greenhouse gas emissions according to the WAM scenario, the net CO_2 emissions from the LULUCF sector for 2020–2050 average −23.7 Mt CO_2 y^{-1}. Emissions from the original scenarios were reported every five years and for this report emissions were linearly interpolated to other years. The GWP100 factors from the IPCC's Fifth Assessment Report were used to convert methane (GWP100 = 28) and nitrous oxide (GWP100 = 265) emissions into CO_2 equivalents. There was no specification for the different F gases, so they were treated only as CO_2 equivalents. The combined emissions of all sectors for these three gases are shown in Figure 1. In the text of the report, this combination of the WAM and WAM-CN scenarios is referred to as the WAM-CN scenario.