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A framework to assess the climate impact of non-CO_2 emissions of Switzerland - Executive and Technical Summaries

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Executive Summary

The scope

1. This study has been commissioned before and completed after the approval of the Swiss Klima- und Innovationsgesetz (KlG, June 2023), i.e., the *Federal Act on Climate Protection Targets, Innovation and Strengthening Energy Security*, hence with its implications for climate policy in mind.

2. The goal of the study is, with specific consideration of the climate impacts of the Swiss agriculture and aviation sectors, to answer the following two questions:

   - What are, from a scientific point of view, appropriate frameworks to account for the emissions of non-CO_2 climate forcers when aiming at climate policy strategies and impact assessment?
   - What are the corresponding amounts of Carbon Dioxide Removals (CDR) required to comply with the KlG, Art.3, taking into consideration the relevant emission reduction pathways, namely the long-term climate strategy building on the Energy Perspectives 2050+?

3. The general approach in addressing these questions is in this study based on the use of a simplified climate model that allows both (i) calculating the climate impact of given emissions of non-CO_2 climate forcers, and (ii) back-calculating the corresponding amounts of CDR required to undo their effects.

The context

4. Climate change and global warming are the consequence of the increase in radiative forcing caused by climate forcers (CFs) in the atmosphere, i.e., CO_2, non-CO_2 greenhouse gases (GHGs, i.e., CH_4, N_2O, NOx, SOx, water vapor), and other agents (aerosols, black carbon, cirrus clouds).

5. The atmospheric abundance of climate forcers is a consequence (i) of the amount emitted, or formed in the case of cirrus clouds (due to anthropogenic activities), and (ii) of their rate of atmospheric decay (due to atmospheric physics and chemistry). The climate impact caused by the CFs is due to each CF's radiative forcing efficiency (due to atmospheric physics) and to the combined effect of the radiative forcing of all CFs on the planetary energy balances hence on global warming (due to the Earth's physics).

6. The climate impact of a climate forcer is larger, (i) the larger its emissions, or (ii) the slower its decay, or (iii) the higher its radiative efficiency. CO_2 is the only climate forcer that does not decay on the time-scales of interest hence its climate impact depends on its cumulative emissions.

7. While lifetimes of climate forcers vary from days to centuries, the time scale of global thermal adjustments (temperature anomaly in scientific terms, global warming in common language) is several decades to centuries, i.e., Earth climate exhibits a high inertia in reacting to changes in radiative forcing.

8. In a *policy-relevant but not policy-prescriptive* language, the Intergovernmental Panel on Climate Change (IPCC) concludes that "Reaching net zero CO_2 or GHG emissions primarily requires deep and rapid reductions in gross emissions of CO_2, as well as substantial reductions of non-CO_2 GHG emissions (high confidence). . . . However, some hard-to-abate residual GHG emissions (e.g., some emissions from agriculture, aviation, shipping, and industrial processes) remain and would need to be counterbalanced by deployment of carbon dioxide removal (CDR) methods to achieve net zero CO_2 or GHG emissions (high confidence). As a result, net zero CO_2 is reached earlier than net zero GHGs (high confidence)." (AR6, Synthesis Report, SPM, B6.2, with reference to Figure SPM.5)

9. Article 3 of the Swiss Klima- und Innovationsgesetz (KlG), i.e., the *Federal Act on Climate Protection Targets, Innovation and Strengthening Energy Security*, states that: (1) "Der Bund sorgt dafür, dass

die Wirkung der in der Schweiz anfallenden von Menschen verursachten Treibhausgasemissionen bis zum Jahr 2050 Null beträgt (Netto-Null-Ziel), indem: (a) die Treibhausgasemissionen so weit möglich vermindert werden; und (b) die Wirkung der verbleibenden Treibhausgasemissionen durch die Anwendung von Negativemissionstechnologien in der Schweiz und im Ausland ausgeglichen wird. (2) Nach dem Jahr 2050 muss die durch die Anwendung von Negativemissionstechnologien entfernte und gespeicherte Menge an CO_2 die verbleibenden Treibhausgasemissionen übertreffen."[1]

10. The IPCC 6th Assessment Report offers comprehensive global-scale information, including detailed scenarios for CO_2 and other greenhouse gas reductions required to limit warming to specified levels, supported by a robust emissions scenario database. However, this global data does not directly translate into national targets. Instead, the Swiss KlG introduces a national net-zero target and sets several intermediate targets from which one can indirectly infer emission reduction pathways.
    Article 3.1b of the KlG prescribes that any remaining residual emissions must be addressed using negative emissions technologies to achieve net-zero "Wirkung," whose amount is obtained by assessing the climate effect or impact of these residual emissions. This report identifies two possible interpretations of the term "Wirkung" in this context, namely, (1) achieving net-zero residual emissions by 2050 (Target 1), or (2) attaining zero residual radiative forcing by 2050 (Target 2). The definition and choice of the target is a political decision. In this work, we assess the climate impact and carbon dioxide removal (CDR) requirements associated with these climate targets, when CDR is started either (i) from 2050 only, or (ii) already from this decade.

11. In this context, emissions of non-CO_2 CFs have been translated in equivalent CO_2 emissions using equivalence metrics. The GWP_{20} or GWP_{100} metrics (GWP = Global Warming Equivalent), the latter used in the scope of the Paris Agreement, establish a proportionality that is known to underestimate the climate impact of CFs on a 20-year or a 100-year time horizon, respectively, and to overestimate it thereafter. To compensate these undesired shortcomings of simple GWP metrics, the GWP* approach has been proposed, which is not a metric but rather a model and is not used in national inventories.

The climate modeling tool

12. Simple climate models, e.g., the benchmark model FaIR (Finite Amplitude Impulse Response model), are able to simulate the globally averaged emission → concentration → radiative forcing → temperature response pathway and are tuned to emulate through parametrizations the Earth System Models (ESMs), which are three dimensional, gridded, and explicit in representing dynamical and physical processes.

13. The Simplified Linear Climate Model (SLCM) developed and used in this work is simplified with respect to and calibrated on FaIR; key assumptions are (i) that each CF's radiative forcing depends only on its abundance, and (ii) that emissions of a specific country or sector are treated as perturbations of the global evolution of GHG emissions hence the results obtained are independent of the background atmospheric composition. The SLCM strikes a balance between simplicity and effectiveness, thus being a useful tool to explore and to comparatively assess climate trends caused by different emissions scenarios and climate strategies.

14. The SLCM can be used to accomplish the following three tasks:

    - Determining the climate impact (radiative forcing and temperature response) of a given past and future emission profile of one or more CFs.

[1] "(1) The Confederation shall ensure that the impact of man-made greenhouse gas emissions in Switzerland is zero by 2050 (net zero target) by: (a) greenhouse gas emissions are reduced as far as possible; and (b) the effect of remaining greenhouse gas emissions is offset through the use of negative emission technologies in Switzerland and abroad. (2) After 2050, the amount of CO_2 removed and stored through the application of negative emission technologies must exceed the remaining greenhouse gas emissions. [Translated with DeepL.com (free version)]"

- Determining the amounts of CO_2 removal needed over time to compensate for any unavoidable emission profile of a non-CO_2 CF. This calculation is done via the linear warming equivalent (LWE) approach, which in the scope of the SLCM and under the associated assumptions provides an explicit result; such approach allows also recalculating the CDR amounts needed at any point in time, e.g., every year or every given number of years, during the execution of a selected CDR deployment pathway.
- Back-calculating the overall radiative forcing profile corresponding to a specified warming scenario (e.g., keeping a constant temperature anomaly). This is possible given the linearity of the SLCM framework. The resulting radiative forcing profile can be translated into emission profiles for different GHGs by assigning allocation quotas. Determining these allocations involves socio-economic and political considerations that are beyond the scope of this work.

The net-zero target

15. The climate impacts of agriculture are due to methane, CH_4 (about two thirds, short-lived) and to nitrous oxide, N_2O (about one third, long-lived), with similar radiative efficiency; note that in the Swiss emission inventory CO_2 emissions due to agriculture are mostly accounted for in other sectors.

16. The climate impacts of aviation are due to CO_2, to non-CO_2 GHGs, and to other climate forcers (in proportions that are non-negligible and will vary over time). The climate impact of some of these CFs, e.g., cirrus clouds, is difficult to average both in space and in time, hence such impact can only be empirically parametrized in simple climate models and be subject to a sensitivity analysis if needed.

17. In this study climate impacts, i.e., radiative forcing and temperature response caused by a given emission scenario, with or without CDR, are calculated using the SLCM with parameters calibrated using FaIR. A sensitivity analysis accounting for the uncertainty of the parameters used in FaIR (mostly ±20%) is beyond the scope of this work. Total GHG emissions from the agriculture and aviation sectors are collected based on the business-as-usual (WWB) and ZeroBasis scenarios from EP2050+ [4]. Additional details on the scenarios and data collection is provided in the Technical Summary and Technical Report. CDR requirements are calculated to ensure netto-zero residual emissions in 2050, for the agriculture and aviation sectors respectively (Target 1), or netto-zero radiative forcing from the emissions of the agriculture and aviation sectors respectively (Target 2). Netto-zero radiative forcing is defined here with respect to the radiative forcing levels at the start of detectable anthropogenic agriculture emissions, i.e., the year 1690. CDR requirements to achieve Target 1 are calculated by means of the GWP_{20} and GWP_{100} equivalence metrics, and the GWP* and LWE models. CDR requirements to achieve Target 2 can only be calculated with the LWE model (see Technical summary for further detail).

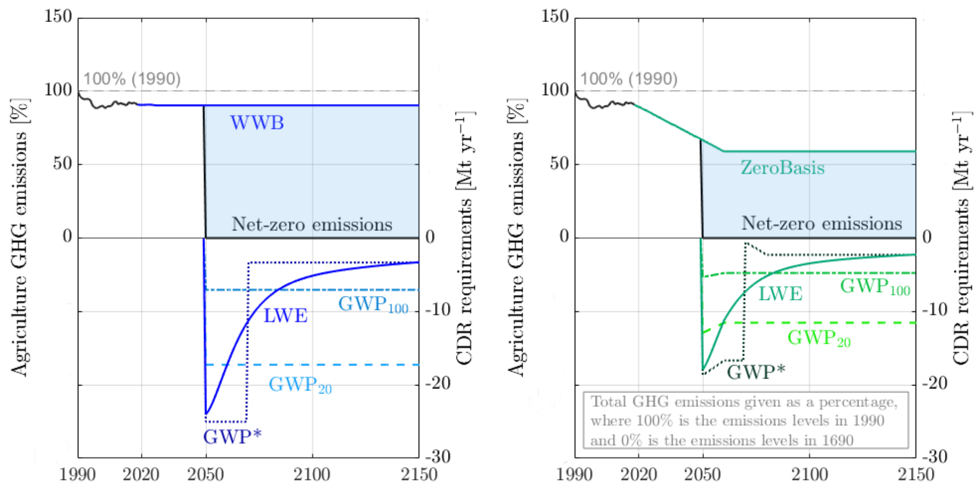
18. For Swiss agriculture, WWB emissions (business-as-usual) and ZeroBasis emissions (from the BfE Energieperspectiven 2050+ dataset, EP2050+), without CDR deployment, would lead to a long-term temperature response of 100% and 30%, respectively, higher than in 1990.

19. When deploying CDR to achieve targets under KlG for Swiss agriculture, targeting either net-zero emissions (Target 1) or zero radiative forcing (Target 2) leads to rather similar radiative forcing and temperature response but entails CDR requirements in the latter case much larger than in the former.

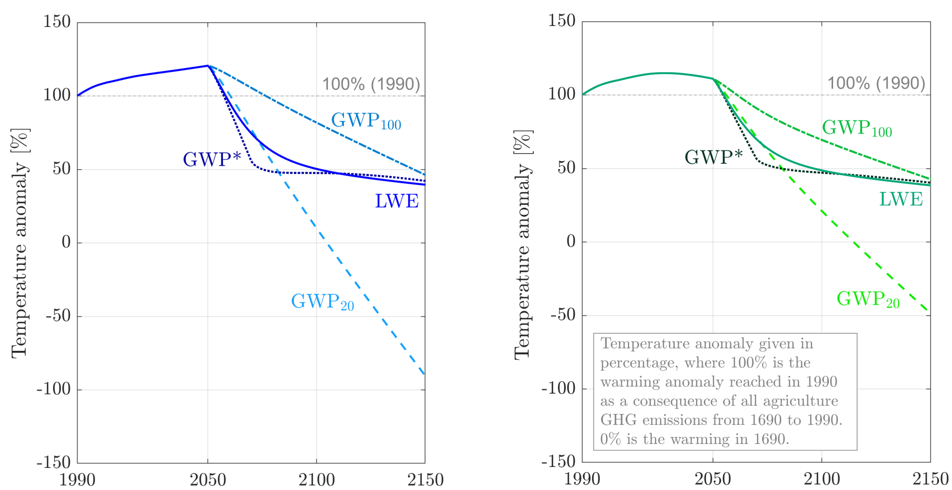
20. For Swiss aviation, WWB emissions without CDR deployment would lead to a larger warming contribution over time due to the cumulative effect of CO_2. ZeroBasis emissions, though assuming 100% use of CO_2-free sustainable aviation fuels (SAFs) from 2050 on, would lead without CDR deployment to a long-term warming contribution about three times larger than in 1990.

21. When deploying CDR to implement the KlG for Swiss aviation, targeting net-zero emissions (Target 1) leads to a higher warming contribution than if targeting zero radiative forcing (Target 2), because of the much larger contribution due to the CO_2 emissions.

22. As to Swiss agriculture and the associated CDR requirements to fulfill Targets 1 and 2:



(a) Total WWB (left) and ZeroBasis (right) GHG emissions from the Swiss agriculture sector, alongside a hypothetical emissions reduction pathway aimed at achieving net-zero emissions by 2050 (grey line). Emissions are expressed as a percentage of 1990 levels for ease of comparison. The light blue area highlights the emissions gap between total emissions and the reduction target, representing the carbon dioxide removal (CDR) requirements. The right vertical axis quantifies the necessary CDR (shown as a negative value) to offset residual emissions of CO_2, CH_4, and N_2O. Methane and nitrous oxide are converted to CO_2 equivalents using different equivalence metrics and models: GWP$_{20}$, GWP$_{100}$, GWP*, and LWE.



(b) Temperature anomaly (Figure 22b) induced by Swiss agricultural emissions, expressed as a percentage of the warming observed in 1990. The anomaly is calculated for scenarios where CDR is deployed to achieve net-zero emissions from 2050, using the GWP$_{100}$, GWP$_{20}$, GWP*, and LWE equivalence approaches.

Figure 1. Net-zero emissions (Target 1) in the Swiss agriculture sector.

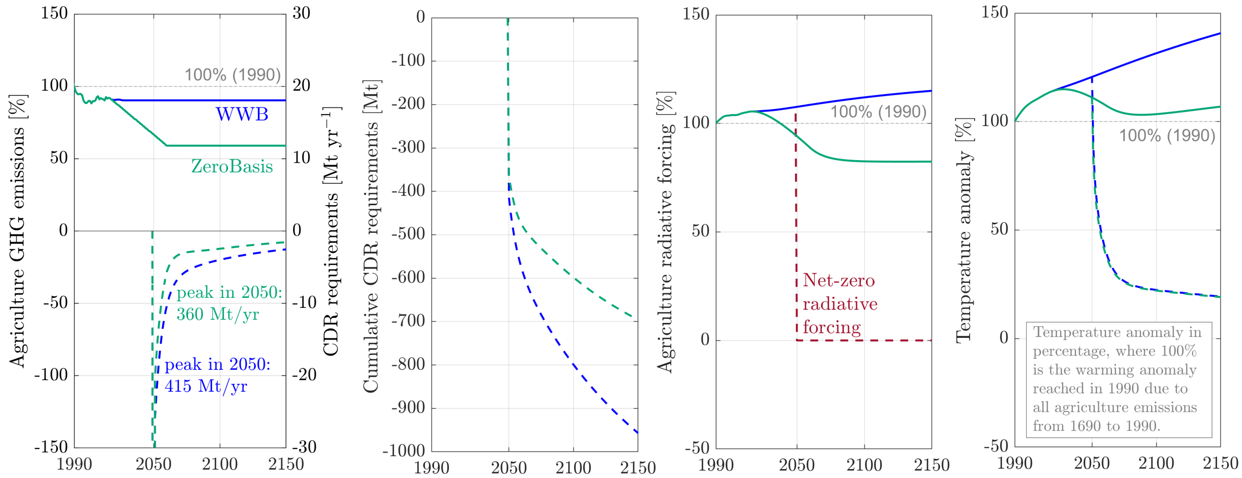


Figure 2. Net-zero radiative forcing (Target 2) in the Swiss agriculture sector. The four panels show: (i) agriculture emissions as a percentage (first panel, left vertical axis), where 100% corresponds to 1990 levels and 0% to the start of anthropogenic agricultural emissions in 1690; (ii) CDR requirements in Mt/yr (first panel, right vertical axis), with CDR rates calculated using the LWE approach shown as negative values; (iii) cumulative CDR requirements to achieve the net-zero radiative forcing target for WWB and ZeroBasis scenarios; (iv) radiative forcing for WWB and ZeroBasis scenarios and the net-zero radiative forcing trajectory from 2050 (third panel), where 100% corresponds to the 1990 level and 0% to 1690; and (v) temperature anomaly for WWB and ZeroBasis scenarios, with and without CDR (fourth panel), where 100% corresponds to the 1990 level and 0% to 1690. Dashed lines represent radiative forcing and temperature anomaly evolutions with CDR implementation.

- Under all assumptions and for all scenarios considered here, both methane (short-lived) and nitrous oxide (long-lived) play an important role in determining the climate impact of Swiss agriculture; neither can be neglected.
- Both net-zero emissions (Target 1) and net-zero radiative forcing (Target 2) can be attained for both the WWB and the ZeroBasis emission scenarios, with similar long-term temperature responses. This occurs through the deployment of corresponding amounts of CDR starting in 2050, which are much larger for Target 2 than for Target 1 and are about 50% larger for the WWB scenario than for the ZeroBasis one.
- As expected, using the GWP-based CO_2 equivalence metrics underestimates and overestimates the CDR demand in the short-term and in the long-term, respectively, with respect to what predicted using the CDR* and the LWE models. This conclusion has been reached by inputting the CDR amounts calculated with the four approaches above to the SLCM, and then calculating the corresponding climate impacts. Even if the absolute values estimated are influenced by the SLCM assumptions, the comparative assessment of different emission scenarios and CDR deployment strategies in terms of climate impact is more robust with respect to the model assumptions.
- Using the SLCM provides insight on which measures may reduce the CDR demand, while still fulfilling the climate objectives. Examples are given that involve (i) starting deploying CDR soon instead of waiting until 2050, (ii) anticipating deployment and shaving the peak of CDR that GWP* and LWE require around 2050, and (iii) back-calculating the CDR needed to comply with a specified temperature response profile (this is a novel feature provided by the SLCM).

23. As to Swiss aviation and the associated CDR requirements to fulfill Targets 1 and 2:

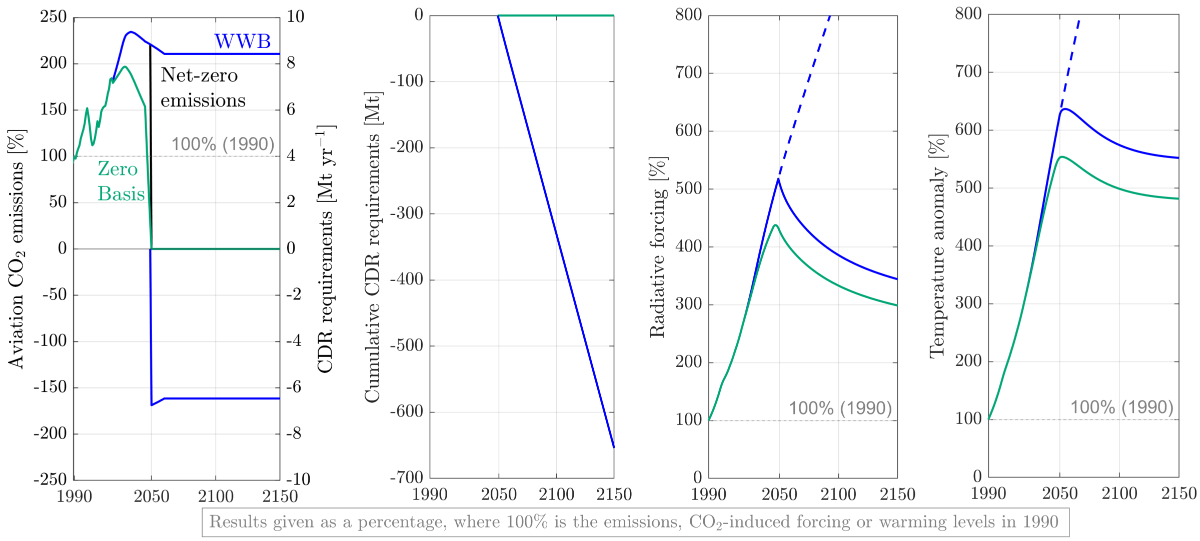


Figure 3. Net-zero emissions (Target 1) in the Swiss aviation sector. The four panels show, from left to right: (i) the emissions in percentage (first panel, left vertical axis), where 100% corresponds to the level of emissions in 1990, while 0% represents their level at the start of anthropogenic aviation emissions, i.e., the year 1950; (ii) in the same first panel the CDR requirements in Mt/yr (first panel, right vertical axis), where rates of CDR are negative numbers, in contrast to emissions that are positive; (iii) the cumulative CDR requirements needed to achieve the net-zero CO_2 emissions target when residual emissions follow either WWB or ZeroBasis (second panel); (iv) the associated radiative forcing for the WWB and ZeroBasis scenarios with and without CDR (third panel), when only the climate impact of CO_2 emissions is considered (100% is the corresponding CO_2-induced level in 1990, and 0% that in 1950); (iv) the associated temperature anomaly for the WWB and ZeroBasis scenarios with and without CDR (fourth panel), when only the CO_2-induced warming is considered (100% is the corresponding CO_2-induced level in 1990, and 0% that in 1950). Radiative forcing and temperature anomaly curves without CDR implementation are showed with dashed lines. Achieving net-zero CO_2 emissions in 2050, while only deploying CDR from that same target year, results in a peak of 7 Mt/yr for the WWB scenario, where CDR deployment is zero for the ZeroBasis pathway (100% SAFs uptake). Considering only the climate impact of aviation-CO_2, and compensating with CDR for only those emissions, the long-term sector's warming contribution is about five times that in 1990.

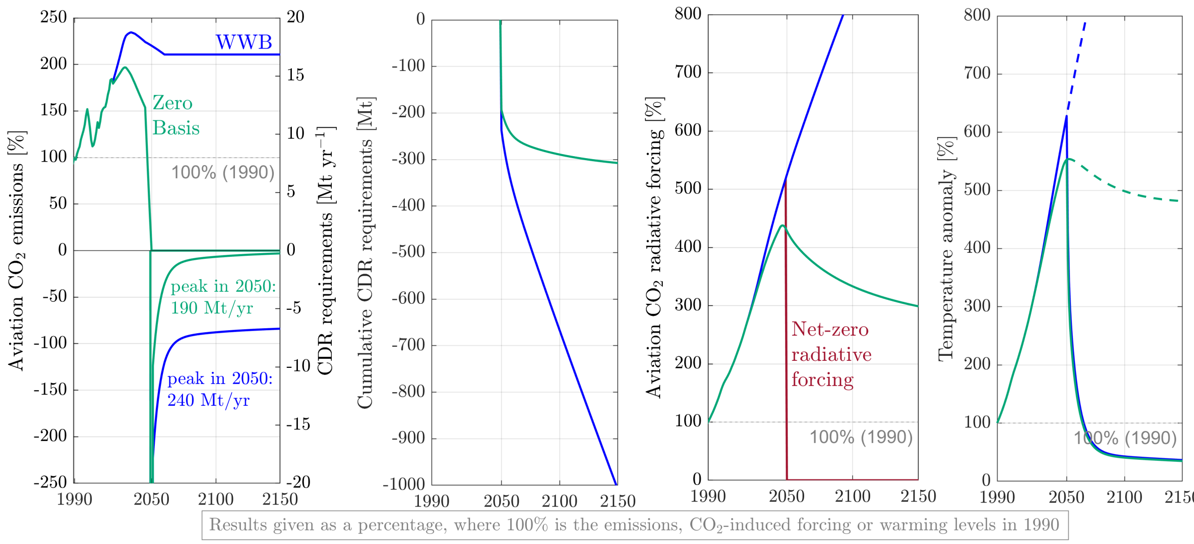


Figure 4. As Figure 29, but for a Target 2 of net-zero radiative forcing. Achieving net-zero forcing in 2050, while only deploying CDR from that same target year, results in a peak of 240 Mt/yr for the WWB scenario and 190 Mt/yr for the ZeroBasis scenario. Considering only the climate impact of aviation-CO_2, and compensating with CDR for its resulting forcing, the sector's warming contribution is eliminated in the long-term.

- The KlG aims at a net-zero-target in 2050, considering CO_2 but neglecting the other non-CO_2 climate forcers.
- For Swiss aviation, the WWB and ZeroBasis emission scenarios show significant differences. In fact, the ZeroBasis scenario assumes 100% use of carbon-neutral sustainable aviation fuels (SAFs) from 2050 onwards, overlooking the fact that the production of SAFs will still have a non-negligible carbon footprint, as demonstrated in the recent, relevant scientific literature.
- The previous two points highlight the fact that both the provisions of the KlG and the emission scenarios considered make it difficult to obtain CDR requirements that are meaningful from a climate impact point of view and that are comparable.
- This study shows that, even under the assumptions outlined, fulfilling Targets 1 and 2 results in very large CDR requirements.
- Also in the case of aviation early CDR deployment reduces the peak and the cumulative CDR requirements. However, it seems that reaching feasible levels of CDR deployment may require two types of measure beyond compensation through CDR deployment: (i) a significant reduction of emissions with respect to the ZeroBasis scenario, which would imply a reduction of air traffic because of reduced demand, and (ii) the implementation of measures to increase the climate efficiency of aviation, through an optimized management of the individual flight from all possible perspectives.

The challenge

24. Achieving in 2050 either net-zero emissions (Target 1) or zero radiative forcing (Target 2) for Swiss agriculture in the ZeroBasis scenario with CDR deployment starting in 2050 is doable, provided sufficiently large amounts of CDR are generated. Depending on the approach used, GWP metrics or GWP* and LWE models, the exact CDR amounts estimated differ, particularly in the long term. The actual temperature response associated to any emission scenario and any CDR deployment strategy must account for the effect of all relevant climate forcers, i.e., methane, nitrous oxide and carbon dioxide,

and must be calculated using a climate model; different approaches to calculate CDR demand lead to different temperature response. The SLCM used in this study offers a trade off between simplicity and accuracy in predicting the climate impacts, which proves to be useful for comparatively assessing the effect of different climate policies.

25. To achieve net-zero emissions for Swiss aviation from 2050 in the ZeroBasis scenario, in principle, no CDR is required if only CO_2 emissions are considered, non-CO_2 effects are excluded, and SAFs with a zero carbon footprint are assumed. In practice, however, the SLCM predicts a temperature anomaly several times larger than in 1990 under these conditions. When non-CO_2 effects are included, the required peak CDR deployment rate in 2050 and the cumulative CDR needed throughout the century reach levels that are likely unfeasible from today's perspective.

26. The CDR requirements determined in this study represent a daunting challenge in both scale and speed of deployment. Such requirements, when keeping the same climate targets, can only be reduced (i) by starting CDR deployment immediately instead of in 2050, (ii) by choosing residual emission pathways more ambitious than ZeroBasis, and (iii) by enforcing structural changes, including reducing demand and taking sector specific measures, whose consideration and discussion are beyond the scope of this study.

Sintesi Esecutiva

L'ambito

1. Questo studio è stato commissionato prima e completato dopo l'approvazione della legge svizzera sul Clima e l'Innovazione (KlG, giugno 2023), ovvero la Legge federale sugli Obiettivi di Protezione del Clima, sull'Innovazione e sul Rafforzamento della Sicurezza Energetica, quindi tenendo conto delle sue implicazioni per la politica climatica.

2. L'obiettivo dello studio è rispondere alle seguenti due domande, considerando specificamente gli impatti climatici dei settori agricolo e aeronautico svizzeri:

   - Quali sono, dal punto di vista scientifico, i quadri di riferimento appropriati per tenere conto delle emissioni dei forzanti climatici non-CO_2 quando si progettano strategie politiche per il clima e la valutazione degli impatti?
   - Quali sono le quantità corrispondenti di Rimozione di Anidride Carbonica (CDR) necessarie per rispettare l'Art. 3 del KlG, prendendo in considerazione i relativi percorsi di riduzione delle emissioni, in particolare la strategia climatica a lungo termine basata sulle Energie 2050+?

3. L'approccio generale per affrontare queste domande in questo studio si basa sull'uso di un modello climatico semplificato che permette sia (i) di calcolare l'impatto climatico delle emissioni di forzanti climatici non-CO_2, sia (ii) di calcolare retrospettivamente le quantità corrispondenti di CDR necessarie per annullare i loro effetti.

Il contesto

4. Il cambiamento climatico e il riscaldamento globale sono la conseguenza dell'aumento del forzante radiativo causato dai fattori climatici (CFs) nell'atmosfera, cioè CO_2, gas serra non-CO_2 (GHG, ad esempio CH_4, N_2O, NOx, SOx, vapore acqueo) e altri agenti (aerosol, carbonio nero, nubi cirrus).

5. L'abbondanza atmosferica dei fattori climatici è una conseguenza (i) della quantità emessa o, nel caso delle nubi cirrus, della quantità formata a causa delle attività antropiche, e (ii) del loro tasso di decadimento atmosferico (determinato dalla fisica e dalla chimica atmosferica). L'impatto climatico dei CFs dipende dall'efficienza radiativa di ciascun fattore (determinata dalla fisica atmosferica) e dall'effetto combinato del forzante radiativo di tutti i CFs sugli equilibri energetici planetari e quindi sul riscaldamento globale (determinato dalla fisica della Terra).

6. L'impatto climatico di un fattore climatico è maggiore (i) quanto maggiori sono le sue emissioni, (ii) quanto più lento è il suo decadimento, oppure (iii) quanto maggiore è la sua efficienza radiativa. Il CO_2 è l'unico fattore climatico che non decade alle scale temporali di interesse; il suo impatto climatico dipende quindi dalle sue emissioni cumulative.

7. Sebbene la durata dei fattori climatici vari da giorni a secoli, la scala temporale degli aggiustamenti termici globali (anomalia di temperatura in termini scientifici, riscaldamento globale nel linguaggio comune) è di diverse decine di anni o secoli. Il clima terrestre mostra quindi un'elevata inerzia nel reagire ai cambiamenti del forzante radiativo.

8. In un linguaggio *rilevante per le politiche ma non prescrittivo*, il Gruppo intergovernativo sui cambiamenti climatici (IPCC) conclude che: "Raggiungere emissioni nette zero di CO_2 o di gas serra richiede principalmente riduzioni profonde e rapide delle emissioni lorde di CO_2, così come riduzioni sostanziali delle emissioni di gas serra non-CO_2 (alta fiducia). ... Tuttavia, alcune emissioni residue difficili da ridurre (ad esempio, alcune emissioni provenienti dall'agricoltura, dall'aviazione, dalla navigazione e dai processi industriali) rimangono e dovrebbero essere compensate mediante l'adozione di metodi di

rimozione del diossido di carbonio (CDR) per raggiungere emissioni nette zero di CO_2 o di gas serra (alta fiducia). Di conseguenza, il raggiungimento di emissioni nette zero di CO_2 avviene prima del raggiungimento di emissioni nette zero di gas serra (alta fiducia)." (AR6, Rapporto di Sintesi, SPM, B6.2, con riferimento alla Figura SPM.5)

9. L'articolo 3 della legge svizzera sul clima e l'innovazione (KlG), cioè la *Legge federale sugli obiettivi climatici, l'innovazione e il rafforzamento della sicurezza energetica*, afferma che: (1) "La Confederazione assicura che l'impatto delle emissioni di gas serra antropogeniche in Svizzera sia pari a zero entro il 2050 (obiettivo net zero), mediante: (a) la riduzione delle emissioni di gas serra il più possibile; e (b) la compensazione dell'impatto delle emissioni residue di gas serra attraverso l'uso di tecnologie a emissioni negative in Svizzera e all'estero. (2) Dopo il 2050, la quantità di CO_2 rimossa e immagazzinata tramite l'applicazione di tecnologie a emissioni negative deve superare le emissioni residue di gas serra."[2]

10. Il rapporto del sesto ciclo di valutazione dell'IPCC offre informazioni dettagliate su scala globale, inclusi scenari per la riduzione di CO_2 e altri gas serra necessari per limitare il riscaldamento a determinati livelli, supportati da un database robusto di scenari di emissioni. Tuttavia, questi dati globali non si traducono direttamente in obiettivi nazionali. La legge KlG svizzera introduce invece un obiettivo nazionale di net zero e stabilisce diversi obiettivi intermedi da cui è possibile dedurre indirettamente percorsi di riduzione delle emissioni.
L'articolo 3.1b della KlG prescrive che tutte le emissioni residue devono essere affrontate utilizzando tecnologie a emissioni negative per raggiungere un "Wirkung" net zero, la cui quantità è determinata valutando l'effetto climatico o l'impatto di queste emissioni residue. Questo rapporto identifica due possibili interpretazioni del termine "Wirkung" in questo contesto, ovvero: (1) raggiungere emissioni residue nette zero entro il 2050 (Obiettivo 1), oppure (2) raggiungere un forzante radiativo residuo zero entro il 2050 (Obiettivo 2). La definizione e la scelta dell'obiettivo sono una decisione politica. In questo lavoro, valutiamo l'impatto climatico e i requisiti di rimozione del diossido di carbonio (CDR) associati a questi obiettivi climatici, quando il CDR inizia (i) solo dal 2050, oppure (ii) già da questo decennio.

11. In questo contesto, le emissioni dei CFs non-CO_2 sono state tradotte in emissioni equivalenti di CO_2 utilizzando metriche di equivalenza. Le metriche GWP_{20} o GWP_{100} (GWP = potenziale di riscaldamento globale), quest'ultima utilizzata nell'ambito dell'Accordo di Parigi, stabiliscono una proporzionalità nota per sottostimare l'impatto climatico dei CFs su un orizzonte temporale di 20 o 100 anni, rispettivamente, e per sovrastimarlo successivamente. Per compensare queste carenze delle metriche GWP semplici, è stato proposto l'approccio GWP*, che non è una metrica ma piuttosto un modello e non viene utilizzato negli inventari nazionali.

Lo strumento di modellizzazione climatica

12. I modelli climatici semplici, come il modello di riferimento FaIR (Finite Amplitude Impulse Response model), sono in grado di simulare il percorso emissione → concentrazione → forzante radiativo → risposta della temperatura su scala globale e sono tarati per emulare attraverso parametri i Modelli del Sistema Terrestre (ESMs), che sono tridimensionali, grigliati e espliciti nella rappresentazione dei processi dinamici e fisici.

[2]"(1) La Confederazione assicura che l'impatto delle emissioni di gas serra antropogeniche in Svizzera sia pari a zero entro il 2050 (obiettivo net zero), mediante: (a) la riduzione delle emissioni di gas serra il più possibile; e (b) la compensazione dell'impatto delle emissioni residue di gas serra attraverso l'uso di tecnologie a emissioni negative in Svizzera e all'estero. (2) Dopo il 2050, la quantità di CO_2 rimossa e immagazzinata tramite l'applicazione di tecnologie a emissioni negative deve superare le emissioni residue di gas serra."

13. Il Modello Climatico Lineare Semplificato (SLCM) sviluppato e utilizzato in questo lavoro è semplificato rispetto a FaIR e calibrato su di esso; le ipotesi principali sono (i) che il forzante radiativo di ogni CF dipenda solo dalla sua abbondanza, e (ii) che le emissioni di un determinato paese o settore siano trattate come perturbazioni dell'evoluzione globale delle emissioni di GHG, rendendo i risultati ottenuti indipendenti dalla composizione atmosferica di fondo. Lo SLCM raggiunge un equilibrio tra semplicità ed efficacia, risultando così uno strumento utile per esplorare e valutare comparativamente le tendenze climatiche causate da diversi scenari di emissione e strategie climatiche.

14. Lo SLCM può essere utilizzato per svolgere le seguenti tre funzioni:

    - Determinare l'impatto climatico (forzante radiativo e risposta della temperatura) di un dato profilo di emissioni passato e futuro di uno o più CF.
    - Determinare le quantità di rimozione di CO_2 necessarie nel tempo per compensare un profilo di emissioni inevitabile di un CF non-CO_2. Questo calcolo viene effettuato tramite l'approccio del Linear Warming Equivalent (LWE), che nel contesto dello SLCM e delle ipotesi associate fornisce un risultato esplicito; tale approccio consente anche di ricalcolare le quantità di CDR necessarie in qualsiasi momento, ad esempio ogni anno o ogni determinato numero di anni, durante l'esecuzione di un percorso di distribuzione di CDR selezionato.
    - Calcolare retroattivamente il profilo di forzante radiativo complessivo corrispondente a uno scenario di riscaldamento specifico (ad esempio mantenere una costante anomalia di temperatura). Ciò è possibile grazie alla linearità del quadro SLCM. Il profilo di forzante radiativo risultante può essere tradotto in profili di emissioni per diversi GHG assegnando quote di allocazione. La determinazione di tali allocazioni implica considerazioni socio-economiche e politiche che esulano dall'ambito di questo lavoro.

L'obiettivo di emissioni nette zero

15. Gli impatti climatici dell'agricoltura sono dovuti al metano, CH_4 (circa due terzi, a vita breve) e al protossido di azoto, N_2O (circa un terzo, a vita lunga), con efficienza radiativa simile; si noti che nell'inventario delle emissioni svizzero le emissioni di CO_2 legate all'agricoltura sono per lo più attribuite ad altri settori.

16. Gli impatti climatici dell'aviazione derivano da CO_2, gas serra non-CO_2 (GHG) e altri fattori climatici (in proporzioni non trascurabili che possono variare nel tempo). L'impatto climatico di alcuni di questi fattori, come le nuvole di cirro, è difficile da mediare sia nello spazio che nel tempo, per cui tale impatto può essere solo parametrizzato empiricamente nei modelli climatici semplici ed eventualmente sottoposto ad analisi di sensibilità.

17. In questo studio gli impatti climatici, ossia il forcing radiativo e la risposta della temperatura causati da un dato scenario di emissioni, con o senza CDR, sono calcolati utilizzando l'SLCM con parametri calibrati usando FaIR. Un'analisi di sensibilità che consideri l'incertezza dei parametri usati in FaIR (per lo più $\pm 20\%$) è al di fuori dello scopo di questo lavoro. Le emissioni totali di GHG dai settori dell'agricoltura e dell'aviazione sono raccolte sulla base degli scenari business-as-usual (WWB) e ZeroBasis da EP2050+ [4]. Ulteriori dettagli sugli scenari e sulla raccolta dei dati sono forniti nel Riassunto Tecnico e nel Rapporto Tecnico. I requisiti di CDR sono calcolati per garantire emissioni residue pari a netto-zero nel 2050 per i settori dell'agricoltura e dell'aviazione rispettivamente (Obiettivo 1), o forcing radiativo netto-zero per le emissioni dei settori dell'agricoltura e dell'aviazione rispettivamente (Obiettivo 2). Il forcing radiativo netto-zero è definito qui rispetto ai livelli di forcing radiativo all'inizio delle emissioni antropogeniche rilevabili dell'agricoltura, ossia l'anno 1690. I requisiti di CDR per raggiungere l'Obiettivo 1 sono calcolati tramite le metriche di equivalenza GWP_{20} e GWP_{100} e i modelli GWP* e LWE. I requisiti di CDR per raggiungere l'Obiettivo 2 possono essere calcolati solo con il modello LWE (vedi Riassunto Tecnico per ulteriori dettagli).

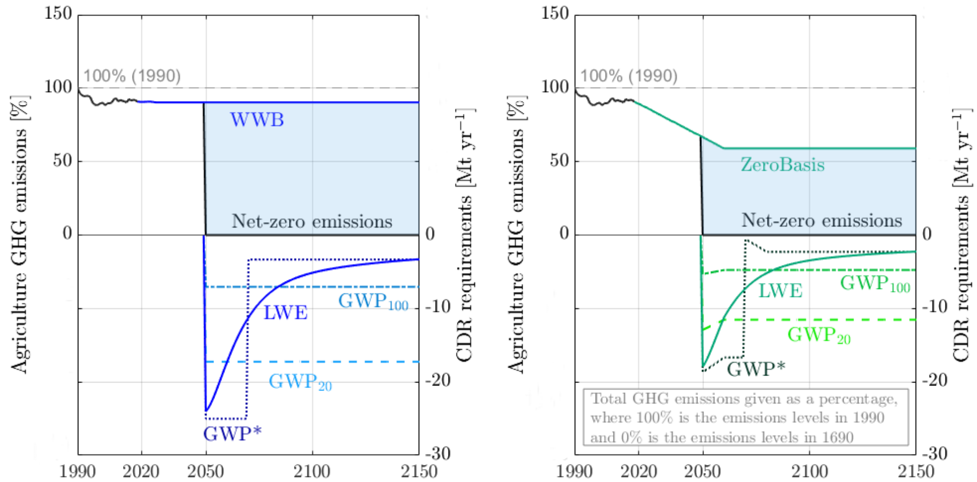
18. Senza l'impiego di CDR, le emissioni WWB (business-as-usual) e ZeroBasis (dal dataset EP2050+ di BfE Energieperspektiven) nell'agricoltura svizzera porterebbero a una risposta termica a lungo termine rispettivamente del 100% e del 30% superiore al 1990.

19. Implementando il CDR per raggiungere gli obiettivi definiti dal KlG per l'agricoltura svizzera, sia l'obiettivo di emissioni nette zero (Obiettivo 1) sia quello di forcing radiativo netto zero (Obiettivo 2) portano a risposte di forcing radiativo e temperatura piuttosto simili, ma con requisiti di CDR molto più elevati nel secondo caso rispetto al primo.

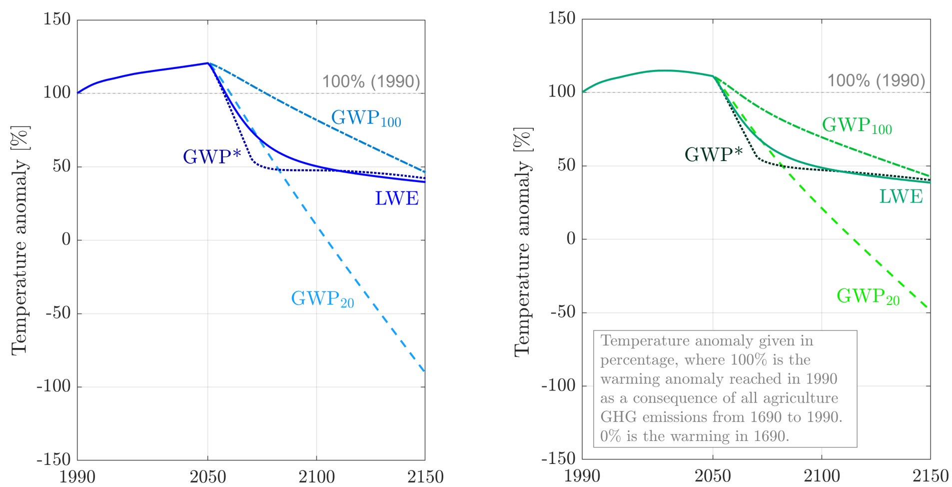
20. Per l'aviazione svizzera, le emissioni WWB senza implementazione di CDR porterebbero a un contributo di riscaldamento maggiore nel tempo a causa dell'effetto cumulativo del CO_2. Le emissioni ZeroBasis, che presumono l'uso al 100% di carburanti sostenibili privi di CO_2 (SAF) a partire dal 2050, porterebbero senza implementazione di CDR a un contributo di riscaldamento a lungo termine circa tre volte superiore a quello del 1990.

21. Implementando il CDR per raggiungere il KlG per l'aviazione svizzera, mirare a emissioni nette zero (Obiettivo 1) porta a un contributo di riscaldamento maggiore rispetto a mirare a un forcing radiativo netto zero (Obiettivo 2), a causa del contributo molto più grande delle emissioni di CO_2.

22. Per quanto riguarda l'agricoltura svizzera e i relativi requisiti di CDR per soddisfare gli Obiettivi 1 e 2:



(a) Le emissioni totali di gas a effetto serra (GHG) del settore agricolo svizzero nei scenari WWB (a sinistra) e ZeroBasis (a destra), insieme a un percorso ipotetico di riduzione delle emissioni volto a raggiungere le emissioni nette zero entro il 2050 (linea grigia). Le emissioni sono espresse come percentuale dei livelli del 1990 per facilitarne il confronto. L'area azzurra chiara evidenzia il divario delle emissioni tra le emissioni totali e l'obiettivo di riduzione, rappresentando i requisiti di rimozione del carbonio (CDR). L'asse verticale a destra quantifica la necessaria CDR (valori negativi) per compensare le emissioni residue di CO_2, CH_4 e N_2O. Il metano e l'ossido di azoto vengono convertiti in equivalenti di CO2 utilizzando vari metriche e modelli di equivalenza: GWP_{20}, GWP_{100}, GWP* e LWE.



(b) Anomalia di temperatura indotta dalle emissioni agricole svizzere, espressa come percentuale del riscaldamento osservato nel 1990. L'anomalia è calcolata per scenari in cui la CDR viene implementata per raggiungere emissioni nette zero a partire dal 2050, utilizzando gli approcci di equivalenza GWP_{100}, GWP_{20}, GWP* e LWE.

Figure 5. Emissioni nette zero (Obiettivo 1) nel settore agricolo svizzero.

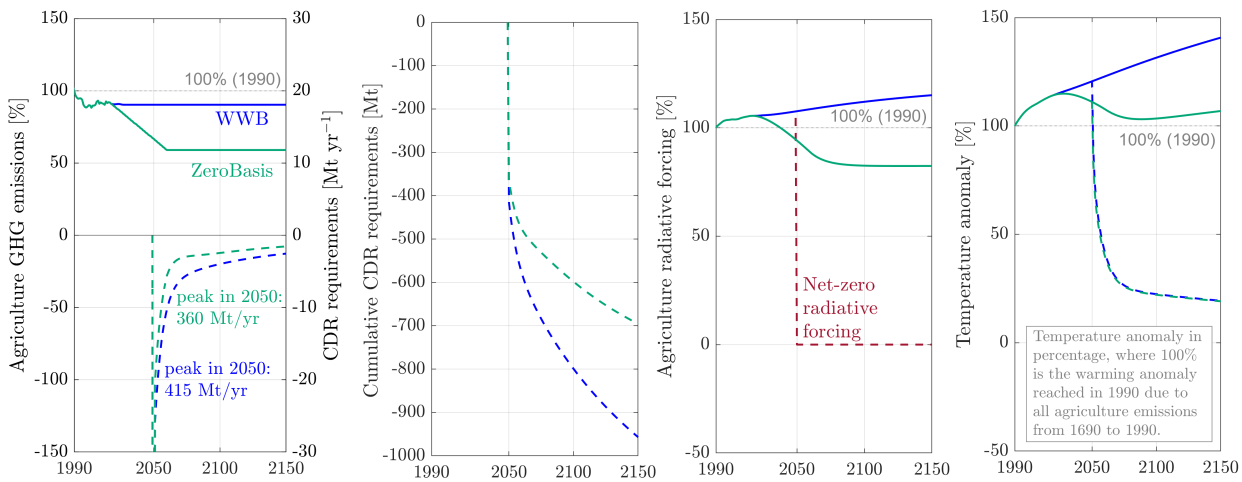


Figure 6. Forza radiativa netta zero (Obiettivo 2) nel settore agricolo svizzero. I quattro pannelli mostrano: (i) le emissioni agricole come percentuale (primo pannello, asse verticale sinistro), dove il 100% corrisponde ai livelli del 1990 e lo 0% all'inizio delle emissioni agricole antropogeniche nel 1690; (ii) i requisiti di CDR in Mt/anno (primo pannello, asse verticale destro), con i tassi di CDR calcolati utilizzando l'approccio LWE mostrati come valori negativi; (iii) i requisiti cumulativi di CDR per raggiungere l'obiettivo di forza radiativa netta zero per gli scenari WWB e ZeroBasis; (iv) la forza radiativa per gli scenari WWB e ZeroBasis e la traiettoria di forza radiativa netta zero dal 2050 (terzo pannello), dove il 100% corrisponde al livello del 1990 e lo 0% al 1690; e (v) l'anomalia di temperatura per gli scenari WWB e ZeroBasis, con e senza CDR (quarto pannello), dove il 100% corrisponde al livello del 1990 e lo 0% al 1690. Le linee tratteggiate rappresentano l'evoluzione della forza radiativa e dell'anomalia di temperatura con l'implementazione del CDR.

- Sotto tutte le ipotesi e per tutti gli scenari considerati in questo studio, sia il metano (a breve durata) che il protossido di azoto (a lunga durata) svolgono un ruolo importante nel determinare l'impatto climatico dell'agricoltura svizzera; nessuno dei due può essere trascurato.
- Sia le emissioni nette zero (Obiettivo 1) che il forzante radiativo netto zero (Obiettivo 2) possono essere raggiunti per gli scenari di emissione WWB e ZeroBasis, con risposte termiche a lungo termine simili. Ciò avviene attraverso l'impiego di quantità corrispondenti di CDR a partire dal 2050, che sono molto maggiori per l'Obiettivo 2 rispetto all'Obiettivo 1 e circa il 50% superiori per lo scenario WWB rispetto a quello ZeroBasis.
- Come previsto, l'utilizzo delle metriche di equivalenza del CO_2 basate sul GWP sottostima e sovrastima la domanda di CDR rispettivamente a breve e lungo termine rispetto alle previsioni ottenute utilizzando i modelli CDR* e LWE. Questa conclusione è stata raggiunta inserendo le quantità di CDR calcolate con i quattro approcci nel SLCM e poi calcolando gli impatti climatici corrispondenti. Anche se i valori assoluti stimati sono influenzati dalle ipotesi del SLCM, la valutazione comparativa di diversi scenari di emissione e strategie di implementazione del CDR in termini di impatto climatico è più robusta rispetto alle ipotesi del modello.
- L'uso del SLCM fornisce indicazioni sulle misure che possono ridurre la domanda di CDR, pur rispettando gli obiettivi climatici. Esempi includono (i) iniziare a implementare il CDR presto anziché aspettare fino al 2050, (ii) anticipare l'implementazione e ridurre il picco di CDR richiesto da GWP* e LWE intorno al 2050, e (iii) calcolare a ritroso il CDR necessario per rispettare un profilo specifico di risposta termica (questa è una caratteristica innovativa fornita dal SLCM).

23. Per quanto riguarda l'aviazione svizzerae i relativi requisiti di CDR per soddisfare gli Obiettivi 1 e 2:

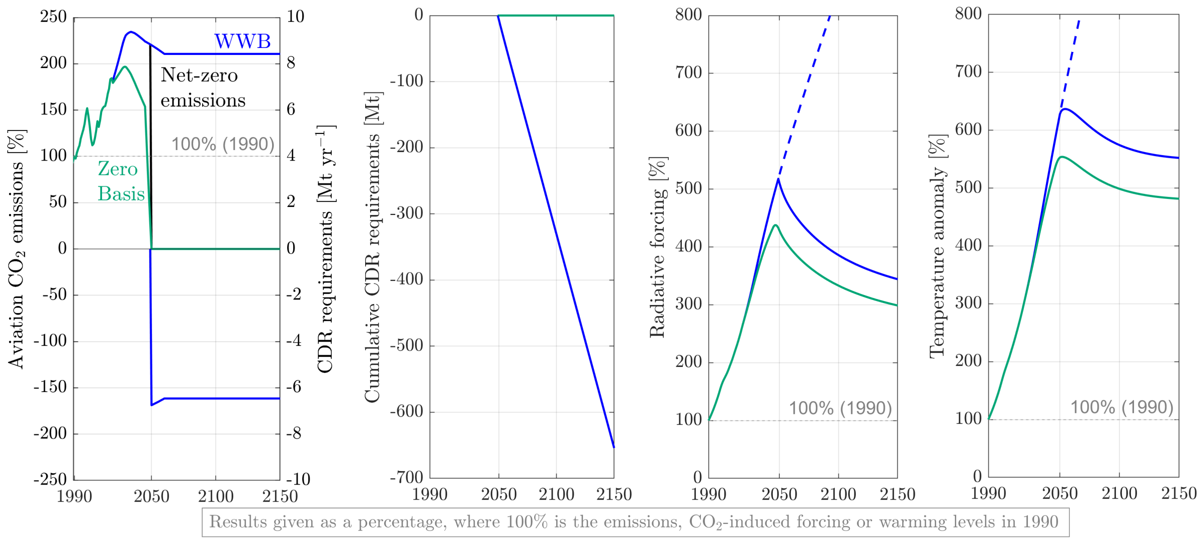


Figure 7. Emissioni nette zero (Obiettivo 1) nel settore dell'aviazione svizzera. I quattro pannelli mostrano, da sinistra a destra: (i) le emissioni in percentuale (primo pannello, asse verticale sinistro), dove il 100% corrisponde al livello delle emissioni nel 1990, mentre lo 0% rappresenta il loro livello all'inizio delle emissioni antropogeniche dell'aviazione, cioè nel 1950; (ii) nello stesso primo pannello, i requisiti di CDR in Mt/anno (asse verticale destro del primo pannello), dove i tassi di CDR sono numeri negativi, a differenza delle emissioni che sono positive; (iii) i requisiti cumulativi di CDR necessari per raggiungere l'obiettivo di emissioni nette zero di CO_2 quando le emissioni residue seguono uno dei due scenari WWB o ZeroBasis (secondo pannello); (iv) il forzante radiativo associato agli scenari WWB e ZeroBasis con e senza CDR (terzo pannello), quando viene considerato solo l'impatto climatico delle emissioni di CO_2 (il 100% è il livello corrispondente indotto dal CO_2 nel 1990, e lo 0% nel 1950); (v) l'anomalia di temperatura associata agli scenari WWB e ZeroBasis con e senza CDR (quarto pannello), quando viene considerato solo il riscaldamento indotto dal CO_2 (il 100% è il livello corrispondente indotto dal CO_2 nel 1990, e lo 0% nel 1950). Le curve di forzante radiativo e di anomalia di temperatura senza implementazione di CDR sono mostrate con linee tratteggiate. Raggiungere emissioni nette zero di CO_2 nel 2050, iniziando a implementare CDR da quello stesso anno di obiettivo, porta a un picco di 7 Mt/anno per lo scenario WWB, dove l'implementazione di CDR è zero per il percorso ZeroBasis (adozione del 100% di SAF). Considerando solo l'impatto climatico del CO_2 dell'aviazione e compensando con CDR solo per queste emissioni, il contributo al riscaldamento a lungo termine del settore è circa cinque volte maggiore rispetto al 1990.

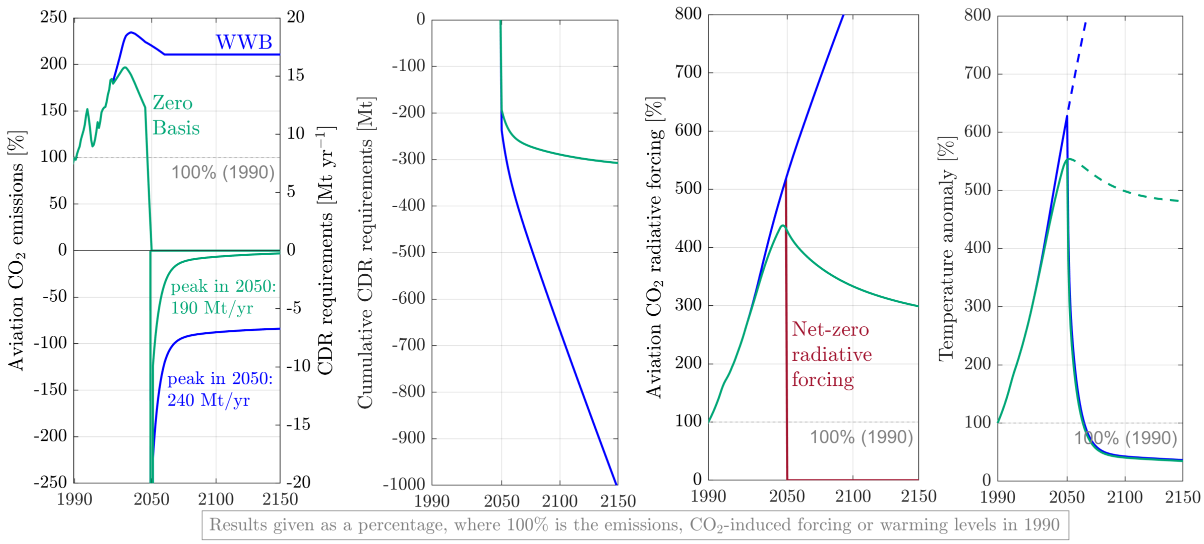


Figure 8. Come Figure 29, ma per un Obiettivo 2 di forzante radiativo netto zero. Raggiungere un forzante netto zero nel 2050, iniziando a implementare CDR dallo stesso anno di obiettivo, porta a un picco di 240 Mt/anno per lo scenario WWB e 190 Mt/anno per lo scenario ZeroBasis. Considerando solo l'impatto climatico del CO_2 dell'aviazione e compensando con CDR per il suo forcing risultante, il contributo al riscaldamento del settore viene eliminato a lungo termine.

- Il KlG punta a un obiettivo netto-zero entro il 2050, considerando le emissioni di CO_2 ma trascurando gli altri agenti climatici non-CO_2.
- Per l'aviazione svizzera, gli scenari emissivi WWB e ZeroBasis mostrano differenze significative. Infatti, lo scenario ZeroBasis assume l'uso al 100% di carburanti sostenibili per l'aviazione (SAFs) carbon-neutral a partire dal 2050, ignorando il fatto che la produzione di SAF avrà comunque un'impronta di carbonio non trascurabile, come dimostrato dalla recente letteratura scientifica pertinente.
- I due punti precedenti evidenziano che sia le disposizioni del KlG sia gli scenari di emissione considerati rendono difficile ottenere requisiti di CDR significativi dal punto di vista dell'impatto climatico e comparabili tra loro.
- Questo studio dimostra che, anche sotto le ipotesi delineate, il raggiungimento degli Obiettivi 1 e 2 comporta requisiti di CDR molto elevati.
- Anche nel caso dell'aviazione, un'implementazione precoce del CDR riduce i picchi e i requisiti cumulativi di CDR. Tuttavia, sembra che raggiungere livelli di CDR praticabili richieda due tipi di misure oltre alla compensazione tramite CDR: (i) una significativa riduzione delle emissioni rispetto allo scenario ZeroBasis, che implicherebbe una diminuzione del traffico aereo a causa di una riduzione della domanda, e (ii) l'attuazione di misure per aumentare l'efficienza climatica dell'aviazione, attraverso una gestione ottimizzata dei singoli voli sotto tutti gli aspetti possibili.

La sfida

24. Raggiungere nel 2050 emissioni nette pari a zero (Obiettivo 1) o forzante radiativa nulla (Obiettivo 2) per l'agricoltura svizzera nello scenario ZeroBasis tramite l'implementazione di CDR a partire dal 2050 è possibile, a condizione che vengano generate quantità sufficientemente grandi di CDR. A seconda dell'approccio utilizzato, metriche GWP o modelli GWP* e LWE, le quantità di CDR stimate differiscono, in particolare nel lungo termine. La risposta termica associata a qualsiasi scenario di emissioni e strategia di implementazione del CDR deve considerare l'effetto di tutti i forzanti climatici

rilevanti, ossia metano, protossido di azoto e anidride carbonica, e deve essere calcolata utilizzando un modello climatico; approcci diversi per calcolare il fabbisogno di CDR portano a risposte termiche differenti. L'SLCM utilizzato in questo studio offre un compromesso tra semplicità e accuratezza nella previsione degli impatti climatici, rivelandosi utile per valutare comparativamente l'effetto di diverse politiche climatiche.

25. Per raggiungere emissioni nette pari a zero per l'aviazione svizzera dal 2050 nello scenario ZeroBasis, in linea di principio, non è richiesto alcun CDR se si considerano solo le emissioni di CO_2, si escludono gli effetti non-CO_2 e si assumono SAF con un'impronta di carbonio pari a zero. In pratica, tuttavia, l'SLCM prevede un'anomalia di temperatura diverse volte superiore a quella del 1990 in queste condizioni. Quando si includono gli effetti non-CO_2, il tasso massimo di implementazione di CDR necessario nel 2050 e il CDR cumulativo richiesto durante il secolo raggiungono livelli che da oggi sembrano difficilmente realizzabili.

26. I requisiti di CDR determinati in questo studio rappresentano una sfida imponente sia per scala sia per velocità di implementazione. Tali requisiti, mantenendo gli stessi obiettivi climatici, possono essere ridotti solo (i) avviando immediatamente l'implementazione di CDR invece che nel 2050, (ii) scegliendo percorsi per le emissioni residue più ambiziosi rispetto allo scenario ZeroBasis, e (iii) adottando cambiamenti strutturali, inclusa la riduzione della domanda e misure specifiche per settore, la cui considerazione e discussione sono al di fuori dell'ambito di questo studio.

Zusammenfassung

Der Umfang

1. Diese Studie wurde vor der Genehmigung und nach der Verabschiedung des Schweizer Klima- und Innovationsgesetzes (KlG, Juni 2023) in Auftrag gegeben und abgeschlossen, d.h. unter Berücksichtigung der Implikationen für die Klimapolitik.

2. Das Ziel der Studie ist es, mit besonderer Berücksichtigung der Klimawirkungen der Schweizer Landwirtschafts- und Luftfahrtsektoren, die folgenden beiden Fragen zu beantworten:

   - Welche wissenschaftlich fundierten Rahmenwerke sind geeignet, um die Emissionen von Nicht-CO_2-Klimafaktoren bei der Entwicklung von Klimapolitikstrategien und der Wirkungsbewertung zu berücksichtigen?
   - Wie hoch sind die entsprechenden Mengen an CO_2-Entfernungen (CDR), die erforderlich sind, um den Anforderungen des KlG, Art.3, zu entsprechen, unter Berücksichtigung der relevanten Emissionsminderungswege, insbesondere der langfristigen Klimastrategie, die auf den Energieperspektiven 2050+ basiert?

3. Der allgemeine Ansatz zur Beantwortung dieser Fragen basiert in dieser Studie auf der Nutzung eines vereinfachten Klimamodells, das sowohl (i) die Klimawirkung von gegebenen Emissionen von Nicht-CO_2-Klimafaktoren berechnen kann als auch (ii) die entsprechenden Mengen an CDR zurückberechnen kann, die erforderlich sind, um ihre Auswirkungen zu kompensieren.

Der Kontext

4. Der Klimawandel und die globale Erwärmung sind die Folge des Anstiegs des Strahlungsantriebs, der durch Klimatreiber (CFs) in der Atmosphäre verursacht wird, d. h. CO_2, nicht-CO_2 Treibhausgase (THGs, z. B. CH_4, N_2O, NOx, SOx, Wasserdampf) und andere Stoffe (Aerosole, Ruß, Zirruswolken).

5. Die atmosphärische Konzentration von Klimatreibern ist eine Folge (i) der ausgestoßenen Menge oder, im Fall von Zirruswolken, der durch anthropogene Aktivitäten gebildeten Menge und (ii) ihrer atmosphärischen Abbaurate (bedingt durch atmosphärische Physik und Chemie). Der durch die CFs verursachte Klimaeinfluss ergibt sich aus der Strahlungseffizienz jedes einzelnen Treibers (bedingt durch die atmosphärische Physik) und dem kombinierten Effekt der Strahlungseinflüsse aller Treiber auf die planetaren Energiebilanzen und damit auf die globale Erwärmung (bedingt durch die Physik der Erde).

6. Der Klimaeinfluss eines Klimatreibers ist größer, (i) je größer seine Emissionen, (ii) je langsamer sein Abbau oder (iii) je höher seine Strahlungseffizienz ist. CO_2 ist der einzige Klimatreiber, der auf den betrachteten Zeitskalen nicht abgebaut wird; sein Klimaeinfluss hängt daher von seinen kumulativen Emissionen ab.

7. Während die Lebensdauern von Klimatreibern von Tagen bis zu Jahrhunderten variieren, beträgt die Zeitskala globaler thermischer Anpassungen (Temperaturanomalie in wissenschaftlichen Begriffen, globale Erwärmung im allgemeinen Sprachgebrauch) mehrere Jahrzehnte bis Jahrhunderte. Das Klima der Erde reagiert daher mit hoher Trägheit auf Veränderungen des Strahlungsantriebs.

8. In einer *politikrelevanten, aber nicht politikvorschreibenden* Sprache kommt der Weltklimarat (IPCC) zu dem Schluss, dass: "Das Erreichen von Netto-Null-CO_2- oder THG-Emissionen erfordert in erster Linie tiefe und schnelle Reduzierungen der Bruttoemissionen von CO_2 sowie substanzielle Reduzierungen der nicht-CO_2-THG-Emissionen (hohe Sicherheit). ... Einige schwer reduzierbare verbleibende THG-Emissionen (z. B. einige Emissionen aus der Landwirtschaft, dem Luftverkehr, der Schifffahrt und

industriellen Prozessen) bleiben jedoch bestehen und müssten durch den Einsatz von Technologien zur Entfernung von Kohlendioxid (CDR) kompensiert werden, um Netto-Null-CO_2- oder THG-Emissionen zu erreichen (hohe Sicherheit). Daher wird Netto-Null-CO_2 früher erreicht als Netto-Null-THGs (hohe Sicherheit).” (AR6, Synthesebericht, SPM, B6.2, mit Bezug auf Abbildung SPM.5)

9. Artikel 3 des Schweizer Klima- und Innovationsgesetzes (KlG), d. h. das *Bundesgesetz über Klimaziele, Innovation und Stärkung der Energiesicherheit*, besagt: (1) ”Der Bund sorgt dafür, dass die Wirkung der in der Schweiz anfallenden von Menschen verursachten Treibhausgasemissionen bis zum Jahr 2050 Null beträgt (Netto-Null-Ziel), indem: (a) die Treibhausgasemissionen so weit möglich vermindert werden; und (b) die Wirkung der verbleibenden Treibhausgasemissionen durch die Anwendung von Negativemissionstechnologien in der Schweiz und im Ausland ausgeglichen wird. (2) Nach dem Jahr 2050 muss die durch die Anwendung von Negativemissionstechnologien entfernte und gespeicherte Menge an CO_2 die verbleibenden Treibhausgasemissionen übertreffen.”[3]

10. Der IPCC-Bericht zur 6. Bewertung bietet umfassende Informationen auf globaler Ebene, einschließlich detaillierter Szenarien für die Reduzierung von CO_2 und anderen Treibhausgasen, die erforderlich sind, um die Erwärmung auf bestimmte Werte zu begrenzen, unterstützt durch eine robuste Emissionsszenariodatenbank. Diese globalen Daten lassen sich jedoch nicht direkt in nationale Ziele übersetzen. Stattdessen führt das Schweizer KlG ein nationales Netto-Null-Ziel ein und legt mehrere Zwischenziele fest, aus denen indirekt Emissionsminderungspfade abgeleitet werden können.
    Artikel 3.1b des KlG schreibt vor, dass verbleibende Emissionen durch negative Emissionstechnologien adressiert werden müssen, um Netto-Null-Wirkung zu erreichen, deren Menge durch die Bewertung des Klimaeffekts oder der Auswirkungen dieser Restemissionen bestimmt wird. Dieser Bericht identifiziert zwei mögliche Interpretationen des Begriffs ”Wirkung” in diesem Kontext, nämlich: (1) Netto-Null-Restemissionen bis 2050 (Ziel 1) zu erreichen, oder (2) bis 2050 eine Null-Rest-Strahlungswirkung (Ziel 2) zu erreichen. Die Definition und Wahl des Ziels ist eine politische Entscheidung. In dieser Arbeit bewerten wir die Klimaauswirkungen und den Bedarf an Kohlendioxid-Entfernung (CDR) in Verbindung mit diesen Klimazielen, wenn CDR entweder (i) erst ab 2050 oder (ii) bereits ab diesem Jahrzehnt eingesetzt wird.

11. In diesem Zusammenhang wurden Emissionen nicht-CO_2 CFs in äquivalente CO_2-Emissionen umgerechnet, indem Äquivalenzmetriken verwendet wurden. Die GWP_{20}- oder GWP_{100}-Metriken (GWP = Global Warming Potential), die letztere im Rahmen des Pariser Abkommens verwendet, legen eine Proportionalität fest, die dafür bekannt ist, den Klimaeinfluss von CFs über einen Zeitraum von 20 oder 100 Jahren zu unterschätzen und danach zu überschätzen. Um diese unerwünschten Nachteile einfacher GWP-Metriken zu kompensieren, wurde der GWP*-Ansatz vorgeschlagen, der keine Metrik, sondern ein Modell ist und in nationalen Inventaren nicht verwendet wird.

Das Klimamodell

12. Einfache Klimamodelle, wie das Benchmark-Modell FaIR (Finite Amplitude Impulse Response model), können den global gemittelten Pfad Emission → Konzentration → Strahlungsantrieb → Temperaturreaktion simulieren und sind durch Parametrisierungen so abgestimmt, dass sie die Erdsystemmodelle (ESMs) nachbilden, die dreidimensional, rasterbasiert und explizit in der Darstellung dynamischer und physikalischer Prozesse sind.

[3]”(1) Der Bund sorgt dafür, dass die Wirkung der in der Schweiz anfallenden von Menschen verursachten Treibhausgasemissionen bis zum Jahr 2050 Null beträgt (Netto-Null-Ziel), indem: (a) die Treibhausgasemissionen so weit möglich vermindert werden; und (b) die Wirkung der verbleibenden Treibhausgasemissionen durch die Anwendung von Negativemissionstechnologien in der Schweiz und im Ausland ausgeglichen wird. (2) Nach dem Jahr 2050 muss die durch die Anwendung von Negativemissionstechnologien entfernte und gespeicherte Menge an CO_2 die verbleibenden Treibhausgasemissionen übertreffen.”

13. Das in dieser Arbeit entwickelte und verwendete Vereinfachte Lineare Klimamodell (SLCM) ist im Vergleich zu FaIR vereinfacht und darauf kalibriert; die wichtigsten Annahmen sind (i), dass der Strahlungsantrieb jedes CFs nur von seiner Konzentration abhängt, und (ii), dass die Emissionen eines bestimmten Landes oder Sektors als Störungen der globalen Entwicklung der Treibhausgasemissionen behandelt werden, sodass die erhaltenen Ergebnisse unabhängig von der Hintergrundzusammensetzung der Atmosphäre sind. Das SLCM findet ein Gleichgewicht zwischen Einfachheit und Effektivität und ist daher ein nützliches Werkzeug, um Klimatrends, die durch verschiedene Emissionsszenarien und Klimastrategien verursacht werden, zu untersuchen und vergleichend zu bewerten.

14. Das SLCM kann für die folgenden drei Aufgaben verwendet werden:

    - Bestimmung des Klimaeffekts (Strahlungsantrieb und Temperaturreaktion) eines gegebenen historischen und zukünftigen Emissionsprofils von einem oder mehreren CFs.
    - Bestimmung der benötigten CO_2-Entfernungsraten im Laufe der Zeit, um ein unvermeidliches Emissionsprofil eines nicht-CO_2-CFs zu kompensieren. Diese Berechnung erfolgt über den Ansatz des Linearen Erwärmungsäquivalents (LWE), der im Rahmen des SLCM und unter den zugehörigen Annahmen ein explizites Ergebnis liefert; dieser Ansatz ermöglicht auch die Neuberechnung der benötigten CDR-Mengen zu jedem Zeitpunkt, z.B. jährlich oder in bestimmten Zeitabständen, während der Durchführung eines ausgewählten CDR-Pfads.
    - Rückberechnung des gesamten Strahlungsantriebsprofils, das einem vorgegebenen Erwärmungsszenario entspricht (z.B. Aufrechterhaltung einer konstanten Temperaturanomalie). Dies ist dank der Linearität des SLCM-Rahmens möglich. Das resultierende Strahlungsantriebsprofil kann in Emissionsprofile für verschiedene Treibhausgase übersetzt werden, indem Zuweisungsquoten festgelegt werden. Die Festlegung dieser Zuweisungen erfordert sozioökonomische und politische Überlegungen, die nicht Gegenstand dieser Arbeit sind.

Das Netto-Null-Ziel

15. Die Klimawirkungen der Landwirtschaft werden durch Methan, CH_4 (etwa zwei Drittel, kurzlebig) und Distickstoffoxid, N_2O (etwa ein Drittel, langlebig) verursacht, wobei beide eine ähnliche Strahlungseffizienz aufweisen; beachten Sie, dass in der Schweizer Emissionsinventur CO_2-Emissionen aus der Landwirtschaft größtenteils anderen Sektoren zugeordnet werden.

16. Die Klimawirkungen der Luftfahrt ergeben sich aus CO_2, nicht-CO_2-Treibhausgasen (GHGs) und anderen Klimatreibern (in nicht vernachlässigbaren Anteilen, die sich über die Zeit ändern können). Die Klimawirkung einiger dieser Klimatreiber, z. B. Zirruswolken, ist sowohl räumlich als auch zeitlich schwer zu mitteln, weshalb solche Wirkungen nur empirisch in einfachen Klimamodellen parametrisiert werden können und, falls erforderlich, einer Sensitivitätsanalyse unterzogen werden.

17. In dieser Studie werden die Klimawirkungen, d. h. Strahlungsantrieb und Temperaturreaktion durch ein gegebenes Emissionsszenario, mit oder ohne CDR, unter Verwendung des SLCM mit auf FaIR kalibrierten Parametern berechnet. Eine Sensitivitätsanalyse, die die Unsicherheit der in FaIR verwendeten Parameter (meist $\pm 20\%$) berücksichtigt, liegt außerhalb des Umfangs dieser Arbeit. Gesamtemissionen von GHGs aus den Bereichen Landwirtschaft und Luftfahrt basieren auf den Business-as-usual (WWB)- und ZeroBasis-Szenarien aus EP2050+ [4]. Zusätzliche Details zu den Szenarien und zur Datenerhebung finden Sie in der Technischen Zusammenfassung und im Technischen Bericht. Die CDR-Anforderungen werden berechnet, um netto-null Restemissionen bis 2050 für die Landwirtschaft und den Luftfahrtsektor zu gewährleisten (Ziel 1) oder netto-null Strahlungsantrieb aus den Emissionen der Landwirtschaft und des Luftfahrtsektors (Ziel 2). Netto-null Strahlungsantrieb wird hier mit Bezug auf die Strahlungsantriebsniveaus zu Beginn der nachweisbaren anthropogenen Landwirtschaftsemissionen, d. h. das Jahr 1690, definiert. Die CDR-Anforderungen für Ziel 1 werden mittels der

Äquivalenzmetriken GWP_{20} und GWP_{100} sowie der Modelle GWP* und LWE berechnet. Die CDR-Anforderungen zur Erreichung von Ziel 2 können nur mit dem LWE-Modell berechnet werden (siehe Technische Zusammenfassung für weitere Details).

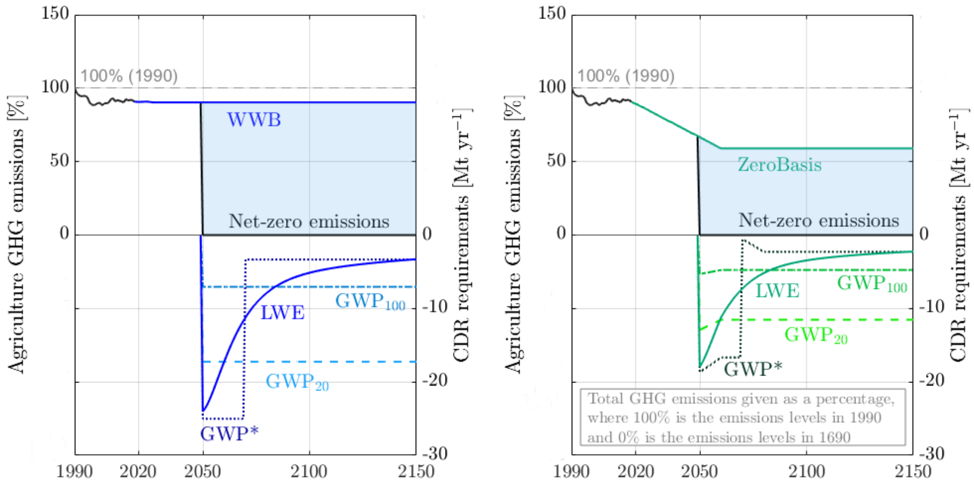
18. Ohne den Einsatz von CDR würden WWB-Emissionen (Business-as-usual) und ZeroBasis-Emissionen (aus dem EP2050+-Datensatz der BfE Energieperspektiven) in der Schweizer Landwirtschaft zu einer langfristigen Temperaturreaktion führen, die 100% bzw. 30% höher ist als 1990.

19. Beim Einsatz von CDR zur Erreichung der Ziele nach KlG für die Schweizer Landwirtschaft führen sowohl das Ziel netto-null Emissionen (Ziel 1) als auch netto-null Strahlungsantrieb (Ziel 2) zu ähnlichen Strahlungsantriebs- und Temperaturreaktionen, wobei die CDR-Anforderungen im letzteren Fall wesentlich höher sind als im ersten.

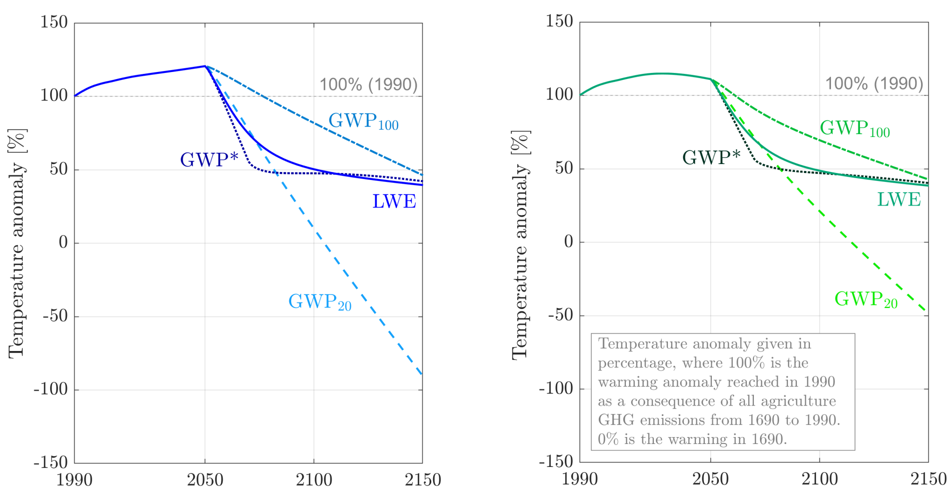
20. Ohne den Einsatz von CDR würden WWB-Emissionen der Schweizer Luftfahrt im Laufe der Zeit zu einem größeren Erwärmungsbeitrag führen, was auf den kumulativen Effekt von CO_2 zurückzuführen ist. ZeroBasis-Emissionen, die ab 2050 den 100%-Einsatz von CO_2-freien nachhaltigen Flugkraftstoffen (SAFs) voraussetzen, würden ohne CDR-Einsatz zu einem langfristigen Erwärmungsbeitrag führen, der etwa dreimal größer ist als 1990.

21. Beim Einsatz von CDR zur Umsetzung des KlG für die Schweizer Luftfahrt führt die Zielsetzung netto-null Emissionen (Ziel 1) zu einem höheren Erwärmungsbeitrag als das Ziel netto-null Strahlungsantrieb (Ziel 2), was auf den wesentlich größeren Beitrag durch CO_2-Emissionen zurückzuführen ist.

22. Bezüglich der Schweizer Landwirtschaft und der damit verbundenen CDR-Anforderungen zur Erfüllung der Ziele 1 und 2:



(a) Gesamte WWB (links) und ZeroBasis (rechts) Treibhausgasemissionen aus dem Schweizer Landwirtschaftssektor, zusammen mit einem hypothetischen Emissionsminderungsweg, der darauf abzielt, bis 2050 netto-null Emissionen zu erreichen (graue Linie). Die Emissionen werden als Prozentsatz der Emissionen von 1990 dargestellt, um den Vergleich zu erleichtern. Der hellblaue Bereich hebt die Emissionslücke zwischen den Gesamtemissionen und dem Reduktionsziel hervor, was die Anforderungen an die CO_2-Entfernung (CDR) darstellt. Die rechte vertikale Achse quantifiziert die erforderliche CDR (als negative Zahl dargestellt), um die verbleibenden Emissionen von CO_2, CH_4 und N_2O auszugleichen. Methan und Distickstoffoxid werden mit verschiedenen Äquivalenzmetriken und Modellen in CO_2-Äquivalente umgerechnet: GWP_{20}, GWP_{100}, GWP* und LWE.



(b) Temperaturabweichung (Figure 22b) verursacht durch die Emissionen der Schweizer Landwirtschaft, ausgedrückt als Prozentsatz der Erwärmung, die 1990 beobachtet wurde. Die Abweichung wird für Szenarien berechnet, in denen CDR eingesetzt wird, um ab 2050 netto-null Emissionen zu erreichen, unter Verwendung der Äquivalenzansätze GWP_{100}, GWP_{20}, GWP* und LWE.

Figure 9. Netto-null Emissionen (Ziel 1) im Schweizer Landwirtschaftssektor.

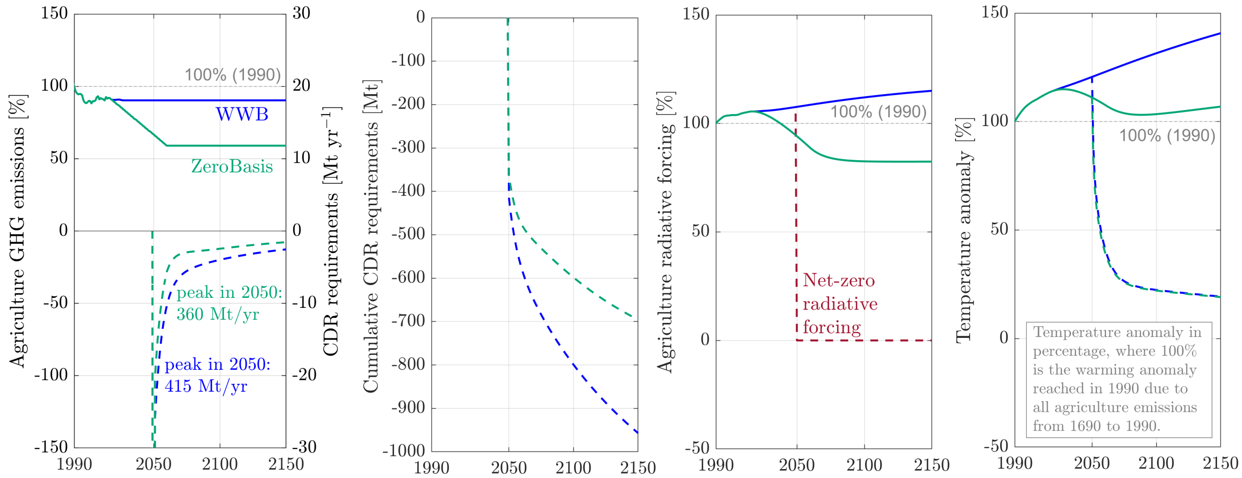


Figure 10. Netto-null radiative forcing (Ziel 2) im Schweizer Landwirtschaftssektor. Die vier Panels zeigen: (i) Landwirtschaftsemissionen als Prozentsatz (erstes Panel, linke vertikale Achse), wobei 100% den Emissionen von 1990 entsprechen und 0% dem Beginn der anthropogenen Landwirtschaftsemissionen im Jahr 1690; (ii) CDR-Anforderungen in Mt/Jahr (erstes Panel, rechte vertikale Achse), wobei die CDR-Raten mit dem LWE-Ansatz als negative Werte dargestellt sind; (iii) kumulative CDR-Anforderungen, um das Ziel des netto-null radiative forcing für die WWB- und ZeroBasis-Szenarien zu erreichen; (iv) radiative forcing für die WWB- und ZeroBasis-Szenarien sowie die netto-null radiative forcing-Trajektorie ab 2050 (drittes Panel), wobei 100% dem Niveau von 1990 und 0% dem Jahr 1690 entspricht; und (v) Temperaturabweichung für die WWB- und ZeroBasis-Szenarien, mit und ohne CDR (viertes Panel), wobei 100% dem Niveau von 1990 und 0% dem Jahr 1690 entspricht. Die gestrichelten Linien stellen die Entwicklungen von radiative forcing und Temperaturabweichung mit CDR-Umsetzung dar.

- Unter allen Annahmen und für alle hier betrachteten Szenarien spielen sowohl Methan (kurzlebig) als auch Distickstoffoxid (langlebig) eine wichtige Rolle bei der Bestimmung der Klimawirkung der Schweizer Landwirtschaft; keines von beiden kann vernachlässigt werden.
- Sowohl netto-null Emissionen (Ziel 1) als auch netto-null Strahlungsantrieb (Ziel 2) können für die WWB- und die ZeroBasis-Emissionsszenarien erreicht werden, mit ähnlichen langfristigen Temperaturreaktionen. Dies geschieht durch den Einsatz entsprechender Mengen an CDR ab 2050, die für Ziel 2 wesentlich größer sind als für Ziel 1 und etwa 50% höher für das WWB-Szenario im Vergleich zum ZeroBasis-Szenario.
- Wie erwartet, unterschätzen und überschätzen die auf GWP basierenden CO_2-Äquivalenzmetriken die CDR-Nachfrage im Vergleich zu den Vorhersagen mit den Modellen CDR* und LWE kurz- bzw. langfristig. Zu diesem Schluss kam man, indem die mit den vier Ansätzen berechneten CDR-Mengen in das SLCM eingegeben und dann die entsprechenden Klimawirkungen berechnet wurden. Selbst wenn die absoluten Werte von den Annahmen des SLCM beeinflusst werden, ist die vergleichende Bewertung verschiedener Emissionsszenarien und CDR-Strategien hinsichtlich ihrer Klimawirkungen robuster gegenüber den Modellannahmen.
- Die Verwendung des SLCM bietet Einblicke, welche Maßnahmen die CDR-Nachfrage reduzieren können, während die Klimaziele weiterhin erfüllt werden. Beispiele umfassen (i) den frühzeitigen Beginn des CDR-Einsatzes statt bis 2050 zu warten, (ii) die Vorverlegung des Einsatzes und die Reduzierung des CDR-Spitzenwerts, den GWP* und LWE um 2050 herum erfordern, und (iii) die Rückberechnung der CDR, die erforderlich ist, um ein bestimmtes Temperaturreaktionsprofil einzuhalten (dies ist eine neue Funktion, die vom SLCM bereitgestellt wird).

23. Was die Schweizer Luftfahrt und der damit verbundenen CDR-Anforderungen zur Erfüllung der Ziele 1 und 2:

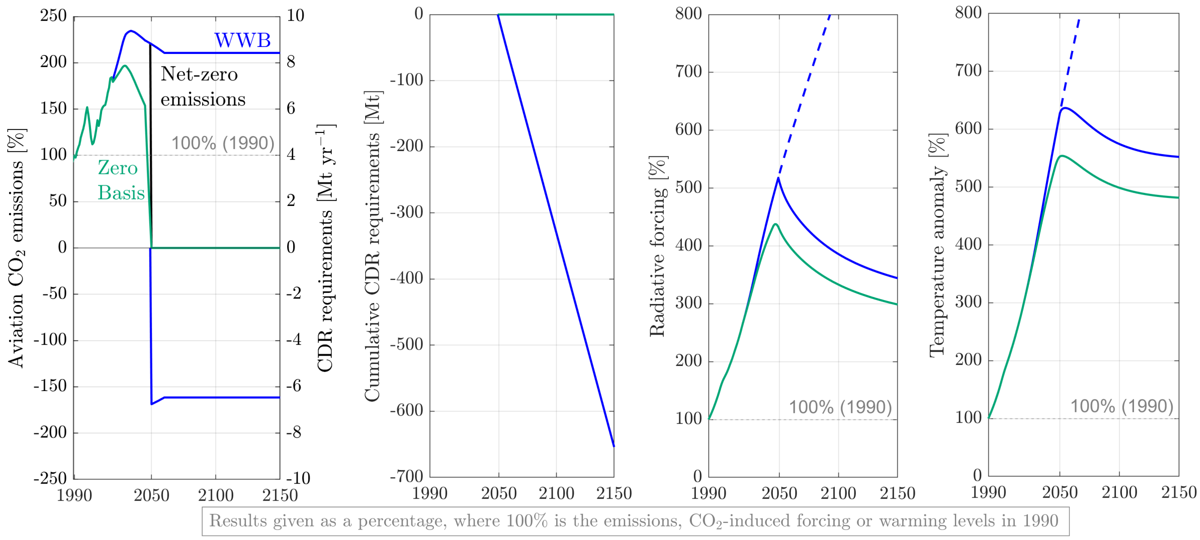


Figure 11. Netto-null Emissionen (Ziel 1) im Schweizer Luftfahrtsektor. Die vier Panels zeigen von links nach rechts: (i) die Emissionen in Prozent (erstes Panel, linke vertikale Achse), wobei 100% dem Emissionsniveau von 1990 entsprechen und 0% dem Niveau zu Beginn der anthropogenen Luftfahrtemissionen, d. h. dem Jahr 1950; (ii) im gleichen ersten Panel die CDR-Anforderungen in Mt/Jahr (rechte vertikale Achse des ersten Panels), wobei CDR-Raten als negative Werte dargestellt werden, im Gegensatz zu den Emissionen, die positive Werte haben; (iii) die kumulierten CDR-Anforderungen, die erforderlich sind, um das Ziel der Netto-null CO_2-Emissionen zu erreichen, wenn die Restemissionen entweder dem WWB- oder ZeroBasis-Szenario folgen (zweites Panel); (iv) das zugehörige radiative forcing für die WWB- und ZeroBasis-Szenarien mit und ohne CDR (drittes Panel), wenn nur die Klimaauswirkungen der CO_2-Emissionen berücksichtigt werden (100% entspricht dem entsprechenden CO_2-induzierten Niveau von 1990 und 0% dem Niveau von 1950); (iv) die zugehörige Temperaturabweichung für die WWB- und ZeroBasis-Szenarien mit und ohne CDR (viertes Panel), wenn nur die CO_2-induzierte Erwärmung berücksichtigt wird (100% entspricht dem entsprechenden CO_2-induzierten Niveau von 1990 und 0% dem Niveau von 1950). Die Radiative forcing- und Temperaturabweichungskurven ohne CDR-Umsetzung sind durch gestrichelte Linien dargestellt. Das Erreichen von Netto-null CO_2-Emissionen im Jahr 2050, bei dem CDR nur ab diesem Zieljahr eingesetzt wird, führt zu einem Spitzenwert von 7 Mt/Jahr für das WWB-Szenario, wobei der CDR-Einsatz für den ZeroBasis-Weg (100% SAF-Nutzung) null ist. Wenn nur die Klimaauswirkungen von Luftfahrt-CO_2 berücksichtigt werden und diese Emissionen mit CDR kompensiert werden, ist der langfristige Erwärmungsbeitrag des Sektors etwa fünfmal so hoch wie im Jahr 1990.

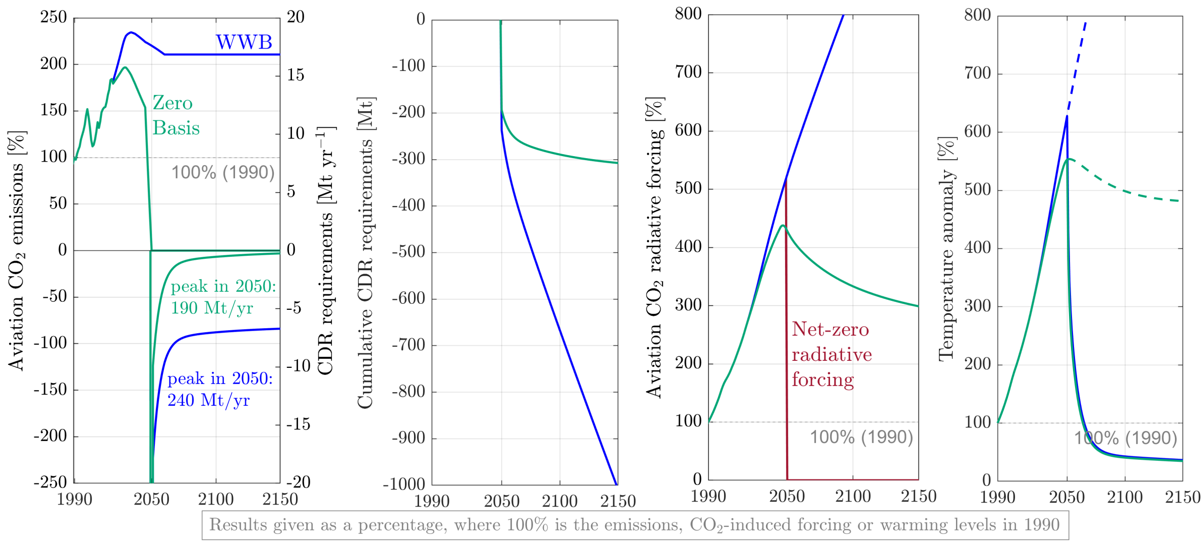


Figure 12. Wie Figure 29, jedoch für ein Ziel 2 von netto-null radiative forcing. Das Erreichen von netto-null radiative forcing im Jahr 2050, bei dem CDR nur ab diesem Zieljahr eingesetzt wird, führt zu einem Spitzenwert von 240 Mt/Jahr für das WWB-Szenario und 190 Mt/Jahr für das ZeroBasis-Szenario. Wenn nur die Klimaauswirkungen von Luftfahrt-CO_2 berücksichtigt werden und diese mit CDR kompensiert werden, wird der langfristige Erwärmungsbeitrag des Sektors vollständig beseitigt.

- Das KlG strebt ein Netto-Null-Ziel für 2050 an, wobei CO_2 berücksichtigt, andere nicht-CO_2-Klimafaktoren jedoch vernachlässigt werden.
- Für die Schweizer Luftfahrt zeigen die WWB- und ZeroBasis-Emissionsszenarien deutliche Unterschiede. Tatsächlich geht das ZeroBasis-Szenario davon aus, dass ab 2050 100% kohlenstoffneutrale nachhaltige Flugkraftstoffe (SAFs) eingesetzt werden, wobei übersehen wird, dass die Produktion von SAFs dennoch einen nicht unerheblichen CO_2-Fußabdruck hinterlassen wird, wie in der aktuellen, relevanten wissenschaftlichen Literatur nachgewiesen.
- Die beiden vorherigen Punkte verdeutlichen, dass sowohl die Bestimmungen des KlG als auch die betrachteten Emissionsszenarien es erschweren, CDR-Anforderungen zu ermitteln, die aus klimawirksamer Sicht sinnvoll und vergleichbar sind.
- Diese Studie zeigt, dass selbst unter den beschriebenen Annahmen die Erfüllung von Ziel 1 und Ziel 2 zu sehr hohen CDR-Anforderungen führt.
- Auch im Fall der Luftfahrt reduziert ein frühzeitiger Einsatz von CDR die Spitzen- und die kumulativen CDR-Anforderungen. Es scheint jedoch, dass das Erreichen praktikabler CDR-Niveaus zwei weitere Maßnahmen erfordert, die über die Kompensation durch den CDR-Einsatz hinausgehen: (i) eine signifikante Reduzierung der Emissionen im Vergleich zum ZeroBasis-Szenario, was eine Verringerung des Flugverkehrs aufgrund einer sinkenden Nachfrage implizieren würde, und (ii) die Implementierung von Maßnahmen zur Steigerung der Klimaeffizienz der Luftfahrt durch eine optimierte Steuerung der einzelnen Flüge aus allen möglichen Perspektiven.

Die Herausforderung

24. Das Erreichen entweder von Netto-Null-Emissionen (Ziel 1) oder von null Strahlungsantrieb (Ziel 2) im Jahr 2050 für die Schweizer Landwirtschaft im ZeroBasis-Szenario durch den Einsatz von CDR ab 2050 ist machbar, vorausgesetzt, es werden ausreichend große Mengen an CDR generiert. Abhängig von der verwendeten Methode, GWP-Metriken oder GWP*- und LWE-Modellen, unterscheiden sich die geschätzten CDR-Mengen, insbesondere langfristig. Die tatsächliche Temperaturreaktion

im Zusammenhang mit einem beliebigen Emissionsszenario und einer beliebigen CDR-Strategie muss die Wirkung aller relevanten Klimafaktoren berücksichtigen, d.h. Methan, Lachgas und Kohlendioxid, und muss mit einem Klimamodell berechnet werden; unterschiedliche Ansätze zur Berechnung des CDR-Bedarfs führen zu unterschiedlichen Temperaturreaktionen. Das in dieser Studie verwendete SLCM bietet einen Kompromiss zwischen Einfachheit und Genauigkeit bei der Vorhersage der Klimawirkungen, was sich als nützlich für die vergleichende Bewertung verschiedener Klimapolitiken erweist.

25. Um Netto-Null-Emissionen für die Schweizer Luftfahrt ab 2050 im ZeroBasis-Szenario zu erreichen, ist theoretisch kein CDR erforderlich, wenn nur CO_2-Emissionen berücksichtigt, nicht-CO_2-Effekte ausgeschlossen und SAFs mit einem kohlenstofffreien Fußabdruck angenommen werden. Praktisch jedoch sagt das SLCM unter diesen Bedingungen eine Temperaturanomalie voraus, die um ein Mehrfaches größer ist als 1990. Wenn nicht-CO_2-Effekte einbezogen werden, erreichen die erforderliche Spitzen-CDR-Rate im Jahr 2050 und der kumulative CDR-Bedarf im Laufe des Jahrhunderts Niveaus, die aus heutiger Sicht wahrscheinlich nicht realisierbar sind.

26. Die in dieser Studie ermittelten CDR-Anforderungen stellen eine enorme Herausforderung sowohl hinsichtlich des Umfangs als auch der Geschwindigkeit der Implementierung dar. Solche Anforderungen können bei gleichbleibenden Klimazielen nur reduziert werden, (i) indem die CDR-Implementierung sofort und nicht erst 2050 beginnt, (ii) indem ambitioniertere Pfade für die Restemissionen als ZeroBasis gewählt werden, und (iii) durch Durchsetzung struktureller Veränderungen, einschließlich einer Reduzierung der Nachfrage und sektorenspezifischer Maßnahmen, deren Berücksichtigung und Diskussion jedoch über den Rahmen dieser Studie hinausgehen.

Résumé Exécutif

Le cadre

1. Cette étude a été commandée avant et achevée après l'approbation de la loi suisse sur le climat et l'innovation (KlG, juin 2023), c'est-à-dire la *Loi fédérale sur les objectifs de protection du climat, l'innovation et le renforcement de la sécurité énergétique*, en tenant compte de ses implications pour la politique climatique.

2. L'objectif de l'étude est, en prenant en compte spécifiquement les impacts climatiques des secteurs agricoles et de l'aviation suisses, de répondre aux deux questions suivantes:

   - Quels sont, du point de vue scientifique, les cadres appropriés pour prendre en compte les émissions des forçages climatiques non-CO_2 lorsqu'on vise des stratégies de politique climatique et l'évaluation des impacts?
   - Quelles sont les quantités correspondantes de retrait de dioxyde de carbone (CDR) nécessaires pour se conformer à la KlG, Art.3, en tenant compte des trajectoires de réduction des émissions pertinentes, à savoir la stratégie climatique à long terme fondée sur les Perspectives énergétiques 2050+?

3. L'approche générale pour aborder ces questions dans cette étude repose sur l'utilisation d'un modèle climatique simplifié qui permet à la fois (i) de calculer l'impact climatique des émissions données de forçages climatiques non-CO_2, et (ii) de calculer rétroactivement les quantités correspondantes de CDR nécessaires pour annuler leurs effets.

Le contexte

4. Le changement climatique et le réchauffement climatique sont la conséquence de l'augmentation du forçage radiatif causée par les agents climatiques (CFs) dans l'atmosphère, c'est-à-dire le CO_2, les gaz à effet de serre autres que le CO_2 (GES, par exemple CH_4, N_2O, NOx, SOx, vapeur d'eau) et d'autres substances (aérosols, carbone noir, nuages cirrus).

5. L'abondance atmosphérique des agents climatiques est une conséquence (i) de la quantité émise ou, dans le cas des nuages cirrus, de la quantité formée en raison des activités anthropiques, et (ii) de leur taux de dégradation atmosphérique (déterminé par la physique et la chimie atmosphériques). L'impact climatique des CFs est dû à l'efficacité radiative de chaque agent (déterminée par la physique atmosphérique) et à l'effet combiné du forçage radiatif de tous les CFs sur les bilans énergétiques planétaires et donc sur le réchauffement global (déterminé par la physique terrestre).

6. L'impact climatique d'un agent climatique est plus important (i) plus ses émissions sont élevées, (ii) plus sa dégradation est lente, ou (iii) plus son efficacité radiative est élevée. Le CO_2 est le seul agent climatique qui ne se dégrade pas à l'échelle des temps considérés; son impact climatique dépend donc de ses émissions cumulées.

7. Bien que la durée de vie des agents climatiques varie de quelques jours à plusieurs siècles, l'échelle temporelle des ajustements thermiques globaux (anomalie de température en termes scientifiques, réchauffement climatique dans le langage courant) s'étend sur plusieurs décennies à des siècles. Le climat terrestre présente donc une grande inertie face aux changements de forçage radiatif.

8. Dans un langage *pertinent pour les politiques mais non prescriptif*, le Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC) conclut que : "Pour atteindre un niveau net zéro d'émissions de CO_2 ou de GES, il faut principalement des réductions profondes et rapides des émissions brutes de CO_2, ainsi que des réductions substantielles des émissions de GES non-CO_2 (niveau de confiance élevé).

... Cependant, certaines émissions résiduelles difficiles à réduire (par exemple, certaines émissions provenant de l'agriculture, de l'aviation, de la navigation et des procédés industriels) subsisteront et devront être compensées par le déploiement de méthodes d'élimination du dioxyde de carbone (CDR) pour atteindre un niveau net zéro d'émissions de CO_2 ou de GES (niveau de confiance élevé). Par conséquent, le niveau net zéro pour le CO_2 est atteint plus tôt que celui pour les GES (niveau de confiance élevé)." (AR6, Rapport de synthèse, SPM, B6.2, avec référence à la figure SPM.5)

9. L'article 3 de la loi suisse sur le climat et l'innovation (KlG), c'est-à-dire la *Loi fédérale sur les objectifs climatiques, l'innovation et le renforcement de la sécurité énergétique*, stipule : (1) "La Confédération veille à ce que l'impact des émissions de gaz à effet de serre anthropiques en Suisse soit nul d'ici 2050 (objectif net zéro), en : (a) réduisant autant que possible les émissions de gaz à effet de serre ; et (b) compensant l'impact des émissions de gaz à effet de serre résiduelles par l'utilisation de technologies d'émissions négatives en Suisse et à l'étranger. (2) Après 2050, la quantité de CO_2 éliminée et stockée grâce à l'application de technologies d'émissions négatives doit dépasser les émissions résiduelles de gaz à effet de serre."[4]

10. Le rapport du GIEC pour le 6ème cycle d'évaluation offre des informations globales complètes, y compris des scénarios détaillés de réduction de CO_2 et d'autres gaz à effet de serre nécessaires pour limiter le réchauffement à des niveaux spécifiques, soutenus par une base de données robuste de scénarios d'émissions. Cependant, ces données globales ne se traduisent pas directement en objectifs nationaux. Au lieu de cela, la KlG suisse introduit un objectif net zéro national et fixe plusieurs objectifs intermédiaires à partir desquels on peut déduire indirectement des trajectoires de réduction des émissions.
    L'article 3.1b de la KlG prescrit que toute émission résiduelle doit être abordée à l'aide de technologies d'émissions négatives pour atteindre une "Wirkung" nette zéro, dont la quantité est obtenue en évaluant l'effet climatique ou l'impact de ces émissions résiduelles. Ce rapport identifie deux interprétations possibles du terme "Wirkung" dans ce contexte, à savoir : (1) atteindre zéro émission résiduelle nette d'ici 2050 (Objectif 1), ou (2) parvenir à une forçage radiatif résiduel nul d'ici 2050 (Objectif 2). La définition et le choix de l'objectif sont une décision politique. Dans ce travail, nous évaluons l'impact climatique et les besoins en élimination de dioxyde de carbone (CDR) associés à ces objectifs climatiques, lorsque la CDR commence soit (i) seulement à partir de 2050, soit (ii) dès cette décennie.

11. Dans ce contexte, les émissions des CFs non-CO_2 ont été traduites en émissions équivalentes de CO_2 en utilisant des métriques d'équivalence. Les métriques GWP_{20} ou GWP_{100} (GWP = potentiel de réchauffement global), cette dernière étant utilisée dans le cadre de l'Accord de Paris, établissent une proportionnalité connue pour sous-estimer l'impact climatique des CFs sur un horizon de 20 ans ou de 100 ans, respectivement, et pour le surestimer par la suite. Pour compenser ces lacunes indésirables des métriques GWP simples, l'approche GWP* a été proposée, qui n'est pas une métrique mais plutôt un modèle et n'est pas utilisée dans les inventaires nationaux.

L'outil de modélisation climatique

12. Les modèles climatiques simples, comme le modèle de référence FaIR (Finite Amplitude Impulse Response model), sont capables de simuler le cheminement global moyen des émissions → concentration → forçage radiatif → réponse en température et sont ajustés par des paramétrisations pour imiter les modèles du système terrestre (ESMs), qui sont tridimensionnels, maillés et explicites dans la représentation des processus dynamiques et physiques.

[4]"(1) La Confédération veille à ce que l'impact des émissions de gaz à effet de serre anthropiques en Suisse soit nul d'ici 2050 (objectif net zéro), en : (a) réduisant autant que possible les émissions de gaz à effet de serre ; et (b) compensant l'impact des émissions résiduelles de gaz à effet de serre par l'utilisation de technologies d'émissions négatives en Suisse et à l'étranger. (2) Après 2050, la quantité de CO_2 éliminée et stockée grâce à l'application de technologies d'émissions négatives doit dépasser les émissions résiduelles de gaz à effet de serre."

13. Le Modèle Climatique Linéaire Simplifié (SLCM) développé et utilisé dans ce travail est simplifié par rapport à FaIR et calibré sur celui-ci ; les principales hypothèses sont (i) que le forçage radiatif de chaque CF ne dépend que de son abondance, et (ii) que les émissions d'un pays ou d'un secteur spécifique sont traitées comme des perturbations de l'évolution globale des émissions de GES, de sorte que les résultats obtenus sont indépendants de la composition atmosphérique de fond. Le SLCM établit un équilibre entre simplicité et efficacité, ce qui en fait un outil utile pour explorer et évaluer comparativement les tendances climatiques causées par différents scénarios d'émissions et stratégies climatiques.

14. Le SLCM peut être utilisé pour accomplir les trois tâches suivantes :

    - Déterminer l'impact climatique (forçage radiatif et réponse en température) d'un profil d'émissions passé et futur d'un ou plusieurs CFs.
    - Déterminer les quantités de retrait de CO_2 nécessaires au fil du temps pour compenser un profil d'émissions inévitable d'un CF non-CO_2. Ce calcul est effectué via l'approche de l'équivalent de réchauffement linéaire (LWE), qui dans le cadre du SLCM et sous les hypothèses associées fournit un résultat explicite ; cette approche permet également de recalculer les quantités de CDR nécessaires à tout moment, par exemple chaque année ou à des intervalles donnés, lors de l'exécution d'une trajectoire de déploiement de CDR sélectionnée.
    - Rétro-calculer le profil global de forçage radiatif correspondant à un scénario de réchauffement spécifié (par exemple, maintenir une anomalie de température constante). Cela est possible grâce à la linéarité du cadre SLCM. Le profil de forçage radiatif résultant peut être traduit en profils d'émissions pour différents GES en attribuant des quotas. La détermination de ces allocations implique des considérations socio-économiques et politiques qui sont hors du champ de ce travail.

L'objectif de neutralité

15. Les impacts climatiques de l'agriculture sont dus au méthane, CH_4 (environ deux tiers, à courte durée de vie), et au protoxyde d'azote, N_2O (environ un tiers, à longue durée de vie), avec une efficacité radiative similaire ; notez que dans l'inventaire suisse des émissions, les émissions de CO_2 liées à l'agriculture sont en grande partie attribuées à d'autres secteurs.

16. Les impacts climatiques de l'aviation sont dus au CO_2, aux gaz à effet de serre non-CO_2 (GHG), et à d'autres forçages climatiques (dans des proportions non négligeables qui peuvent varier dans le temps). L'impact climatique de certains de ces forçages, comme les nuages cirrus, est difficile à moyenner à la fois dans l'espace et dans le temps ; par conséquent, cet impact peut uniquement être paramétré de manière empirique dans des modèles climatiques simples et soumis à une analyse de sensibilité si nécessaire.

17. Dans cette étude, les impacts climatiques, c'est-à-dire le forçage radiatif et la réponse en température causés par un scénario d'émissions donné, avec ou sans CDR, sont calculés à l'aide du SLCM avec des paramètres calibrés en utilisant FaIR. Une analyse de sensibilité prenant en compte l'incertitude des paramètres utilisés dans FaIR (principalement ±20%) dépasse le cadre de ce travail. Les émissions totales de GHG des secteurs de l'agriculture et de l'aviation sont collectées sur la base des scénarios business-as-usual (WWB) et ZeroBasis d'EP2050+ [4]. Des détails supplémentaires sur les scénarios et la collecte de données sont fournis dans le Résumé Technique et le Rapport Technique. Les exigences en matière de CDR sont calculées pour garantir des émissions résiduelles nettes nulles d'ici 2050 pour les secteurs de l'agriculture et de l'aviation respectivement (Objectif 1), ou un forçage radiatif net zéro des émissions des secteurs de l'agriculture et de l'aviation respectivement (Objectif 2). Le forçage radiatif net zéro est ici défini par rapport aux niveaux de forçage radiatif au début des émissions anthropiques agricoles détectables, c'est-à-dire l'année 1690. Les exigences en matière de CDR pour

atteindre l'Objectif 1 sont calculées au moyen des métriques d'équivalence GWP_{20} et GWP_{100}, et des modèles GWP* et LWE. Les exigences en matière de CDR pour atteindre l'Objectif 2 ne peuvent être calculées qu'avec le modèle LWE (voir Résumé Technique pour plus de détails).

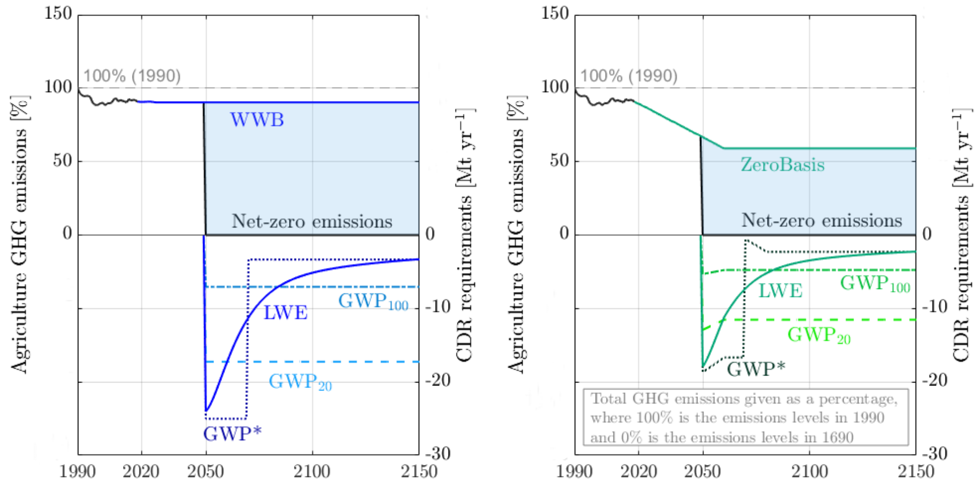
18. Sans recours à la CDR, les émissions WWB (business-as-usual) et ZeroBasis (issues du jeu de données EP2050+ des perspectives énergétiques BfE Energieperspektiven) dans l'agriculture suisse entraîneraient une réponse thermique à long terme respectivement de 100% et 30% supérieure à celle de 1990.

19. En déployant la CDR pour atteindre les objectifs définis par le KlG pour l'agriculture suisse, viser des émissions nettes nulles (Objectif 1) ou un forçage radiatif net zéro (Objectif 2) conduit à des réponses en termes de forçage radiatif et de température assez similaires, mais avec des exigences en matière de CDR bien plus élevées dans le second cas que dans le premier.

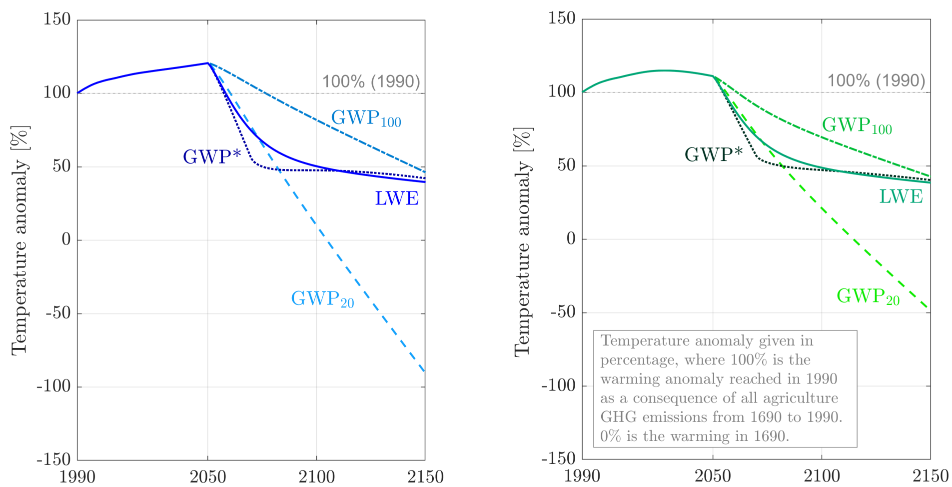
20. Pour l'aviation suisse, les émissions WWB sans recours à la CDR entraîneraient une contribution accrue au réchauffement au fil du temps en raison de l'effet cumulatif du CO_2. Les émissions ZeroBasis, bien qu'elles supposent l'utilisation à 100% de carburants d'aviation durables (SAF) sans CO_2 à partir de 2050, entraîneraient sans recours à la CDR une contribution au réchauffement à long terme environ trois fois supérieure à celle de 1990.

21. En déployant la CDR pour atteindre les objectifs définis par le KlG pour l'aviation suisse, viser des émissions nettes nulles (Objectif 1) entraîne une contribution au réchauffement plus élevée que viser un forçage radiatif net zéro (Objectif 2), en raison de la contribution beaucoup plus importante des émissions de CO_2.

22. Concernant l'agriculture suisse et les exigences en matière de CDR associées pour atteindre les Objectifs 1 et 2 :



(a) Émissions totales de GES pour les scénarios WWB (gauche) et ZeroBasis (droite) dans le secteur agricole suisse, ainsi qu'une trajectoire hypothétique de réduction des émissions visant à atteindre la neutralité carbone d'ici 2050 (ligne grise). Les émissions sont exprimées en pourcentage des niveaux de 1990 pour faciliter la comparaison. La zone bleu clair met en évidence l'écart entre les émissions totales et l'objectif de réduction, représentant les besoins en captage et stockage du dioxyde de carbone (CDR). L'axe vertical droit quantifie les besoins en CDR nécessaires (montrés comme une valeur négative) pour compenser les émissions résiduelles de CO_2, CH_4, et N_2O. Le méthane et le protoxyde d'azote sont convertis en équivalents CO_2 en utilisant différentes métriques d'équivalence et modèles : GWP_{20}, GWP_{100}, GWP* et LWE.



(b) Anomalie de température (Figure 22b) induite par les émissions agricoles suisses, exprimée en pourcentage du réchauffement observé en 1990. L'anomalie est calculée pour des scénarios où le CDR est déployé pour atteindre la neutralité carbone à partir de 2050, en utilisant les approches d'équivalence GWP_{100}, GWP_{20}, GWP*, et LWE.

Figure 13. Neutralité carbone (Objectif 1) dans le secteur agricole suisse.

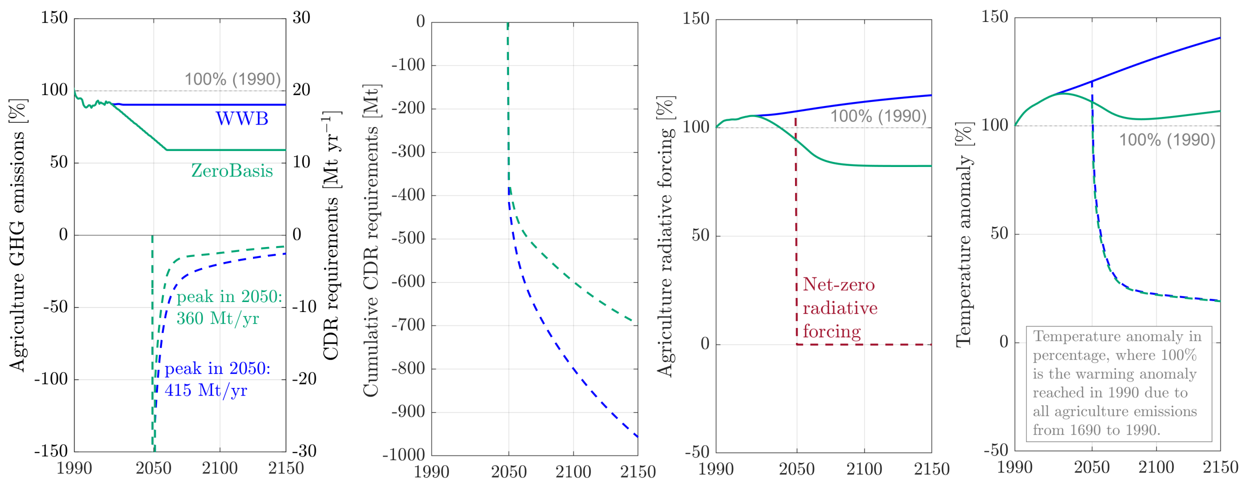


Figure 14. Forçage radiatif net nul (Objectif 2) dans le secteur agricole suisse. Les quatre panneaux montrent : (i) les émissions agricoles en pourcentage (premier panneau, axe vertical gauche), où 100% correspond aux niveaux de 1990 et 0% au début des émissions agricoles anthropiques en 1690 ; (ii) les besoins en CDR en Mt/an (premier panneau, axe vertical droit), avec des taux de CDR calculés à l'aide de l'approche LWE montrés comme des valeurs négatives ; (iii) les besoins cumulatifs en CDR pour atteindre l'objectif de forçage radiatif net nul pour les scénarios WWB et ZeroBasis ; (iv) le forçage radiatif pour les scénarios WWB et ZeroBasis et la trajectoire de forçage radiatif net nul à partir de 2050 (troisième panneau), où 100% correspond au niveau de 1990 et 0% à 1690 ; et (v) l'anomalie de température pour les scénarios WWB et ZeroBasis, avec et sans CDR (quatrième panneau), où 100% correspond au niveau de 1990 et 0% à 1690. Les lignes en pointillés représentent les évolutions du forçage radiatif et de l'anomalie de température avec la mise en œuvre du CDR.

- Sous toutes les hypothèses et pour tous les scénarios considérés ici, le méthane (à courte durée de vie) et le protoxyde d'azote (à longue durée de vie) jouent un rôle important dans la détermination de l'impact climatique de l'agriculture suisse ; aucun des deux ne peut être négligé.
- Les émissions nettes nulles (Objectif 1) et le forçage radiatif net zéro (Objectif 2) peuvent être atteints pour les scénarios d'émission WWB et ZeroBasis, avec des réponses thermiques à long terme similaires. Cela se produit grâce au déploiement de quantités correspondantes de CDR à partir de 2050, lesquelles sont bien plus importantes pour l'Objectif 2 que pour l'Objectif 1, et environ 50% plus élevées pour le scénario WWB que pour le scénario ZeroBasis.
- Comme prévu, l'utilisation des métriques d'équivalence en CO_2 basées sur le GWP sous-estime et sur-estime respectivement la demande en CDR à court terme et à long terme, par rapport aux prédictions des modèles CDR* et LWE. Cette conclusion a été atteinte en entrant les quantités de CDR calculées avec les quatre approches dans le SLCM, puis en calculant les impacts climatiques correspondants. Même si les valeurs absolues estimées sont influencées par les hypothèses du SLCM, l'évaluation comparative des différents scénarios d'émissions et des stratégies de déploiement du CDR en termes d'impact climatique est plus robuste vis-à-vis des hypothèses du modèle.
- L'utilisation du SLCM fournit un éclairage sur les mesures qui peuvent réduire la demande en CDR tout en atteignant les objectifs climatiques. Des exemples incluent (i) commencer le déploiement du CDR dès maintenant au lieu d'attendre 2050, (ii) anticiper le déploiement et réduire le pic de CDR que GWP* et LWE nécessitent autour de 2050, et (iii) calculer à rebours le CDR nécessaire pour respecter un profil spécifié de réponse thermique (c'est une fonctionnalité innovante fournie par le SLCM).

23. Concernant l'aviation suisse et les besoins associés en CDR pour atteindre les Objectifs 1 et 2:

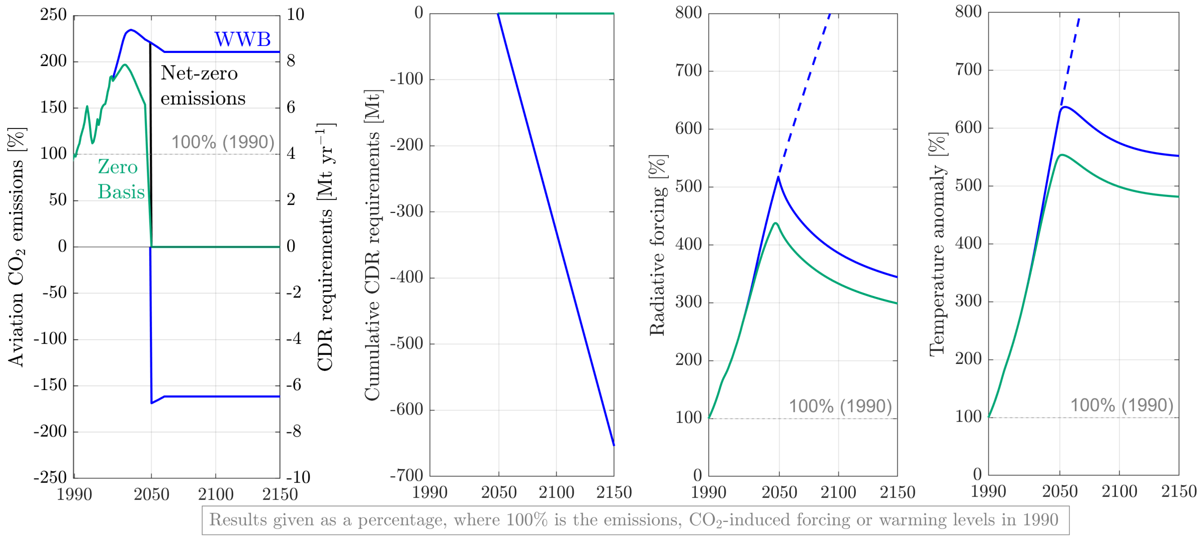


Figure 15. Neutralité carbone (Objectif 1) dans le secteur de l'aviation suisse. Les quatre panneaux montrent, de gauche à droite : (i) les émissions en pourcentage (premier panneau, axe vertical gauche), où 100% correspond au niveau des émissions en 1990, tandis que 0% représente leur niveau au début des émissions anthropiques liées à l'aviation, c'est-à-dire l'année 1950 ; (ii) dans ce même premier panneau, les besoins en CDR en Mt/an (premier panneau, axe vertical droit), où les taux de CDR sont des nombres négatifs, contrairement aux émissions qui sont positives ; (iii) les besoins cumulatifs en CDR nécessaires pour atteindre l'objectif de neutralité des émissions de CO_2 lorsque les émissions résiduelles suivent soit le scénario WWB, soit le scénario ZeroBasis (deuxième panneau) ; (iv) le forçage radiatif associé pour les scénarios WWB et ZeroBasis, avec et sans CDR (troisième panneau), lorsque seul l'impact climatique des émissions de CO_2 est pris en compte (100% correspond au niveau induit par le CO_2 en 1990, et 0% à celui de 1950) ; (iv) l'anomalie de température associée pour les scénarios WWB et ZeroBasis, avec et sans CDR (quatrième panneau), lorsque seul le réchauffement induit par le CO_2 est pris en compte (100% correspond au niveau induit par le CO_2 en 1990, et 0% à celui de 1950). Les courbes de forçage radiatif et d'anomalie de température sans mise en œuvre de CDR sont indiquées par des lignes en pointillés. Atteindre la neutralité carbone des émissions de CO_2 en 2050, tout en ne déployant le CDR qu'à partir de cette année cible, entraîne un pic de 7 Mt/an pour le scénario WWB, tandis que le déploiement de CDR est nul pour la trajectoire ZeroBasis (adoption à 100% des SAF). En ne considérant que l'impact climatique de l'aviation-CO_2 et en compensant ces émissions par le CDR, la contribution au réchauffement à long terme du secteur est environ cinq fois celle de 1990.

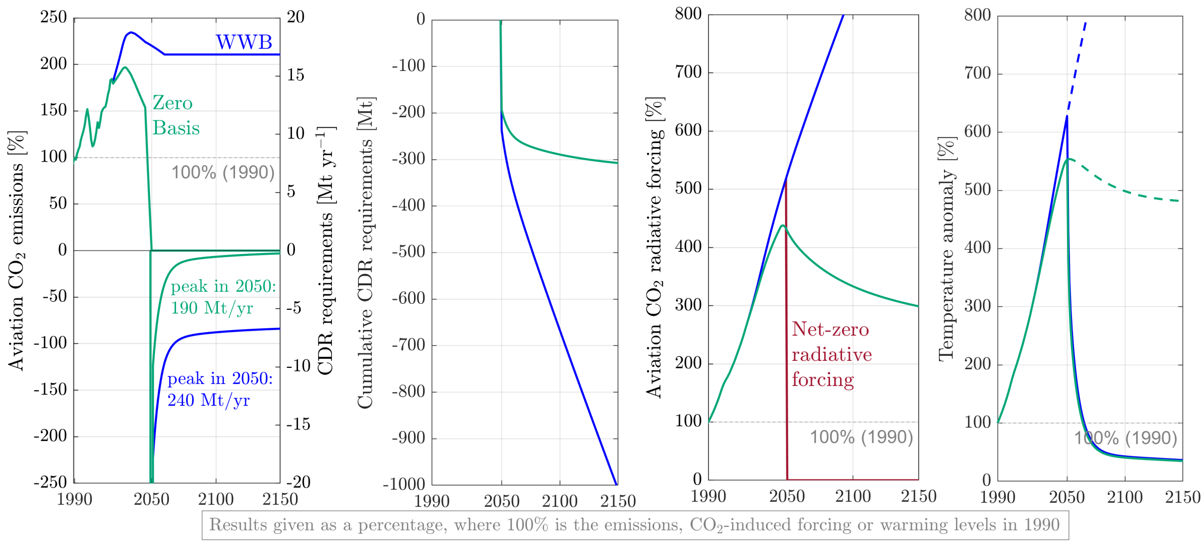


Figure 16. Comme la figure Figure 29, mais pour l'Objectif 2 de forçage radiatif net nul. Atteindre un forçage net nul en 2050, tout en ne déployant le CDR qu'à partir de cette année cible, entraîne un pic de 240 Mt/an pour le scénario WWB et de 190 Mt/an pour le scénario ZeroBasis. En ne considérant que l'impact climatique de l'aviation-CO_2 et en compensant le forçage correspondant par le CDR, la contribution au réchauffement à long terme du secteur est éliminée.

- Le KlG vise un objectif de neutralité carbone d'ici 2050, en prenant en compte le CO_2, mais en négligeant les autres forçages climatiques non liés au CO_2.
- Pour l'aviation suisse, les scénarios d'émissions WWB et ZeroBasis présentent des différences significatives. En effet, le scénario ZeroBasis suppose une utilisation à 100% de carburants d'aviation durables (SAFs) neutres en carbone à partir de 2050, tout en négligeant le fait que la production de SAFs aura toujours une empreinte carbone non négligeable, comme démontré dans la littérature scientifique récente et pertinente.
- Les deux points précédents soulignent que les dispositions du KlG et les scénarios d'émissions considérés rendent difficile l'établissement de besoins en CDR qui soient significatifs du point de vue de l'impact climatique et comparables.
- Cette étude montre que, même sous les hypothèses décrites, atteindre les Objectifs 1 et 2 entraîne des besoins en CDR très élevés.
- Dans le cas de l'aviation également, un déploiement précoce du CDR réduit le pic et les besoins cumulatifs en CDR. Cependant, il semble que pour atteindre des niveaux de CDR réalisables, deux types de mesures supplémentaires soient nécessaires au-delà de la compensation par le déploiement du CDR : (i) une réduction significative des émissions par rapport au scénario ZeroBasis, ce qui impliquerait une réduction du trafic aérien en raison d'une baisse de la demande, et (ii) la mise en œuvre de mesures visant à améliorer l'efficacité climatique de l'aviation, grâce à une gestion optimisée des vols individuels sous tous les angles possibles.

Le défi

24. Atteindre en 2050 des émissions nettes nulles (Objectif 1) ou un forçage radiatif nul (Objectif 2) pour l'agriculture suisse dans le scénario ZeroBasis, grâce au déploiement de CDR à partir de 2050, est faisable, à condition de générer des quantités suffisamment importantes de CDR. Selon la méthode utilisée, métriques GWP ou modèles GWP* et LWE, les quantités de CDR estimées diffèrent, notamment à long terme. La réponse thermique associée à tout scénario d'émissions et à toute stratégie de déploiement

de CDR doit prendre en compte l'effet de tous les forçages climatiques pertinents, c'est-à-dire le méthane, l'oxyde nitreux et le dioxyde de carbone, et doit être calculée à l'aide d'un modèle climatique ; différentes approches pour calculer la demande en CDR conduisent à des réponses thermiques différentes. Le SLCM utilisé dans cette étude offre un compromis entre simplicité et précision dans la prédiction des impacts climatiques, ce qui s'avère utile pour évaluer comparativement l'effet de différentes politiques climatiques.

25. Pour atteindre des émissions nettes nulles pour l'aviation suisse à partir de 2050 dans le scénario ZeroBasis, en principe, aucun CDR n'est requis si seules les émissions de CO_2 sont prises en compte, les effets non liés au CO_2 sont exclus, et des SAF avec une empreinte carbone nulle sont supposés. En pratique, cependant, le SLCM prévoit une anomalie de température plusieurs fois supérieure à celle de 1990 dans ces conditions. Lorsque les effets non liés au CO_2 sont inclus, le taux maximal de déploiement de CDR requis en 2050 et le CDR cumulatif nécessaire au cours du siècle atteignent des niveaux qui, du point de vue actuel, semblent irréalisables.

26. Les exigences en matière de CDR déterminées dans cette étude représentent un défi colossal, tant en termes d'échelle que de vitesse de déploiement. Ces exigences, tout en conservant les mêmes objectifs climatiques, ne peuvent être réduites que (i) en lançant immédiatement le déploiement de CDR au lieu d'attendre 2050, (ii) en choisissant des trajectoires pour les émissions résiduelles plus ambitieuses que le scénario ZeroBasis, et (iii) en mettant en œuvre des changements structurels, notamment la réduction de la demande et des mesures spécifiques à chaque secteur, dont la prise en compte et la discussion dépassent le cadre de cette étude.

Technical Summary

The scope

1. This study has been commissioned before and completed after the approval of the Swiss Klima- und Innovationsgesetz (KlG, June 2023), i.e., the *Federal Act on Climate Protection Targets, Innovation and Strengthening Energy Security*, hence with its implications for climate policy in mind.

2. The goal of the study is, with specific consideration of the climate impacts of the Swiss agriculture and aviation sectors, to answer the following two questions:

   - What are, from a scientific point of view, possible appropriate frameworks to account for the emissions of non-CO_2 climate forcers when aiming at climate impact assessment?
   - What are the corresponding amounts of Carbon Dioxide Removals (CDR) required to comply with the KlG, Art.3, taking into consideration the relevant emission reduction pathways, namely the long-term climate strategy building on the Energy Perspectives 2050+?

3. This study's approach to address these questions is based on the use of climate models, including a simplified one especially utilized for comparative purposes, to allow both (i) calculating the climate response of given emissions of non-CO_2 climate forcers, and (ii) back-calculating the corresponding amounts of CDR required to undo their effects.

The context of this study

4. Climate change and global warming are a direct consequence of anthropogenic activities emitting climate forcers (CF) in the atmosphere, which are then responsible for the increase in the Earth's radiative forcing.

5. Example of such climate forcers are: CO_2, non-CO_2 greenhouse gases (GHGs, e.g., CH_4, N_2O, NO_x, SO_x, water vapor), and other agents (aerosols, black carbon and cirrus clouds - cirrus clouds are not emitted but formed due to flights). Depending on the rate of their atmospheric decay, these climate forcers can be classified as short-lived climate forcers (SLCFs) or long-lived climate forcers (LLCFs). However, CO_2, while being emitted into the atmosphere, is partitioned also into the oceans and the biosphere; the decay of its concentration in the atmosphere is extremely slow hence its effect can be assumed to be cumulative.

6. To strengthen the global response to the threat of climate change the Paris Agreement set the goal to "limit the increase in the global average temperature to well below 2°C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5°C above pre-industrial levels." One of its crucial provisions is in Article 4: "To achieve this temperature goal, Parties aim to reach global peaking of greenhouse gas emissions (GHGs) as soon as possible, recognizing peaking will take longer for developing country Parties, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of GHGs in the second half of the century".[1]

7. In a *policy-relevant but not policy-prescriptive* language, the Intergovernmental Panel on Climate Change (IPCC) concludes that "Reaching net zero CO_2 or GHG emissions primarily requires deep and rapid reductions in gross emissions of CO_2, as well as substantial reductions of non-CO_2 GHG emissions (high confidence). . . . However, some hard-to-abate residual GHG emissions (e.g., some emissions from agriculture, aviation, shipping, and industrial processes) remain and would need to be counterbalanced by deployment of carbon dioxide removal (CDR) methods to achieve net zero CO_2 or GHG emissions (high confidence). As a result, net zero CO_2 is reached earlier than net zero GHGs (high confidence)." (AR6, Synthesis Report, SPM, B6.2, with reference to Figure SPM.5)

8. In compliance with the Paris Agreement, the Swiss government has adopted a long-term climate strategy in 2021 setting a net-zero greenhouse gas emission target by 2050; the Klima- und Innovationsgesetz (KlG, approved in June 2023) translates this net zero target into national law. Article 3 of the KlG, i.e., the *Federal Act on Climate Protection Targets, Innovation and Strengthening Energy Security*, states that: (1) "Der Bund sorgt dafür, dass die Wirkung der in der Schweiz anfallenden von Menschen verursachten Treibhausgasemissionen bis zum Jahr 2050 Null beträgt (Netto-Null-Ziel), indem: (a) die Treibhausgasemissionen so weit möglich vermindert werden; und (b) die Wirkung der verbleibenden Treibhausgasemissionen durch die Anwendung von Negativemissionstechnologien in der Schweiz und im Ausland ausgeglichen wird. (2) Nach dem Jahr 2050 muss die durch die Anwendung von Negativemissionstechnologien entfernte und gespeicherte Menge an CO_2 die verbleibenden Treibhausgasemissionen übertreffen." [5]

9. Therefore, Article 3.1b of the KlG prescribes that any remaining residual emissions must be addressed using negative emissions technologies in order to achieve net-zero "Wirkung," which translates into the climate effect or impact, of these residual emissions. This report identifies two possible interpretations of the term "Wirkung" in this context, namely, (1) achieving net-zero residual emissions by 2050 (Target 1), or (2) attaining zero residual radiative forcing by 2050 (Target 2). The definition and decision of the target is a political decision. In this work, we assess the climate impact and carbon dioxide removal (CDR) requirements associated with these climate targets, (i) when CDR is started from 2050, (ii) or already from this decade.

10. The CDR requirements needed to fulfill Target 1 may be calculated by means of multiple approaches (e.g., the Global Warming Potential metric, GWP, or the Linear Warming Equivalent model, LWE), while CDR requirements for Target 2 can only be calculated by means of the LWE model. It is worth noting that fulfilling one or the other target leads to a different climate outcome regarding radiative forcing and temperature response, also depending on the selected equivalence approach for non-CO_2 emissions.

11. The long-term climate strategy of Switzerland lays out scenarios to reach the *net-zero* target by primarily reducing GHG emissions in all sectors. Despite these GHG emissions reductions, there will remain hard-to-abate emissions from the production of cement and chemicals, and from waste treatment that can be captured with Carbon Capture and Storage (CCS), and hard-to-avoid effects from agriculture and aviation that need to be undone by implementing Carbon Dioxide Removal (CDR) measures.

12. The Energy Perspectives 2050+ (EP2050+) estimated a total demand, in 2050, of about 12 Mio tCO_2-eq of hard-to-abate emissions that have to be addressed by CCS and CDR. This includes a demand of ca. 5 Mio tCO_2-eq from the agricultural sector, which has been calculated from the conversion of non-CO_2 emissions, namely methane and nitrous oxide, using the GWP_{100} metric. There is no CDR demand for the international aviation sector, because the EP2050+ assume complete transition to the use of Sustainable Aviation Fuels (SAFs) before 2050.

13. The scope of this study is to develop a scientifically appropriate, simple, and versatile modeling framework with which to assess the long-term temperature response associated with different projected emissions pathways. This modeling framework can also be used to back-calculate the Carbon Dioxide Removal (CDR) requirements needed to compensate exactly for the radiative forcing caused by the emissions of residual non-CO_2 climate forcers. After briefly presenting the framework and the assumptions in the next section ("The climate modeling tool"), we employ it to assess the long-term

[5] "(1) The Confederation shall ensure that the impact of man-made greenhouse gas emissions in Switzerland is zero by 2050 (net zero target) by: (a) greenhouse gas emissions are reduced as far as possible; and (b) the effect of remaining greenhouse gas emissions is offset through the use of negative emission technologies in Switzerland and abroad. (2) After 2050, the amount of CO_2 removed and stored through the application of negative emission technologies must exceed the remaining greenhouse gas emissions. [Translated with DeepL.com (free version)]"

climate impact and CDR requirements for the Swiss agriculture and aviation sectors, as to the Klima und Innovationsgesetz (KlG law).

The climate modeling tool

14. In this work, we have identified a minimum level of structural complexity in climate models with the aim of creating a simplified, linear, and easily tunable modeling tool that we call the Simplified Linear Climate Model (SLCM). The SLCM is simplified with respect to Simple Climate Models (SCMs), e.g., the FaIR model[2] and MAGICC (*Model for the Assessment of Greenhouse Gas Induced Climate Change*). SCMs are able to simulate the globally averaged emission → concentration → radiative forcing → temperature response pathway. Their model parameters are tuned to emulate the Earth System Models (ESMs), which are three dimensional, gridded, and explicit in describing physico-chemical processes. As with all climate models, the SLCM presented here is designed to analyze the climate effects of different pollutants, emissions scenarios, and policies, its advantage being that of an even greater simplicity of structure and ease of use. A schematic of this modeling tool, and of the equations involved, is presented in Figure 17. The model proposed here determines the climate impacts of climate forcers over a specified time span by following a chain of causality inspired by earlier literature and by more complex models[3].

15. Both ESMs and SCMs have the ambition to produce quantitative projections of future climate, based on different meaningful emission scenarios, and on historical data. The results of both are subject to significant uncertainties due to the intrinsic complexity of the Earth's system and to the assumptions and approximations implicitly made when modeling it.

16. In the SLCM, each climate forcer (both CO_2 and non-CO_2), changes its concentration $c_i(t)$ due to emissions of that forcer in the atmosphere, $E_i(t)$. Besides, non-CO_2 climate forcers, such as methane (CH_4) and nitrous oxide (N_2O), are assumed to decay in the atmosphere following first-order kinetics, with a characteristic decay time, τ_i, assumed to be independent of the atmosphere's composition (left branch of the scheme in Figure 17). For instance, the decay times of CH_4 and N_2O are about 10 and about 110 years, respectively. Instead, CO_2 does not decay but is exchanged among various Earth compartments that are assumed to be well-mixed. They are typically four, namely: atmosphere (where emissions occur), shallow ocean, deep ocean, and biota, i.e., all living organisms that uptake CO_2 from the atmosphere. Exchanges between compartments are governed by linear driving forces. Therefore, the resulting model equations consist of a system of four first-order ordinary differential equations, whose solution depends on four characteristic times, i.e., the reciprocals of the four eigenvalues of the matrix of coefficients $\bar{\bar{A}}$, one of which is zero because CO_2 is conserved in the system (right branch of the scheme in Figure 17). Easy to memorize, approximate values of the four characteristic times are, in decreasing order, ∞, 400, 40, and 4 years; the dimensionless parameters a_i in the formula, that gives the CO_2 concentration in the atmosphere as a function of the emissions, are all about 0.25 (their sum must be one).

17. In the SLCM, rather than following the global evolution of GHG emissions, concentrations, related radiative forcing, and thermal response, we focus on the impact of a small subset of the global emissions, e.g., that of a specific country, or that of a sector of a country's economy. If the fraction of global emissions considered is small enough, we can apply a perturbation approach that allows for model linearization and further simplifications. To this aim, we decompose the total emissions of a climate forcer i into two components: emissions from the specific emitter ($E_{i,\mathrm{s}}(t)$, where s stands for "specific") and global emissions ($E_{i,\mathrm{g}}(t)$, where g stands for "global"). The specific emitter's emissions are considered a differential perturbation of the global background, while global emissions are beyond the control of the specific emitter. This differential perturbation approach enables a focused analysis of specific emissions without requiring calibration based on the initial state or on the historical and

future trends of background emissions. From the specific emissions, $E_{i,s}(t)$ or $E_{c,s}(t)$, we calculate the differential concentration perturbation, $\Delta c_{i,\mathrm{s}}(t)$ or $\Delta c_{c,\mathrm{s}}(t)$, for non-$CO_2$ and for CO_2, respectively.

18. Once the differential atmospheric concentration perturbations of climate forcers are determined, the model calculates the resulting specific radiative forcing perturbation, which measures the change in energy balance due to this specific concentration perturbation. This is obtained by locally linearizing the relationship between concentration and radiative forcing (which is a monotonically increasing, convex function) while neglecting the effect of the global atmospheric composition on such relationship, namely as $\Delta F_{i,s}(t) = A_i \Delta c_{i,s}(t)$, where A_i is the derivative of the concentration-radiative forcing relationship, and is called radiative efficiency. Finally, the SLCM approximates A_i as constant within the analyzed time intervals.

19. The specific radiative forcing perturbations from all climate forcers considered are added to determine the total specific radiative forcing perturbation, $\Delta F_s(t)$ (see where the two branches meet in Figure 17). The total radiative forcing perturbation is then used to solve planetary energy balances, allowing us to compute the resulting temperature anomaly (or temperature response) and climate change attributable to the specific emissions of all climate forcers considered. Notably, if the radiative forcing $\Delta F_{i,s}(t)$ from one climate forcer i is replaced by the radiative forcing from another forcer j, where $\Delta F_{j,s}(t) = \Delta F_{i,s}(t)$, the total radiative forcing $\Delta F_s(t)$ remains unchanged. Consequently, the total resulting temperature anomaly also remains unchanged, regardless of which specific forcer contributes to the radiative forcing. This concept is expressed with reference to a generic climate forcer i and to CO_2 by the Linear Warming Equivalent equation in the central blue box of Figure 17.

20. The energy model consists of energy balances in and exchanges among three homogeneous layers, namely the first layer representing the atmosphere and the shallow ocean (with temperature anomaly T_s), and the second and the third layers representing the mid-ocean zone and the abyssal-ocean zone, with temperature anomalies T_m and T_a, respectively (see lower part of Figure 17). Heat is exchanged between these layers at a rate proportional to the corresponding driving forces, i.e., temperature differences. Hence, the model consists of three linear ordinary differential equations, whose solution gives the evolution of the global temperature over time. The key parameters in this model are the heat capacities of the layers and the heat exchange coefficients, which together govern how quickly temperatures adjust to changes in radiative forcing. When $F(t) = \Delta F_s(t)$, one can solve the energy balances to obtain the specific surface temperature anomaly perturbation, $\Delta T_s(t)$, which represents the contribution of the specific emissions considered to the deviation from a reference temperature, such as pre-industrial levels. The three eigenvalues associated with this system are real and negative; the reciprocals of the absolute values of these eigenvalues define three characteristic time constants, denoted as s_k, which govern the temperature anomaly evolution, the longest of which being almost 400 years. These timescales dictate how the system responds to perturbations in radiative forcing, which depends on the speed of heat transfer between the layers, with rapid adjustments occurring in the surface layer and slower adjustments in the deeper layers, and thus explains the inertia of the climate system.

21. The results of the simplified linear climate model (SLCM) proposed in this study are compared with the well-established Finite Amplitude Impulse Response (FAIR) simplified climate model, as illustrated in Figure 18. SLCM results are better aligned to the 50% FAIR quantile results by parametrizing indirect effects through an empirical model calibration of the radiative forcing efficiency of different polluters (A_i) within the uncertainty of the effective radiative forcing (ERF) as provided by FAIR[4]. In fact, due to the linearity of the SLCM model, the uncertainties of the ERFs are reflected on the radiative forcing efficiencies of each polluter (A_i).

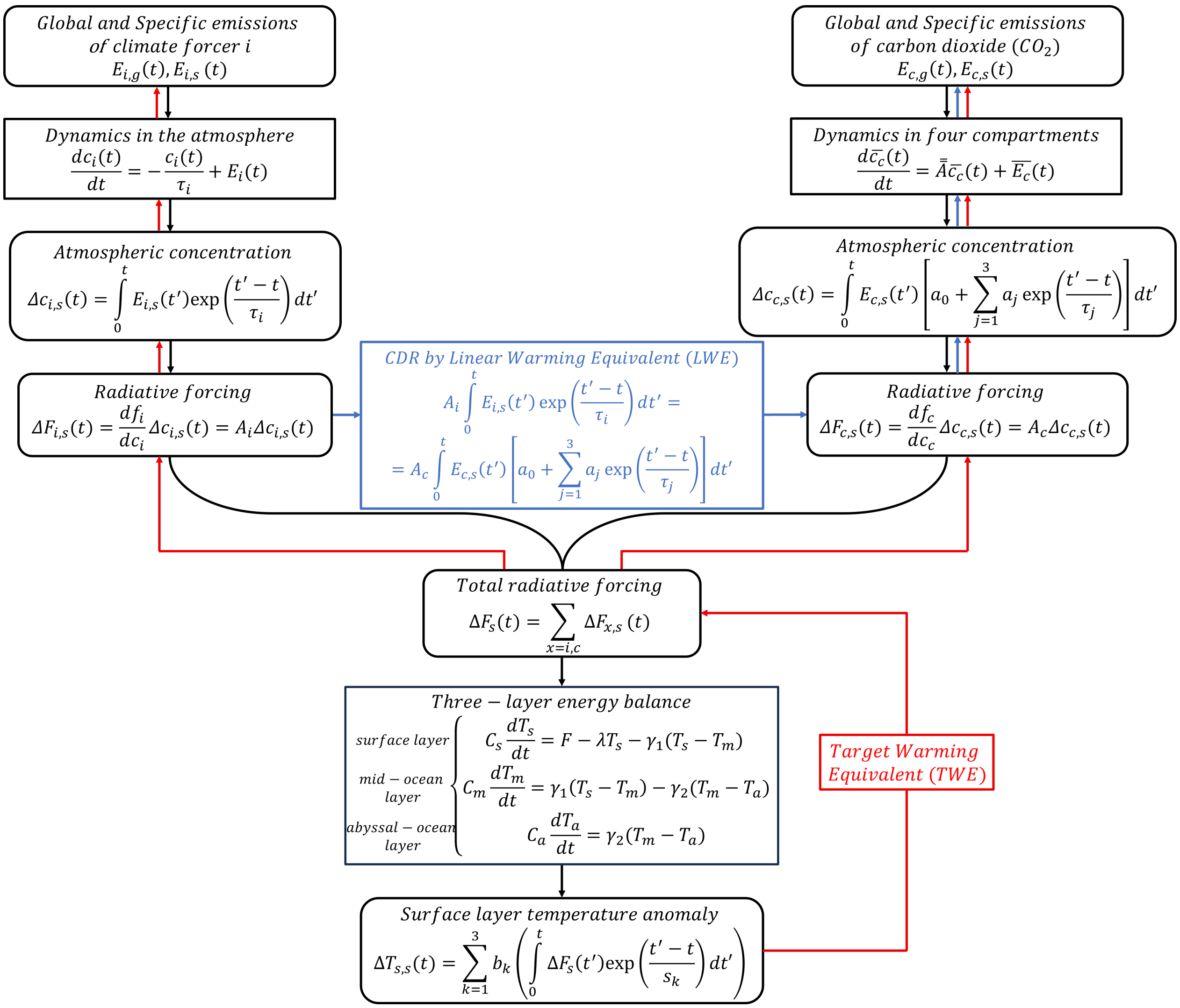
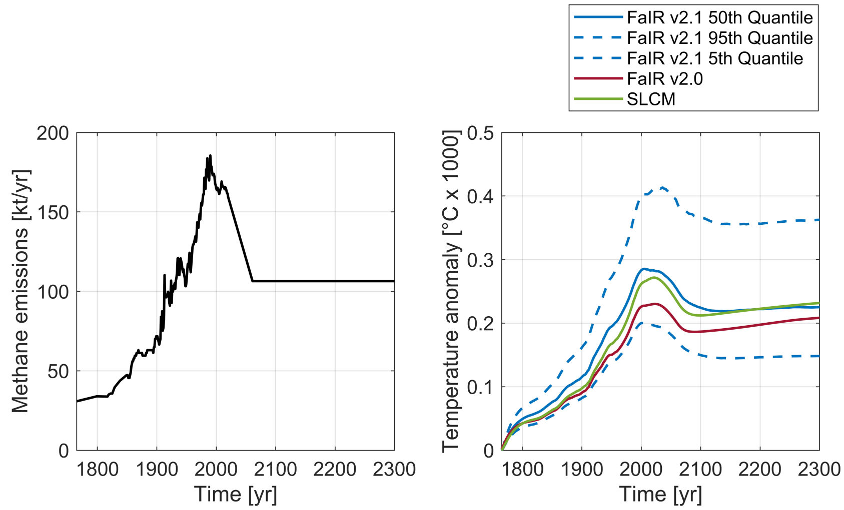
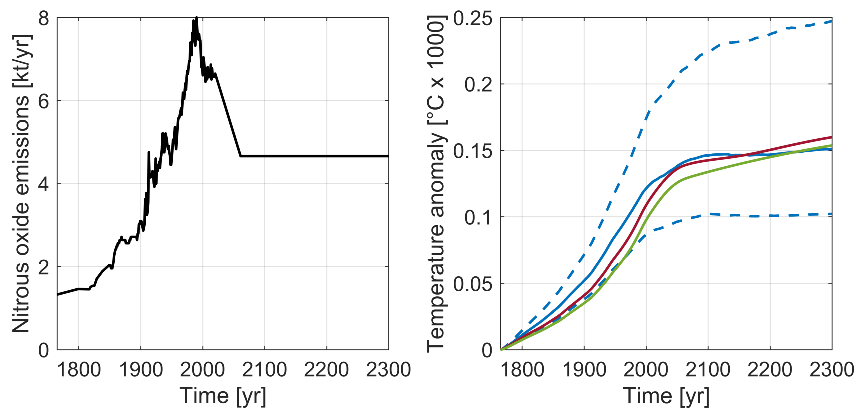


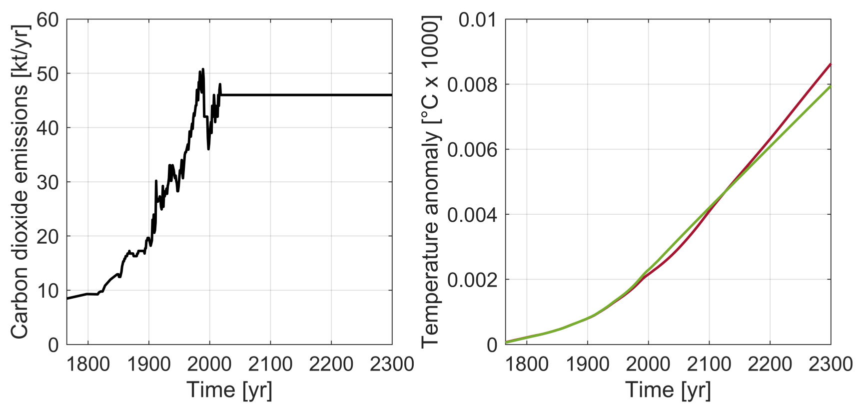
Figure 17. Visual representation of the Simplified Linear Climate Model (SLCM) following the chain of causality from emissions to radiative forcing (for non-CO_2 and CO_2 polluters), and from total radiative forcing (by means of superposition of each polluter's contribution) to total surface temperature anomaly (depicted in black). Linear Warming Equivalence (LWE, showed in blue) can be established between two different climate forcers (CFs) i or between a CF i and CO_2, to calculate explicitly the Carbon Dioxide Removal (CDR) requirements to compensate for the CF i emissions. Target Warming Equivalence (TWE, showed in red) is an additional policy-relevant tool by which a target temperature anomaly is defined and, inversely, the necessary net-emissions profiles are calculated. These net emissions profiles may be achieved through emissions reduction, CDR, or a combination of both. A more detailed description of the model is provided in Part I of the Technical Report.



(a) Methane induced warming



(b) Nitrous oxide induced warming



(c) Carbon dioxide induced warming

Figure 18. The right panels of Figure 18a, Figure 18b, and Figure 18c show the warming effects of CH_4, N_2O, and CO_2, respectively, for the specific emission profile shown in the left panels of the same figures (indicated in black). The temperature anomalies are simulated using the SLCM model (in green) and are compared with results from FaIR version 2.0 (in red) and FaIR version 2.1 (in blue). For FaIR version 2.1, the 5^{th} and 95^{th} percentiles are also shown (dashed blue lines), to highlight the uncertainty even of a climate model that is routinely used to discuss climate policies.

22. The calculation of the climate impact of any emissions scenario, for both CO_2 and non-CO_2 climate forcers, must be performed using a climate model, whereby the simplified linear climate model used in this study allows, for instance, to comparatively assess different climate scenario and emissions reduction pathways and to estimate differences in radiative forcing and temperature response among them. The prediction of the climate impact, given the emissions profile, does not involve CO_2-equivalence metrics.

23. Instead, equivalence metrics can be used for consistent comparisons among different greenhouse gases, making it possible to quantify the amount of CDR required to offset emissions from non-CO_2 GHGs, which can be neither easily reduced nor effectively removed, with removals of CO_2. Additionally, equivalence metrics are crucial in carbon budgeting, where emissions allowances are based on the potential of each GHG to contribute to global warming. By employing such metrics, the climate impacts of various GHGs can be expressed as "CO_2-equivalents," thus allowing them to be aggregated into a unified, comparable measure. This approach streamlines the planning and implementation of climate policies, ensuring that all GHG emissions are considered in a consistent manner. These approaches, including the Global Warming Potential metric (GWP) and the Linear Warming Equivalent model (LWE), provide different ways to compare the climate impacts of various GHGs over specific time horizons. Understanding these metrics is critical for accurately evaluating the relative contributions of different gases to climate change, and for formulating effective mitigation strategies that account for all relevant GHGs.

24. GWP measures the cumulative climate impact of a GHG relative to CO_2 over a specified time horizon, typically 20 or 100 years. Although widely used and easily applicable, GWP has limitations, such as the underestimation of near-term climate impacts and the overestimation of long-term ones. GWP* is an improved model addressing some of these limitations by accounting for both the stock and flow effects of GHG emissions. However, GWP* still has some inaccuracies, particularly with abrupt changes in emissions, i.e., both the amounts actually emitted and the rate of change of such amounts. Additionally, the parameters in GWP* are typically calibrated for methane. To better represent nitrous oxide emissions, we recalibrated these parameters, improving the accuracy of GWP* when describing long-lived climate forcers. Further details are provided in the technical report. Lastly, the LWE equivalence model offers a more precise method by equating the warming effects of different GHGs to CO_2, ensuring exact equivalence in temperature outcomes, in a context where the same assumptions are applied to both climate forcers. This model is particularly useful for designing carbon removal strategies to offset specific GHG emissions.

25. An additional tool of the SLCM proposed in this study, which allows to back-calculate the climate forcers' emissions driving a specific climate effect, is what we call the Target Warming Equivalent (TWE) approach. The linearity of the model allows the users (e.g., policy makers) to define a target temperature anomaly profile (e.g., peak temperature and/or long-term warming effect) and then back-calculate from that the net-emissions profiles necessary to achieve that specific climate impact. These net-emissions profiles may be achieved through emissions reduction, CO_2 removal and storage, or a combination of both.

26. The modeling instruments presented in this study are employed to assess the climate impact of different climate forcers. The following considerations on the impact of the greenhouse gas lifetime are worth making. The atmospheric concentration, and therefore radiative forcing, stabilize at different levels for non-CO_2 climate forcers that are emitted at the same constant rate but have different lifetimes. The steady- state concentration is that at which the emission rate equals the rate of decay, which is lower for shorter-lived climate forcers. Moreover, such steady-state concentration, hence forcing, is attained sooner or later the shorter or the longer the lifetime of the climate forcer. Conversely, for any rate of ongoing emissions, CO_2 reaches neither a steady state concentration nor a steady state radiative forcing as it accumulates in the atmosphere. Additionally, the larger the radiative forcing efficiency (A_i) of the polluter, the greater its potential to negatively impact the climate.

27. Aviation contributes to climate change through emissions of CO_2 and of short-lived GHGs such as NO_x, SO_2, black carbon (BC) and water vapour (H_2O).[5] The understanding of these non-CO_2 impacts has advanced over time, making it possible to characterize, with an acceptable level of accuracy, the radiative efficiency describing the relationship between atmospheric non-CO_2 SLCF emissions and the associated increase in radiative forcing.[5–8] Aviation is also responsible for "non-GHG climate effects" such as the formation of cirrus clouds.[5] Cirrus clouds are extremely short-lived climate forcers and their evolution and behavior can be described in terms of their characteristic time, τ_{cc}, and their mixing time, t_{cc}. For these non-GHG effects, it can be assumed that $\tau_{cc} \ll t_{cc}$, leading to heterogeneity in their atmospheric mixing. Therefore, the resulting radiative forcing, F_{cc}, is not a function of the climate forcer's concentration, but rather of the local conditions at the time of the emissions.

28. Following the relevant state of art[5,9,10], and being one of the objectives of this modeling approach to assess the global climate impact of the Swiss aviation sector, rather than the impact of a specific flight, we simplify the behavior of these very short-lived cirrus clouds by parametrizing their radiative forcing in terms of kilometers of air traffic volume.
Though local, flight cirrus effects are averaged globally, where the parametrization of their total radiative forcing based on the kilometers flown is a justified and consistent choice in literature and global climate models. In fact, despite being a critical parameter, the radiative forcing potential of these very-short lived "non-GHG effects" presents a significant uncertainty stemming from the undetermined time-dependent and location-dependent conditions leading to their formation.[5] Due to the lack of information and comprehensive models accurately describing the mechanisms and effects influencing the formation and radiative forcing potential of cirrus clouds, parametrization in terms of kilometers of air traffic volume currently remains the only meaningful approach to determine the climate impact of "non-GHG effects" in this study.

Swiss agriculture sector

29. Figure 19 presents the time series for methane, nitrous oxide, and carbon dioxide emissions from Swiss agriculture, spanning historical data from 1690 and projections to 2150. Methane and nitrous oxide emissions peaked around 1990, then decreased slightly by more than 10 % until 2000, and have since remained relatively stable. In contrast, carbon dioxide emissions peaked around 1980, decreased rapidly by 20 % until 1990, and have since increased again, resulting in a new peak. Projected future emission pathways are based on the business-as-usual (WWB) and ZeroBasis scenarios from EP2050+[6], as well as an additional Scenario D, where GHG emission levels follow the ZeroBasis scenario until 2060 but continue to decrease steadily after that until emissions reach a level that is half that of the 2060 value. Total GHG emissions from the agriculture sector between 1690 and 2150 are shown in Figure 20 (left panel) for the period from 1990 to 2150. [7].

[6] As described by the "EP2050+ Szenarienvergleich Storylines"[11], for the agriculture sector, both the WWB and ZeroBasis scenarios assume that the quantity of animal husbandry and plant breeding (greenhouses) follow the LWT prospects, extrapolated (with saturation) to 2060. Moreover, they both assume a decrease in other service areas in agriculture by around 28% between 2020 and 2060 (e.g. warehouses, depending on employment). Lastly, they both assume a decrease in employment in agriculture (i.e., -22% from 2020 to 2060, with a flattening decline after 2035). The main differences between the WWB and the ZeroBasis scenarios, is that the latter assumes a greater improvement in agriculture efficiency and a higher substitution of oil with biogas and wood as energy sources.

[7] Additional information on the data collection is provided in the Technical Report

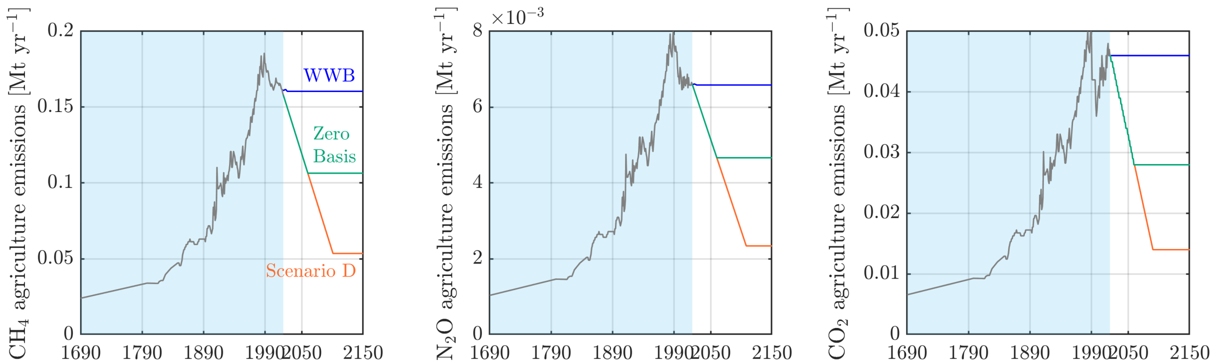


Figure 19. Methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) emission profiles of the Swiss agriculture sector. Past emissions (from 1690 to 2020) are highlighted by a light blue background, while three different projections are shown for future emissions: WWB ("Weiter Wie Bisher", in blue) a business as usual scenario where emissions are kept constant after 2020, ZeroBasis (in green) where emissions are decreased until 2060 and then kept constant afterwards, and Scenario D ("Deeper reduction", in orange) where emissions follow the ZeroBasis scenario until 2060, but further decrease until a level of emissions that is half that of 2060 is reached. The WWB and ZeroBasis projections are taken from the Energieperspektive 2050+ (EP2050+), while Scenario D is further provided for comparison purposes.

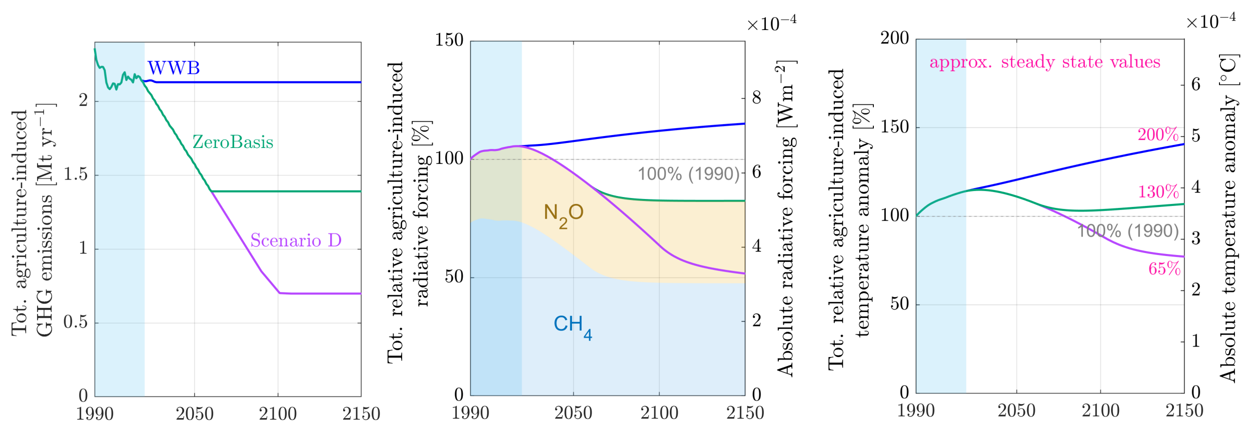


Figure 20. The first panel shows the total agriculture-induced GHG emissions in Mt/yr (i.e., the sum of CH_4, N_2O and CO_2 emissions) for the WWB, ZeroBasis and Scenario D projections. The second and third panels show, respectively, the total curves of radiative forcing perturbation and temperature anomaly as a result of the CH_4, N_2O and CO_2 emissions from Swiss agriculture practices since 1690. For the total ZeroBasis radiative forcing curve, the individual contributions of the three polluters are shown: currently CH_4 contributes to approximately two-thirds of the ZeroBasis (EP2050+) radiative forcing, and N_2O to one-third, while CO_2 contribution is negligible. All curves are shown from 1990 to 2150. The extended timeline is chosen to better visualize the longer time scale required by the temperature anomaly to stabilize after radiative forcing has been altered by anthropogenic GHG emissions. Long-term steady-state temperature anomalies are shown in pink.

30. The middle and right panels of Figure 20 show the radiative forcing and temperature anomaly resulting from the total GHG agriculture emissions, as calculated with the SLCM. Both radiative forcing and temperature anomaly are plotted as such, but also in percentage values of the corresponding levels observed in 1990 (100% is the 1990 level, while 0% is the 1690 level, the start of anthropogenic agricultural impact). The climate impact of Swiss agriculture is predominantly driven by short-lived

methane, accounting for approximately two-thirds of its total climate impact, and by long-lived nitrous oxide, which contributes about one-third of it. In contrast, carbon dioxide emissions from Swiss agriculture are negligible [8]. The WWB and ZeroBasis scenarios would result in a long-term additional warming contribution of 100% and 30%, respectively, relative to 1990 levels. In contrast, scenario D would lead to approximately a 35% reduction in agriculture-induced warming compared to 1990.

31. The following remarks are important regarding the evolution of the temperature anomaly as a result of forcing perturbation. Temperature anomaly follows radiative forcing, but its time scale is longer, i.e., in the order of 300-400 years. The final steady state temperature anomaly is determined by the final constant radiative forcing value (and by the equilibrium climate sensitivity parameter); in fact, the former is equal to the latter divided by the equilibrium climate sensitivity. When the future final constant forcing level is sufficiently low, i.e., lower than the peak value determined by past and current emissions, the temperature reaches its peak value and then starts to decrease, thus reaching the steady-state temperature value from above. Conversely, if the future final constant forcing level is still too high, i.e., higher than the peak value, the temperature keeps increasing over time, and the temperature anomaly reaches its final steady state from lower levels.

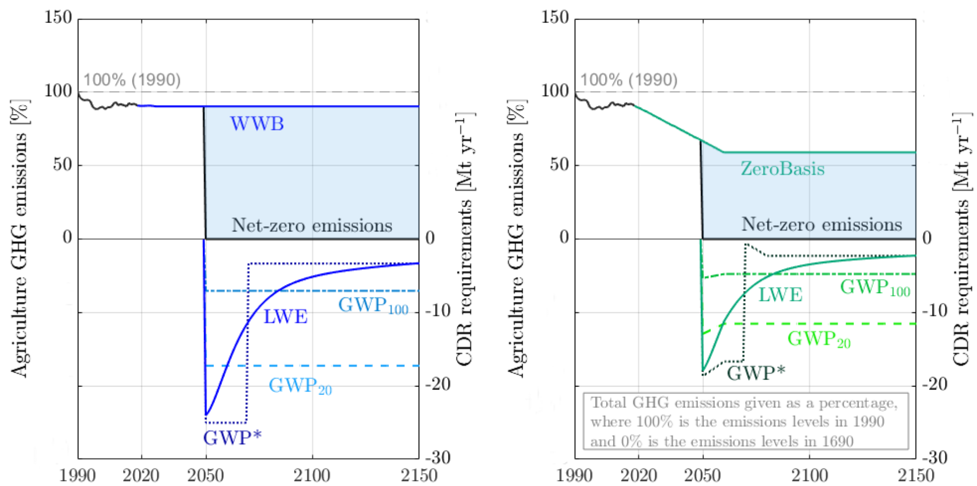
32. Agriculture is a very important case of a hard-to-transition sector, which will have residual hard-to-abate emissions in 2050, for which CDR needs to be deployed in order to align with the binding ”Klima- und Innovationsgesetz” (KlG), requiring net-zero ”Wirkung” by 2050. This study has identified two possible interpretations of the term ”Wirkung” in this context, namely, (1) achieving net-zero residual emissions by 2050 (Target 1), or (2) attaining zero residual radiative forcing by 2050 (Target 2). Each of these objectives deterEach objective highlights the gap between the climate change mitigation ambition—defined by the target reduction pathway set by Swiss law—and a realistic mitigation pathway, represented by either the WWB or ZeroBasis scenarios (feasible emissions reductions without CDR deployment or emissions certificates). This gap, shown as a shaded light blue area in the emissions profiles below, reflects the emissions reductions that must be achieved through carbon dioxide removal (CDR) and/or the purchase of emissions avoidance certificates, which are only permitted until 2050. This approach is applied to both Swiss agriculture and Swiss aviation. The results of this study pertaining to Swiss agriculture are presented in Figure 21 and in Figure 22 for Target 1, and in Figure 23 for Target 2.

33. Let us consider Target 1 first. Figure 21 and Figure 22 present diagrams organized in two columns and two rows each. The diagrams in the column on the left hand side and those in the right hand side column show results for the business-as-usual (WWB) and for the ZeroBasis scenarios, respectively. Overall GHG emissions profiles and GHG cumulative emissions are shown in Figure 21(a) and in Figure 21(b), respectively. The associated evolution of the radiative forcing and of the temperature response calculated using the Simplified Linear Climate Model (SLCM) are plotted in Figure 22(a) and in Figure 22(b), respectively. Figure 21(a) shows the relative WWB and ZeroBasis emissions profiles (the same as in Figure 20, left panel), and the Target 1 emission profiles. The shaded light-blue area, representing the gap between emission scenario and climate ambition, is compensated by CDR amounts, whose absolute amounts are plotted vs. time in the same figures (negative vertical axis, labelled on the right hand side of the figures). Such CDR amounts are calculated in four different ways, namely using the GWP_{100} (dash-dotted lines), and the GWP_{20} (dashed lines) metrics, as well as the GWP* (dotted lines) and the LWE (solid lines) models. Accordingly, also in Figure 21(b) and in Figure 22 four curves are plotted, corresponding to the four approaches how to calculate CDR amounts utilized in Figure 21(a).

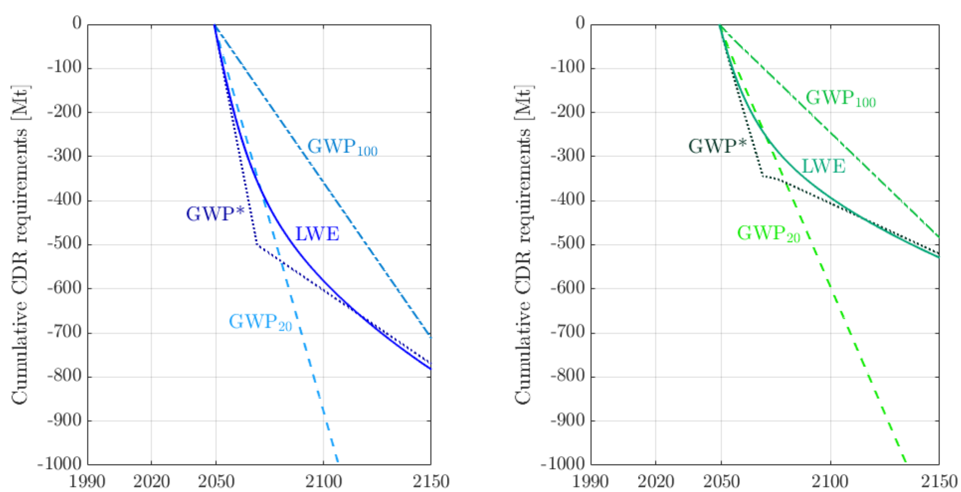
34. With reference to Figure 21 first, it is obvious that the CDR amounts calculated using the GWP_{20} metric are always larger than those obtained using the GWP_{100} metric; this is a consequence of the fact that

[8]This is due to the accounting assumptions in the Energieperspektive 2050+, where the CO_2 emissions associated to croplands and grasslands are reported in the land-use sector rather than together with the other agriculture emissions.

agriculture GHGs decay hence the metric calibrated on short-term impacts, i.e., the GWP_{20} metric, is more conservative than the longer-term one, i.e., GWP_{100}. Both the GWP* approach and the LWE model try and account for the effect in time of the decay of methane and nitrous oxide, thus yielding CDR amounts that are rather similar, though different than those obtained with the GWP metrics. It is also worth noting that the CDR requirements, both rate of deployment and cumulative deployment, are about 50% smaller for the ZeroBasis scenario than for the WWB scenario for all equivalence approaches.

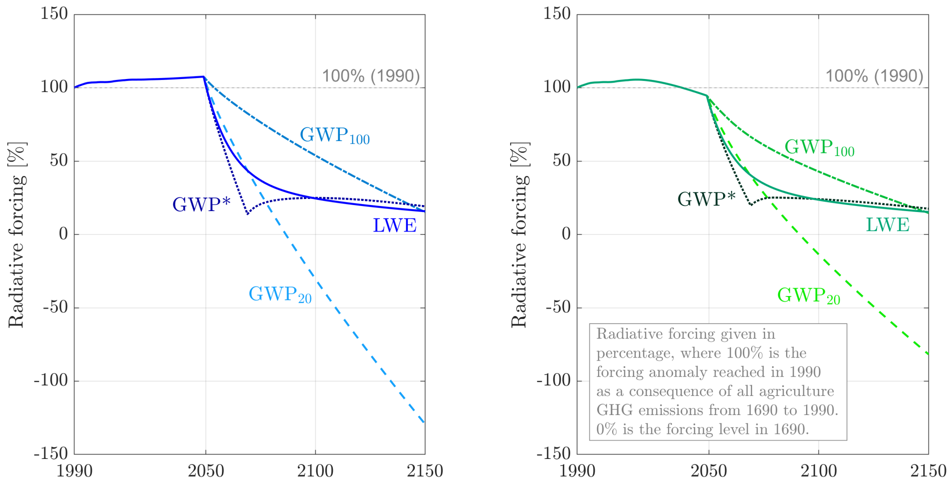


(a) Total WWB (left) and ZeroBasis (right) GHG emissions from the Swiss agriculture sector and a hypothetical emissions reduction scenario aimed at achieving net-zero emissions in 2050 (grey line). Both curves are expressed as a percentage of 1990 emissions for comparison. The light blue area represents the emissions gap between total emissions and the reduction target, which defines the carbon dioxide removal (CDR) requirements. The right vertical axis shows the amount of CDR (plotted as a negative quantity) needed to offset residual CO_2, CH_4, and N_2O emissions, with CH_4 and N2O converted to CO_2 equivalents using various equivalence metrics and models (GWP_{20}, GWP_{100}, GWP*, and LWE).

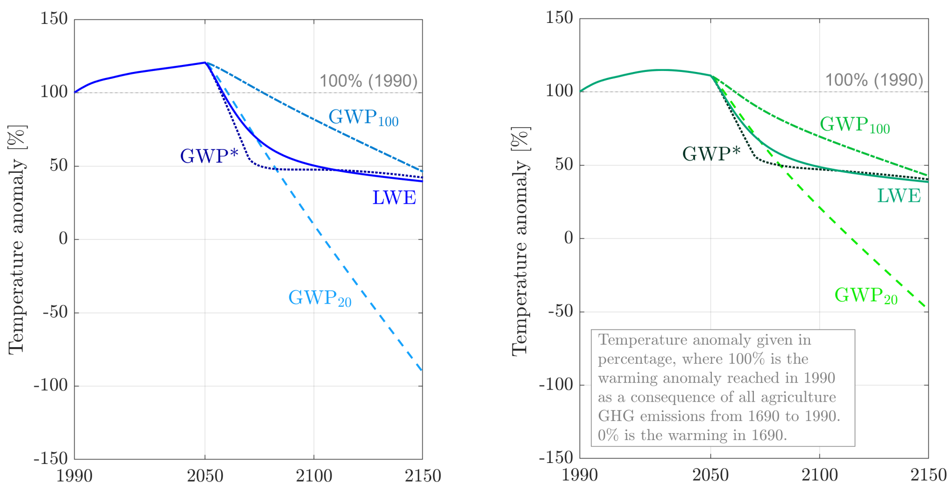


(b) Cumulative CDR requirements following the GWP_{100}- (dashed-dotted line), the GWP_{20}- (dashed line), the GWP*- (dotted line), and the LWE- (solid line) strategies of Figure 21a.

Figure 21. CDR requirements for a Target 1 of net-zero emissions, as calculated by means of the GWP_{100}, GWP_{20}, GWP*, and LWE metrics.



(a) Radiative forcing



(b) Temperature response

Figure 22. Radiative forcing Figure 22a and temperature response Figure 22b from Swiss agricultural emissions, expressed as a percentage of the warming observed in 1990 when CDR is deployed to achieve net-zero emissions from 2050, as calculated by the GWP_{100}, GWP_{20}, GWP*, and LWE metrics.

35. As regards Figure 22, it is apparent that the SLCM predicts, when using CDR amounts calculated with the GWP* and the LWE models, radiative forcing and temperature response profiles that are quite similar, though they differ in the details. Three remarks are worth making. First, since the emission gap between climate ambition and emission scenario is constant after 2060 for both WWB and ZeroBasis scenarios, both radiative forcing and temperature response tend to stabilize in the long-term for CDR amounts calculated with both GWP* and LWE models: this happens thanks to the ability of both models to account for the decay of the main contributors to climate impacts in Swiss agriculture. Secondly, there is an important difference though: radiative forcing for the case where CDR requirements are calculated using the LWE model approaches indeed zero in the long-term, whereas this does not happen for the GWP* model, due to its stock component that leads to a long-term compensation even when emissions of non-CO_2 GHGs are constant. These differences are very evident here because the emission profiles are unrealistically simple, and would be almost not visible for more realistic emission profiles.

Thirdly, the long-term behavior observed is very similar for both WWB and ZeroBasis scenarios: this is a consequence of the fact that the CDR amounts deployed are different in the two cases as they account properly for the different demands of compensation of the two scenarios. The results are very different for the CDR amounts calculated using the GWP metrics, which yield higher radiative forcing and temperature response in the short term, and lower ones after the time horizon on which they are calibrated; actually, radiative forcing and temperature response never stabilize and evolve towards long-term levels below the 1690 reference value of zero. As a consequence GWP_{20} results do not differ much from those of the GWP* and LWE models on multi-decadal timescale, but are very different afterwards. In turn, GWP_{100} results are close to those of the two models only around a time 100 years from the start of the deployment of CDRs, but are different both before and thereafter.

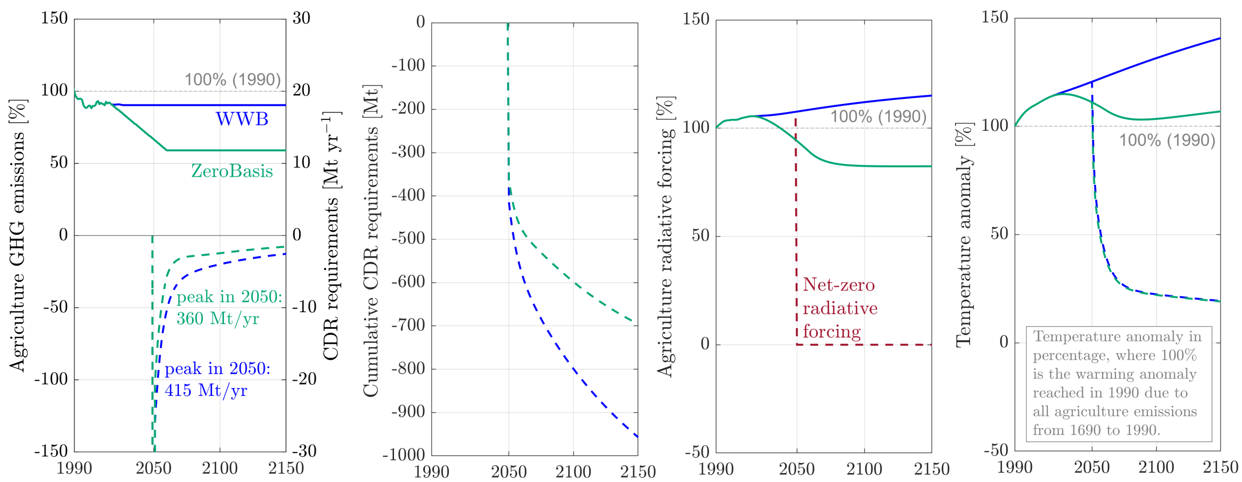


Figure 23. Target 2, net-zero forcing from 2050. The four panels show, from left to right: (i) the emissions in percentage (first panel, left vertical axis), where 100% corresponds to the level of emissions in 1990, while 0% represents their level at the start of detectable anthropogenic agriculture emissions, i.e., the year 1690; (ii) in the same first panel the CDR requirements in Mt/yr (first panel, right vertical axis), where rates of CDR (calculated with the LWE approach) are negative numbers, in contrast to emissions that are positive; (iii) the cumulative CDR requirements needed to achieve the net-zero radiative forcing target when residual emissions follow either WWB or ZeroBasis; (iv) the associated radiative forcing for the WWB and ZeroBasis scenarios and the net-zero radiative focing trajectory from 2050 (third panel), where 100% is the corresponding level in 1990, and 0% that in 1690; (iv) the associated temperature anomaly for the WWB and ZeroBasis scenarios with and without CDR (fourth panel), where 100% is the corresponding level in 1990, and 0% that in 1690. Radiative forcing and temperature anomaly evolutions with CDR implementation are shown as dashed lines.

36. Let us now consider Target 2. CDR requirements to achieve zero radiative forcing from 2050 on can only be calculated using the LWE model, which is defined indeed to establish equivalence in terms of radiative forcing. The four panels in Figure 23 provide the same information as the previous figures for Target 1, namely from left to right they show (i) the relative GHG emission profiles for the WWB and ZeroBasis scenarios, together with the calculated absolute rate of CDR deployment (negative vertical axis), (ii) the cumulative CDR amounts, (iii) the relative radiative forcing, including the target zero radiative forcing (dashed red line), and (iv) the relative temperature response. In the last two diagrams the climate impacts of the WWB and ZeroBasis scenarios with neither CDR nor use of certificates are reported for comparison.

37. The results reported in Figure 23 indicate that Target 2 can be fulfilled for both emissions scenarios,

with a CDR requirement when emissions follow a WWB pathway that is larger than in the ZeroBasis case. The latter CDR demand is however much larger than in the corresponding cases where Target 1 is pursued, as expected. Since for both emission scenarios the radiative forcing target profile is fulfilled, the evolution of the temperature response is the same. It is worth underlining that though the accuracy of the temperature response predictions in Figure 23, rightmost panel, and in Figure 22(b) is affected by the assumptions on which the SLCM is based, the comparative assessment of the different scenarios for the different equivalence approaches is insightful nevertheless, as all cases are affected by the model assumptions to a similar extent.

38. A few other remarks on Swiss agriculture and the associated CDR requirements to achieve net-zero emissions are worth making:

- CDR deployment as calculated by the LWE model limits the warming contribution to 100% and 50% with respect to the 1990 level in ca. 2060 and in 2100, respectively, when either the WWB or the ZeroBasis emission scenarios are followed until 2050. However, not only does the business-as-usual (WWB) scenario require an additional cumulative 200 Mt of CDR by 2100, but also its associated peak temperature anomaly is larger than that of the ZeroBasis scenario (where more ambitious mitigation targets are implemented): in the WWB scenario, peak warming would be 20% higher than the 1990 level, while in the ZeroBasis scenario it would be only 15% higher. From a climate perspective, this is a significant difference, as even a briefly higher global peak warming, can trigger irreversible planetary system feedbacks (the so-called tipping points) and exacerbate anthropogenic climate interference.
- Peak rate of CDR deployment can be reduced of about 50% in the ZeroBasis scenario without major changes in the other figures of merit, when CDR deployment starts immediately and then ramps up, instead of starting only in 2050, as illustrated in Figure 24.

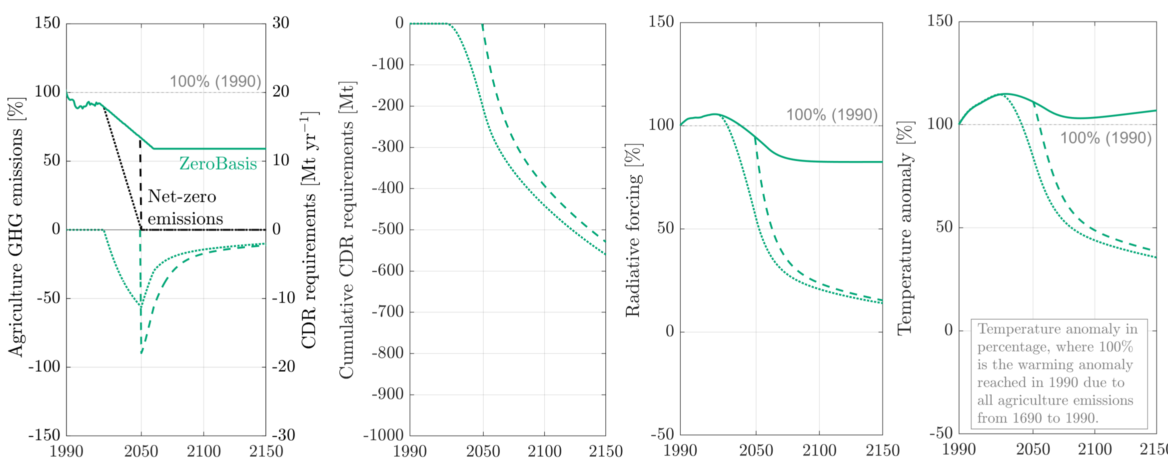


Figure 24. In the first panel, the required profile of CDR deployment is shown for a target 1 of net-zero emissions in 2050 when CDR is started early on (i.e., in 2020, showed in dotted lines) or only from 2050 (showed in dashed lines), as two follow the two black target lines of net-zero emissions. Cumulative CDR requirements, the resulting radiative forcing perturbation, and the temperature anomaly are shown for the two CDR profiles, starting from 2020 or from 2050, in the second, third, and fourth panels, respectively. From this figure, it is possible to see that early CDR deployment allows for a sooner decrease in the agriculture-induced climate impact, but more importantly, it allows for almost halving peak CDR demand to a maximum of 10 Mt/yr.

- Furthermore, we have analyzed the climate impact of a policy that follows the CDR pathway projected by the Swiss long-term climate strategy (building on the EP2050+). Such CDR amounts were calculated using the GWP_{100} metric and the corresponding curves for CDR requirements and climate impacts as calculated using the SLCM are plotted in all panels of Figure 25 as dashed orange lines. These are compared (i) with the results obtained using the LWE model for the ZeroBasis scenario and plotted in Figure 21 and in Figure 22 (dashed green lines), and (ii) with results obtained considering a modified EP2050+ CDR strategy (light blue lines), where the deployment of negative emissions follows the EP2050+ strategy (until about 2080), and it approaches the green lines thereafter. These comparisons highlight two aspects. On the one hand, shaving the peak of CDR demand around the year 2050, as implied by the approach following the EP2050+ scenario, worsens significantly the climate impact with respect to a strategy based on the use of the LWE approach (which yields similar results as using the GWP* model, as discussed above). On the other hand, adapting this approach by converging towards the CDR deployment calculated using the LWE model, while not improving much the short-term effectiveness, eliminates the long-term overestimation of the CDR deployment that is typical of the GWP_{100} metric.

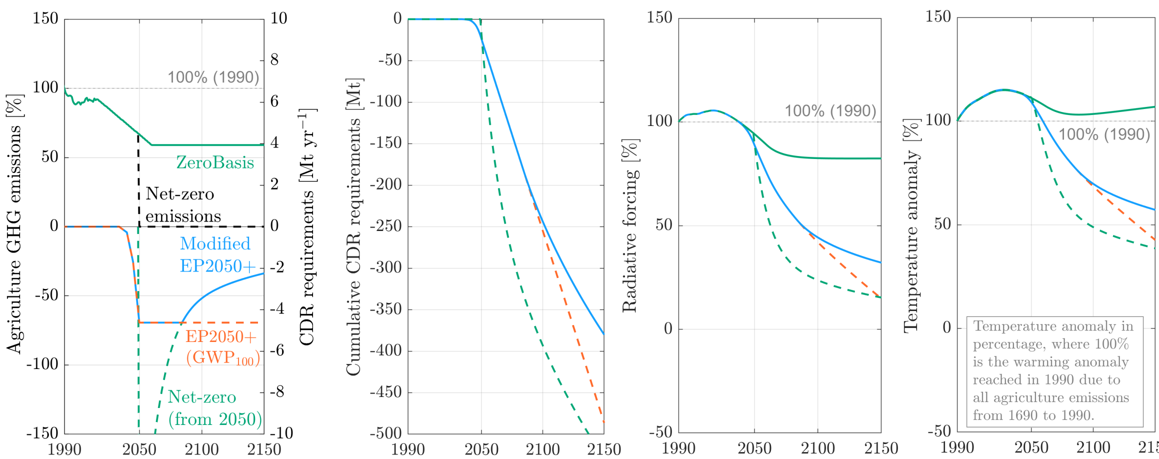


Figure 25. On the right vertical axis of the first panel, the CDR requirements as calculated in the EP2050+ with the GWP100 metric are shown with a dashed orange line. Shown in dashed green are the LWE-calculated CDR requirements to achieve net-zero emissions (with CDR starting from 2050). This CDR demand corresponds to the dashed green lines of Figure 21 and Figure 24. Lastly, portrayed in light blue, is a modified EP2050+ CDR strategy, where the deployment of negative emissions follows the EP2050+ strategy (until about 2080), while long-term it resembles an LWE-calculated CDR pathway. This latter CDR pathway is added for illustration purposes.

39. It is worth noting that the modeling tool adopted in this study may also be used to back-calculate net-emissions to achieve a selected target temperature response, by means of the Target Warming Equivalent (TWE) approach. The TWE is a tool proposed in this study, as previously described in point 13, to complement the standard chain of causality modeling framework and was not inferred or taken from the KlG. This is illustrated in Figure 26, where we analyze a target warming profile (fourth panel, red-solid line), where warming follows the ZeroBasis profile until the end of the century, stabilizing at a constant value thereafter. From that, one can calculate the radiative forcing profile corresponding to the targeted temperature anomaly evolution (third panel). The total target radiative forcing can then be separated into the contributions of each single polluter (i.e., methane, nitrous oxide, and carbon dioxide in the case of agriculture). There are infinite combinations that lead to the same total radiative

forcing profile; here a split in line with the EP2050+ ZeroBasis projection was selected. From the specific polluters' forcings, the individual GHG emissions' pathways necessary to yield the targeted temperature anomaly evolution can be calculated (first panel). As expected, to maintain a constant temperature (outweighing the longer time scale required by the temperature anomaly to stabilize) a minor, prolonged decrease in the net-forcing with respect to the ZeroBasis pathway is necessary (see red line compared to the dashed green line in the radiative forcing panel of Figure 26). This difference may be achieved either through further emissions reduction with respect to the ZeroBasis scenario, or a combination of this and of more CDR amounts, or only through the deployment of more CDR measures; the latter case is shown in Figure 26, in negative values on the right vertical axis of the first panel.

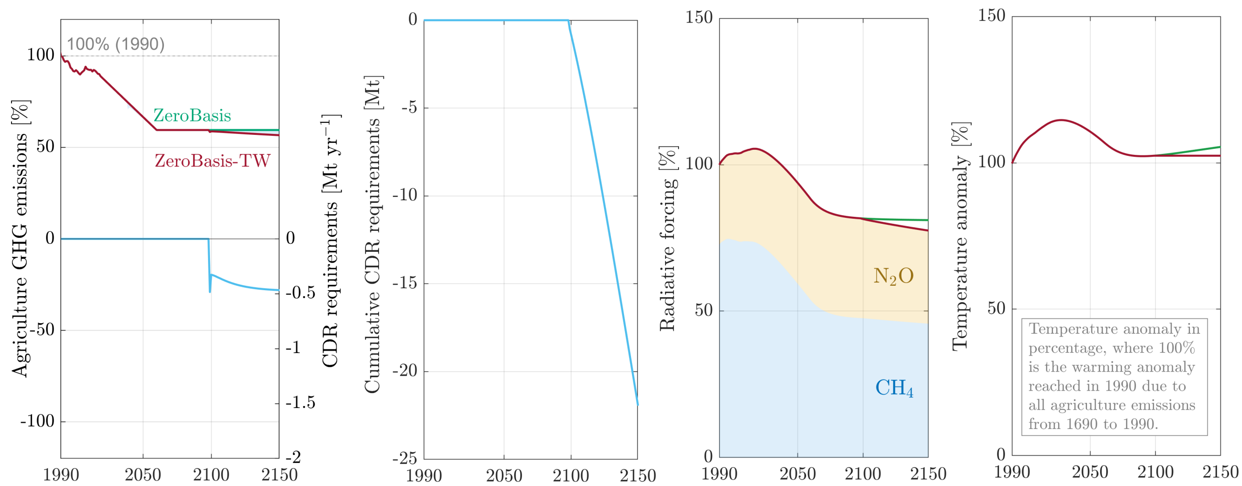


Figure 26. The four panels show, from right to left: (first panel) the target temperature anomaly profile (red solid line) and the ZeroBasis curve (green dashed line). (second panel) the GHG-induced radiative forcing curve, reversely calculated from the desired warming profiles, and the ZeroBasis forcing pathway. (fourth panel) on the left vertical axis in Mt GHG/yr, the ZeroBasis agriculture GHG emissions profile and the ZeroBasis-TW (ZeroBasis-Target Warming) pathway, necessary to adhere to the target temperature anomaly profile; on the right vertical axis, in negative values, the CDR requirements in Mt/yr resulting from the difference between the ZeroBasis and ZeroBasis-TW GHG emissions pathways (third panel) the cumulative CDR requirements needed.

Swiss aviation sector

40. The time series of CO_2, NO_x, SO_x, BC (black carbon), and H_2O emissions from Swiss aviation, covering the period from 1950 to projected values through 2150, are illustrated in Figure 19. [9]. Methane and nitrous oxide emissions from aviation are negligible and, therefore, excluded from this report. Unlike the agricultural sector, most GHG emission categories from aviation continue to follow an upward trend, with emissions projected to peak at a future date.

[9]Additional information on the data collection is provided in the Technical Report

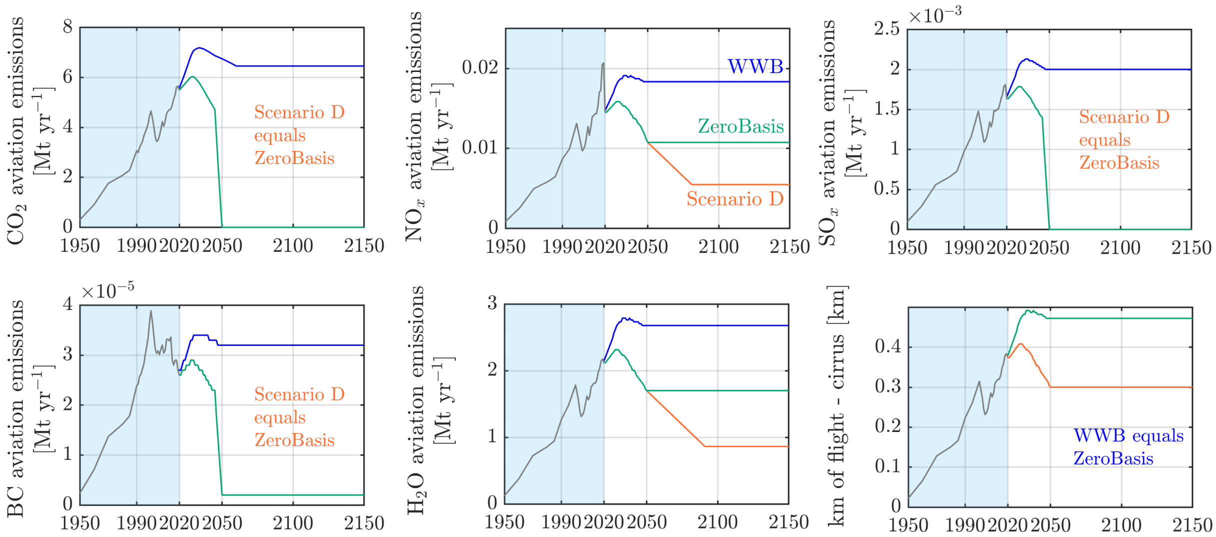


Figure 27. Emissions of CO_2, NO_x, SO_x, BC (black carbon), and H_2O from the Swiss aviation sector, along with the profile of flight kilometers, are shown. Past emissions (1950–2020) are shaded with a light blue background, while future projections are illustrated for three scenarios: WWB ("Weiter Wie Bisher," in blue), a business-as-usual scenario with constant emissions after 2020; ZeroBasis (in green), with emissions decreasing until 2060 and stabilizing thereafter; and Scenario D ("Deeper reduction," in orange), which follows ZeroBasis until 2060 but continues to decline, halving emissions by 2060 levels. WWB and ZeroBasis scenarios are based on the Energieperspektive 2050+ (EP2050+), while Scenario D is included for comparison. For pollutants projected to reach near-zero emissions under ZeroBasis, Scenario D is omitted. Flight kilometers are identical in the WWB and ZeroBasis scenarios.

41. As already mentioned above, the climate impact of some of these aviation-induced non-GHG climate forcers is affected by local atmospheric and flight conditions, which poses a challenge in assessing the climate impact of such forcers both in time and space. The limited accuracy of global climate models, especially in predicting the concentration of climate forcers that are strongly affected by local conditions (such as those induced by aviation practices) is a common limitation to all models, both the more complex ones (e.g., Earth System Models) and the simplified ones (e.g., FAIR and the SLCM proposed here). Following relevant state-of-the-art literature[5,10], we assess the global climate impact of the Swiss aviation sector by simplifying the behavior of these very short-lived cirrus clouds through parametrization of their radiative forcing in terms of kilometers of air traffic volume. [10] [11]

42. Total emissions from the Swiss aviation sector (from 1950 to 2150), following the business-as-usual (WWB) and the ZeroBasis projected scenarios from EP2050+ and an additional scenario of deeper emissions reduction (Scenario D), without CDR deployment, are shown in Figure 28 from 1990 to 2150. Additionally, total air traffic volume from Swiss aviation (international flight) is reported in red (right vertical axis in the leftmost panel), which will be used to estimate cirrus clouds formation (following relevant literature[5,10]). Worth mentioning is that the EP2050+ ZeroBasis scenario assumes

[10]Reduction of non-CO_2 and non-GHG climate forcers as a result of SAFs implementation is considered through the implementation of emission correction factors, as also implemented in the literature (Sacchi and Becattini et al.[10]).

[11]It is also important to mention that FOCA states that policies for reducing CO_2 and non-CO_2 effects from flights have to be based on three pillars: fuel (energy source), engines and operations. The FOCA addresses all three of them through active collaboration in the ICAO UN body, which is responsible for setting global standards and recommended practices in aviation. In this study, the only aviation policy directly considered and addressed with the modeling framework is the fuel policy. Aviation policies addressing the other two pillars are not directly considered, but rather only indirectly through the assumptions embedded in the EP2050+ WWB and ZeroBasis databases.

100% sustainable aviation fuels (SAFs) use from 2050 on[12] (alongside large efficiency improvements); consequently, the same assumption is carried over to Scenario D. ZeroBasis and Scenario D would lead to a long-term additional warming contribution of over 300% and of 170%, respectively, higher than in 1990. In WWB, both forcing and temperature anomaly do not stabilize, and maintain instead their upward trajectory, as a result of the continued CO_2 emissions.

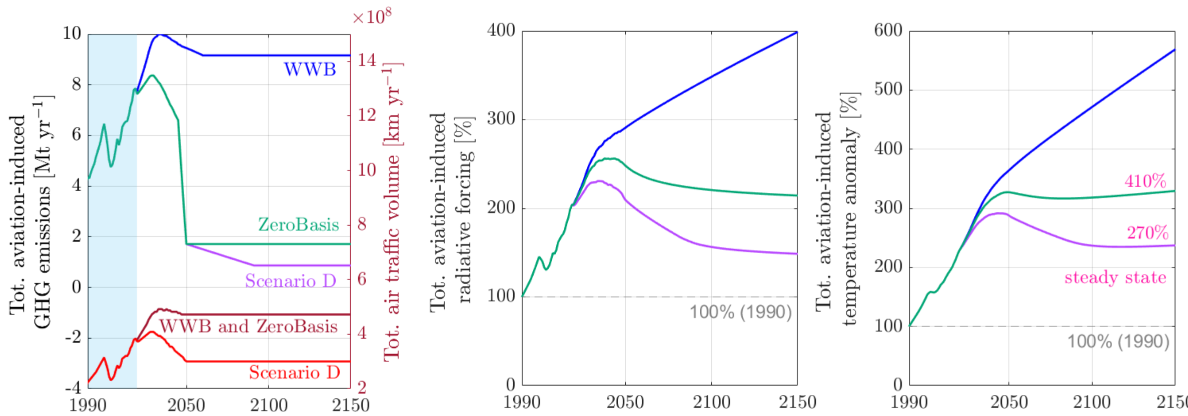


Figure 28. Total curves of radiative forcing perturbation and temperature anomaly as a result of the CO_2, NO_x, SO_x, BC and H_2O emissions, as well as cirrus clouds formation, from Swiss aviation practices since 1950. The three considered future scenarios, namely WWB, ZeroBasis and Scenario D, are shown in their respective colors, blue, green and purple. The curves are shown from 1990 to 2150. The extended timeline is chosen to better visualize the longer time scale required by the temperature anomaly to stabilize after radiative forcing has been altered by anthropogenic GHG emissions. Long-term steady state temperature anomalies are shown in pink for ZeroBasis and Scenario D; in the WWB case, forcing and temperature anomaly do not stabilize a result of the continued CO_2 emissions.

[12]The evolution of CO_2 emissions to follow the ZeroBasis scenario can be regarded as unrealistic, as it is improbable for SAFs to cover 100% of the fuel requirements[12] (e.g., the EU counterpart, ReFuelEU only requests 70% blending). FOCA reported more realistic projections and policy information; however, information from this up-to-date assessment could not yet be included in this project as it was not available at the beginning of the study.

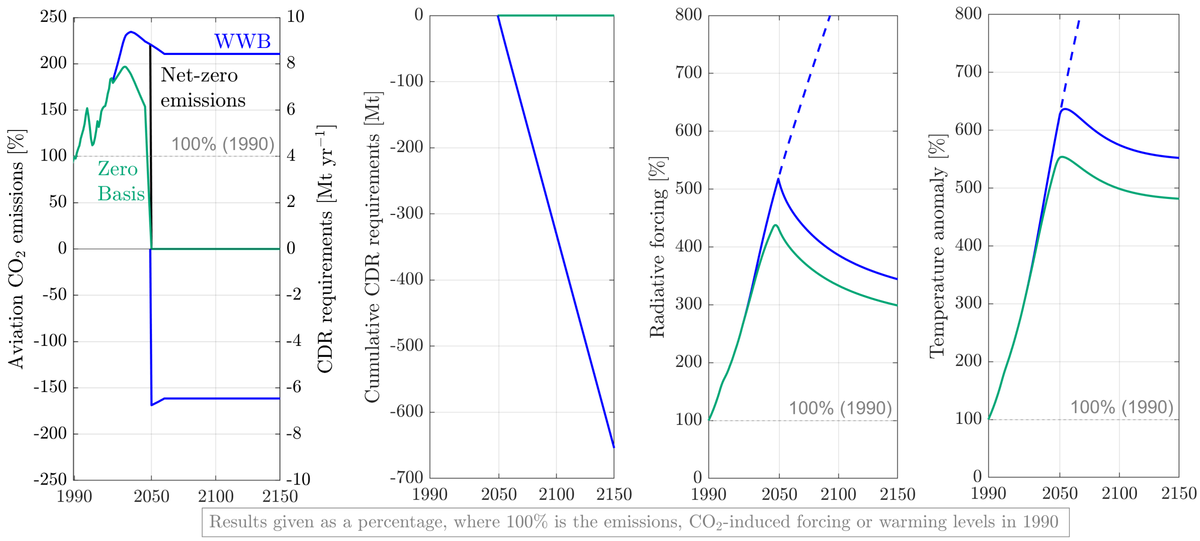


Figure 29. The four panels show, from left to right: (i) the emissions in percentage (first panel, left vertical axis), where 100% corresponds to the level of emissions in 1990, while 0% represents their level at the start of anthropogenic aviation emissions, i.e., the year 1950; (ii) in the same first panel the CDR requirements in Mt/yr (first panel, right vertical axis), where rates of CDR are negative numbers, in contrast to emissions that are positive; (iii) the cumulative CDR requirements needed to achieve the net-zero CO_2 emissions target when residual emissions follow either WWB or ZeroBasis (second panel); (iv) the associated radiative forcing for the WWB and ZeroBasis scenarios with and without CDR (third panel), when only the climate impact of CO_2 emissions is considered (100% is the corresponding CO_2-induced level in 1990, and 0% that in 1950); (iv) the associated temperature anomaly for the WWB and ZeroBasis scenarios with and without CDR (fourth panel), when only the CO_2-induced warming is considered (100% is the corresponding CO_2-induced level in 1990, and 0% that in 1950). Radiative forcing and temperature anomaly curves without CDR implementation are showed with dashed lines. Achieving net-zero CO_2 emissions in 2050, while only deploying CDR from that same target year, results in a peak of 7 Mt/yr for the WWB scenario, where CDR deployment is zero for the ZeroBasis pathway (100% SAFs uptake). Considering only the climate impact of aviation-CO_2, and compensating with CDR for only those emissions, the long-term sector's warming contribution is about five times that in 1990.

43. For the Swiss aviation sector, the KlG currently targets net-zero emissions in 2050 , considering CO_2 but neglecting all other aviation-induced climate forcers [13] [14]. Considering only the climate impact of CO_2 emissions, and also compensating only for CO_2, the long-term sector's warming contribution

[13]Explanation for this comes from the "BBl 2022 1536 - Parlamentarische Initiative. Indirekter Gegenentwurf zur Gletscher-Initiative. Netto-Null-Treibhausgasemissionen bis 2050. Bericht der Kommission für Umwelt, Raumplanung und Energie des Nationalrates (admin.ch)". This document from the parliament states that "air traffic also has an additional impact on the climate caused by NOx, water vapor, sulfate and soot particles in the atmosphere. However, depending on the period under consideration, weather conditions, and flight altitude, this effect varies between one and three times the CO_2 emissions caused by the combustion of fossil aviation fuel. This climate impact of aviation can, therefore, not be assigned a uniform factor across the board, but can only be determined approximately. The atmospheric effect should, therefore, not be included, but only the clearly identifiable emissions from the consumption of fossil aviation fuels, which are also the focus of intra-European emissions trading and the global CORSIA system."

[14]However, the Swiss long-term climate strategy partially addresses and considers non-CO_2 aviation climate forcers. The following is stated: "[...] the Federal Council proposes including the emissions of international aviation in the net-zero target for 2050 provided this is scientifically and technically feasible in line with the data in the greenhouse gas inventory. This is currently possible for the greenhouse gases CO_2, methane (CH_4) and nitrous oxide (N_2O). [...] In addition to these gases covered by the greenhouse gas inventory, international aviation also generates other emissions that have an impact on the climate. These include water vapour (H_2O), nitrogen oxide (NO_x), sulphur dioxide (SO_2) and black carbon. [...] the CO_2 emissions of aviation must be multiplied by a factor of

is about five times that in 1990, with a peak temperature anomaly about 10% higher than the final value, for both the WWB and ZeroBasis scenarios. Peak rate of CDR deployment and cumulative requirements until 2100 are about 7 Mt CO_2 per year and 350 Mt CO_2 in WWB, whereas they are zero in the ZeroBasis pathway, as this EP2050+ scenario assumes 100% uptake of CO_2-free Sustainable Aviation Fuels (SAFs) until 2050.

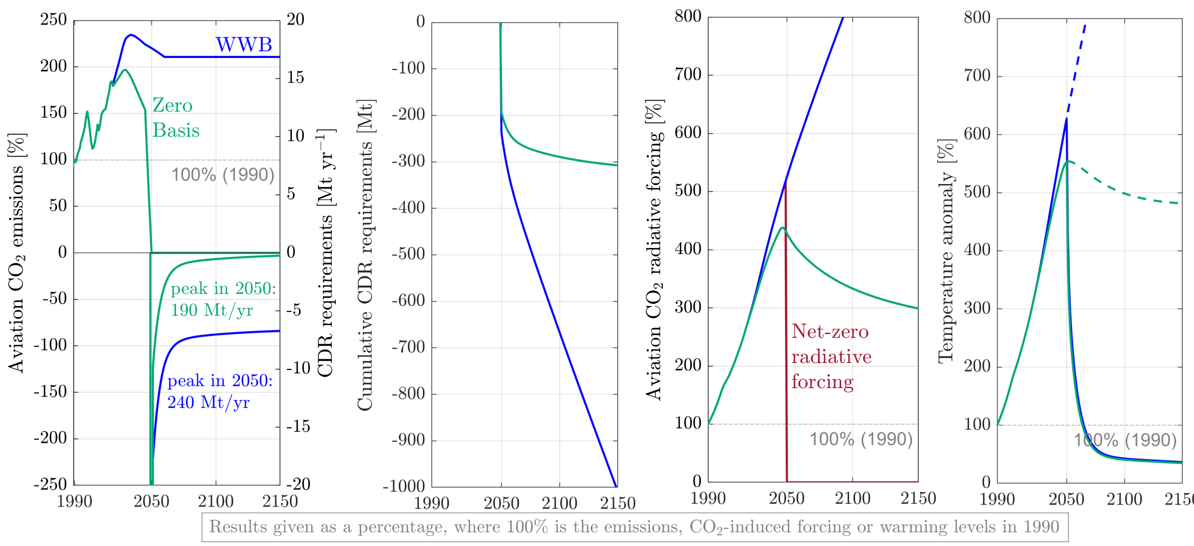
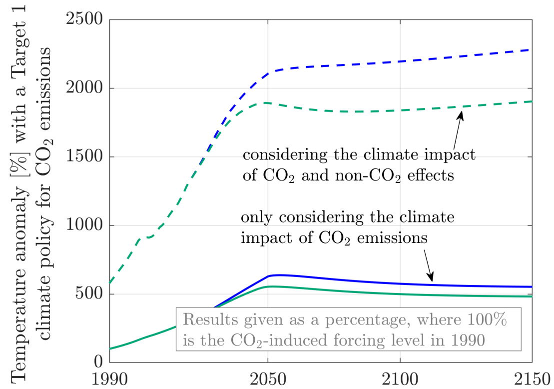


Figure 30. As Figure 29, but for a Target 2 of net-zero radiative forcing. Achieving net-zero forcing in 2050, while only deploying CDR from that same target year, results in a peak of 240 Mt/yr for the WWB scenario and 190 Mt/yr for the ZeroBasis scenario. Considering only the climate impact of aviation-CO_2, and compensating with CDR for its resulting forcing, the sector's warming contribution is eliminated in the long-term.

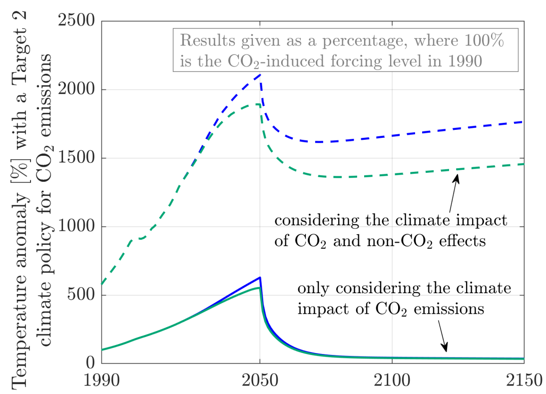
44. Targeting net-zero forcing in 2050 (Target 2, shown in Figure 30 and chapter 13.1.2 of the technical report), with CDR starting from 2050, allows for a long-term temperature decrease to 0%, hence back to the warming level at the start of detectable anthropogenic aviation emissions. However, to achieve target 2, CDR deployment reaches extremely high levels at more than 190 and 240 Mt CO_2 per year, in the ZeroBasis and in the WWB scenarios, respectively.

45. When the climate impact of aviation-induced non-CO_2 climate forcers is accounted for, the overall warming contribution from aviation becomes significantly larger than when these forcers are not considered. For instance, in 1990, warming levels with non-CO_2 forcers included are approximately 400% higher than the temperature anomaly without them, as illustrated by the dashed lines in Figure 31a. Moreover, long-term temperature stabilization becomes unattainable without compensatory actions, as non-CO_2 pollutants continue to contribute to warming without being offset by CDR or mitigated through targeted measures. Consequently, the sector's long-term warming contribution is projected to be about four times higher under ZeroBasis (green) and five times higher under WWB (blue) compared to 1990 levels when both CO_2 and non-CO_2 impacts are considered (Figure 31a, dashed lines).

around 2.5 according to the information currently available to reflect the total impact on the climate. This figure is a global average. The factor can fluctuate significantly depending on weather conditions and altitude for an individual flight which means there is an element of uncertainty. These emissions are not currently included in the greenhouse gas inventory on account of this element of uncertainty. [...] They [these emissions] should also decrease long-term. However, the cutting of these emissions should not come at the expense of reducing fossil-based CO_2 emissions which remain in the atmosphere for significantly longer".



(a) Target 1, net-zero emissions



(b) Target 2, net-zero radiative forcing

Figure 31. Temperature anomaly evolution for a net-zero emissions and net-zero forcing climate policies when only aviation-CO_2 emissions are compensated with CDR and when only the climate impact from CO_2 emissions is considered (solid lines, as presented in the last plot of Figure 29). Instead, the dashed lines show the temperature anomaly evolution when CDR compensation is deployed only for CO_2 emissions, but the warming caused by CO_2 and non-CO_2 polluters is considered. Here, all temperature anomaly curves are normalized to aviation CO_2-induced warming in 1990.

46. If non-CO_2 climate forcers are also offset through CDR measures (or reduced via targeted industry-specific actions), the long-term warming contribution from aviation under both the ZeroBasis and WWB pathways can return to 1990 levels. However, the peak temperature anomaly in 2050 still exceeds 300% of the 1990 level in both cases. While this represents a positive outcome from a climate perspective, it comes at the cost of a significantly higher peak CDR deployment rate, reaching 300 Mt CO_2 per year, with cumulative CDR requirements exceeding 700 Mt CO_2 by 2100. However, these peaks in warming and CDR deployment can be mitigated. If CDR deployment begins immediately and ramps up gradually, rather than starting in 2050, the peak warming can be reduced to 230% of the 1990 level, and the peak CDR deployment rate can be limited to 30 Mt CO_2 per year. This approach highlights the importance of early and proactive CDR deployment strategies.

47. We present an illustrative case of more ambitious emissions reduction for the aviation sector, represented by the orange curve in Figure 32. In this scenario, aviation demand—along with fuel consumption and flight kilometers—is simulated to decrease linearly from today, ultimately reaching half the demand projected in the ZeroBasis scenario. This adjustment significantly reduces CDR requirements, lowering peak demands from 26 Mt/year to 10 Mt/year and cutting cumulative CDR needs by 550 Mt by 2150 to

achieve the net-zero emissions target.

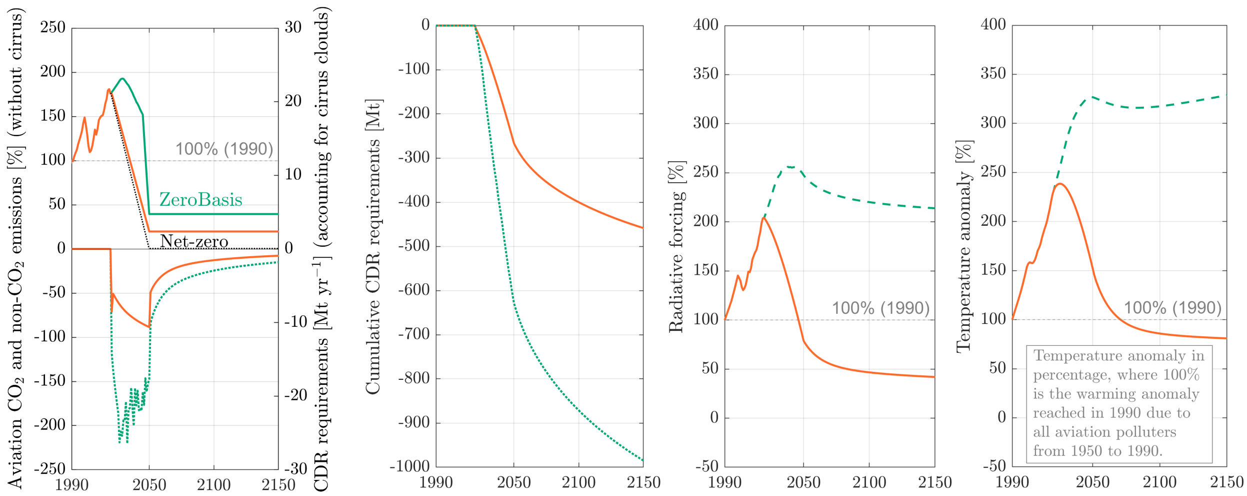


Figure 32. In the first panel, the required profile of CDR deployment is showed for a target 1 of net-zero emissions in 2050, with CDR starting from 2020, when the EP2050+ ZeroBasis emissions scenario is followed (in green) or when a more ambitious pathway of emissions reduction is deployed (in orange). Here, emissions of CO_2 and non-CO_2 polluters are shown on the left vertical axis, normalized to their values in 1990. Cirrus clouds formation, based on the kilometers of flight, is not showed here. The CDR deployment curves, shown in negative values on the right vertical axis of the first panel, compensate for CO_2 and non-CO_2 polluters and aviation-induced cirrus clouds formation. Radiative forcing (third panel) and temperature anomaly (fourth panel) are normalized to their respective, aviation-induced values in 1990 (resulting from emissions and cirrus clouds).
As expected, being more ambitious in the decrease of residual emissions before 2050 lowers both peak and cumulative CDR deployment. For aviation, namely from 26 to 10 Mt/yr and from 1000 to 450 Mt in 2150.he radiative and temperature anomaly curves after CDR deployment are equal for both the ZeroBasis (green) and more ambitious (orange) residual emissions scenarios, as the same target curve of net-zero emissions is respected.

48. Figure 32 highlights that for aviation-induced warming to remain below 1990 levels, while keeping CDR demand within feasible ranges, aviation demand—encompassing fuel consumption and total air traffic volume—must consistently decrease, starting immediately. This aligns with findings from Sacchi, Becattini et al.[10], which emphasize that "*a continuous increase in air traffic would cause synthetic jet fuel produced with renewable electricity to place excessive pressure on economic and natural resources. Alternatively, offsetting the climate impacts of fossil jet fuel via DACCS would necessitate massive* CO_2 *storage volumes and prolong dependence on fossil fuels. . . . A European climate-neutral aviation will fly if air traffic is reduced to limit the scale of the climate impacts to mitigate.*"[10]

Concluding remarks

49. Achieving either net-zero emissions (Target 1) or zero radiative forcing (Target 2) for Swiss agriculture by 2050 under the ZeroBasis scenario, with CDR deployment starting that same year, is feasible if sufficiently large amounts of CDR are generated. The required CDR amounts vary depending on the method used—whether GWP metrics or models like GWP* and LWE—particularly in the long-term projections. The actual temperature response for any emission scenario and CDR strategy must consider all relevant climate forcers—methane, nitrous oxide, and carbon dioxide—and requires calculation

using a climate model. Different methods for estimating CDR demand yield varying temperature outcomes. The SLCM employed in this study balances simplicity and accuracy in predicting climate impacts, making it a valuable tool for comparatively assessing the effectiveness of different climate policy approaches.

50. Achieving net-zero emissions (Target 1) for Swiss aviation under the ZeroBasis scenario from 2050 onward, theoretically, requires no CDR if only CO_2 emissions are considered and SAFs with a zero carbon footprint are assumed. However, in practice, the SLCM predicts a temperature anomaly several times larger than in 1990 even under these conditions. When non-CO_2 effects are considered, the required maximum CDR deployment rate in 2050 and the cumulative CDR needed throughout the century reach levels that are likely unfeasible from today's perspective. This highlights the significant challenges in fully addressing aviation's climate impact and the need for structural changes, including industry-specific measures and a possible reduction in demand.

51. The CDR requirements identified in this study present a significant challenge in both scale and speed of deployment. To meet the same climate targets, these requirements can only be reduced by: (i) initiating CDR deployment immediately rather than waiting until 2050, (ii) adopting more ambitious residual emission pathways than the ZeroBasis scenario, and (iii) implementing structural changes outside the scope of this study, including reducing demand and applying sector-specific measures for agriculture (e.g., Rosa et al.[13]) and aviation (e.g., Frias et al.[14]).

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