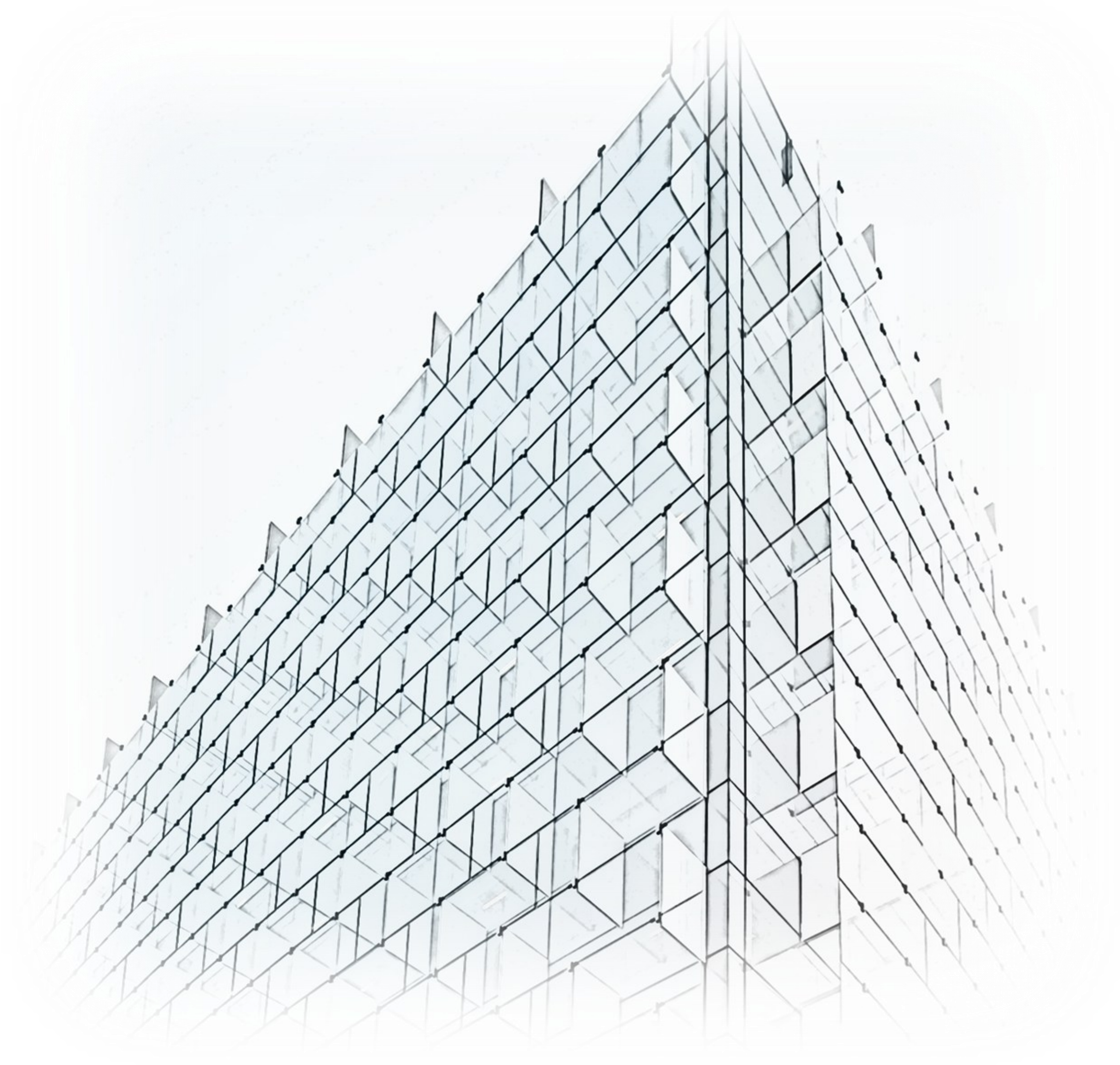

Perspectives on Switzerland's net-negative target after 2050

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Executive Summary

Recent trends in greenhouse gas (GHG) emissions and global mean temperature make it virtually certain that global warming of 1.5°C will be exceeded within the next ten years. Limiting global warming to 1.5°C in the long run will therefore almost certainly rely on global pathways in which global warming peaks above this level and subsequently returns to 1.5°C through sustained global net-negative CO2 and potentially even net-negative GHG emissions.[†]

In this context, countries with high income, strong technological, institutional and economic capacity, and substantial historical contributions to global warming are widely expected to move beyond net-zero targets and contribute to global net atmospheric carbon removal. In broad terms, scaling Switzerland's contribution to global warming – accounting for territorial CO2 and other GHGs and using its current share of the global population – implies that the median global temperature increase would already be approximately 1.8°C. Although Swiss territorial CO_2 emissions per capita fell below the global average around 2015, emissions embodied in imports substantially exceed domestic emissions. At the same time, Switzerland possesses considerable economic capacity to contribute to global mitigation efforts. Taken together, these factors suggest that Switzerland's contribution to achieving global temperature goals through carbon removals could reasonably exceed those of many other countries.

Switzerland's climate legislation already reflects this expectation by mandating net-zero GHG emissions by 2050 and a transition to net-negative GHG emissions thereafter. This report supports the operationalization of Switzerland's transition to net-negative emissions after 2050 by providing benchmark targets, discussing possible national allocation of responsibilities, and outlining policy design considerations for delivering net-negative outcomes at scale.

Swiss Net-Negative Targets after 2050

First, the report examines how Switzerland's post-2050 climate ambition for net-negative GHG emissions could be derived and provides indicative ranges for net-negative emissions in 2060. The analysis considers both equity-based burden-sharing and practical feasibility.

Burden-sharing frameworks determine how global mitigation (i.e. emission reduction and carbon removal) requirements consistent with a given temperature goal may be allocated across countries. Such frameworks depend on several key choices and parameters, including the size of the remaining global carbon budget, the accounting methods used to attribute emissions to countries, the equity principles guiding the distribution of mitigation effort, the planned future pathway leading to net-zero, and the degree of international cooperation allowed in achieving targets. These technical parameters and ethical choices significantly influence national outcomes in burden-sharing calculations and explain why published estimates vary widely.

The remaining global carbon budget describes the cumulative amount of CO_2 that can still be emitted while limiting warming to a given temperature level. Estimates of this budget depend on methodological choices, including whether temporary overshoot pathways are

[†] Net-negative CO_2 emissions occur when carbon dioxide removals exceed residual CO_2 emissions, whereas net-negative greenhouse gas (GHG) emissions require that removals exceed the residual emissions of GHGs. Net-negative GHG emissions therefore represent a more stringent requirement than net-negative CO_2 emissions.

considered, assumptions about non-CO_2 GHG emissions, and the confidence level associated with achieving a given temperature goal. As a result, even for the same temperature target, available carbon budget estimates vary substantially. Carbon budgets often serve as the starting point for burden-sharing calculations that distribute allowable emissions or removal obligations to countries, while separate accounting approaches determine countries' actual emissions. International reporting under the UNFCCC is based on territorial emissions occurring within national borders. Alternative consumption-based approaches attribute emissions embedded in international trade to final consumers and may be relevant for ethical considerations in burden-sharing discussions.

Equity principles provide the normative basis for allocating emission allowances and mitigation efforts among countries. Three principles are most commonly discussed in the literature. *Responsibility*-based approaches assign greater mitigation efforts to countries with higher cumulative historical emissions. *Capability*-based approaches allocate greater effort to countries with higher economic capacity and ability to absorb mitigation costs. *Equality*-based approaches typically distribute emission rights on a per-capita basis, implying equal access to the "atmospheric common". In practice, these "pure" principles are often combined, adjusted to account for basic development needs in lower-income countries, or implemented with transition periods from current emission levels toward common equity-based allocations.

Each principle yields qualitatively different implications for Switzerland.

- Capability-based approaches often produce the most stringent requirements given Switzerland's high per-capita income and economic output.
- Responsibility-based frameworks typically assign somewhat lower, but still substantial, mitigation efforts reflecting Switzerland's historical emissions relative to its population. Because Swiss per-capita territorial CO_2 emissions have been below the global average since around 2015, responsibility-based allocations generally become more stringent for Switzerland as the historical accounting period is extended. However, recent studies indicate that Switzerland accumulated a partial "credit" due to below-average per-capita LULUCF emissions between 1850 and 1950. As a result, allocation approaches that include land-use change emissions and very long historical time frames tend to reduce Switzerland's responsibility-derived mitigation burden. However, if consumption-based rather than territorial emissions are used, Switzerland's responsibility share is significantly higher, especially for more recent starting years.
- Equal-per-capita approaches tend to yield comparatively generous allocations. Since Switzerland's current territorial CO_2 emissions per capita are below the global average, the country could be interpreted as already overachieving under such an allocation. However, many equal-per-capita calculations for Switzerland suggest that the long-term pathway to net-zero by 2050 could still exceed the emissions levels implied by a equal-per-capita allocation.

Applying these frameworks to Switzerland yields a very wide range of possible net-negative emission targets. Existing online burden-sharing calculators and studies suggest outcomes for 2060 ranging from modest net-positive emissions under equality-based approaches (around 1 $MtCO_2$-eq) to very large net-negative emissions under some capability-based frameworks of around 230 $MtCO_2$-eq, far exceeding Switzerland's current national emission levels. Overall, however, the literature suggests that pathways derived from equity-based burden-sharing principles tend to imply mitigation efforts that are more ambitious than Switzerland's currently legislated trajectory toward net-zero emissions by 2050, indicating that additional ambition beyond 2050 could be justified.

A complementary benchmark for Switzerland's potential net-negative ambition can be derived on technical grounds by extrapolating existing national climate policy scenarios. Current modelling for Switzerland's long-term climate strategy assumes that net-zero emissions are achieved in 2050 through a combination of emission reductions (including carbon capture and storage), and domestic and international carbon dioxide removal. If the scale-up of emission avoidance and removal technologies envisaged in the decade 2040-2050 were to continue into the following decade 2050-2060, Switzerland could plausibly achieve net-negative GHG emissions exceeding 10 $MtCO_2$-eq per year by 2060.

Finally, a simple and transparent benchmarking approach is introduced that relates Switzerland's potential gross removal targets to global removal requirements under 1.5°C mitigation pathways. The method assumes that a coalition of economically developed countries contributes to carbon dioxide removal in proportion to their economic capacity. Under this framework, the Swiss removal target – and the corresponding targets for other countries in the coalition – depend on both the size of the coalition considered and the level of confidence required that global removal needs are met. Under these assumptions, a Swiss net-negative GHG target of approximately 20 $MtCO_2$-eq by 2060 – assuming that residual GHG emissions can be reduced to around 6 $MtCO_2$-eq – would represent a sufficient contribution at a 50% confidence level[†]. Moreover, the potential Swiss target of around 20 $MtCO_2$-eq by 2060 could be interpreted as reciprocating Denmark's level of ambition. Denmark is one of the few countries with relatively concrete net-negative targets and may therefore serve as a potential reference point.

Taken together, equity-based burden-sharing frameworks consistently suggest that high-income industrialized countries such as Switzerland should move beyond net-zero emissions to contribute to global temperature stabilization and the potential reversal of warming. This conclusion is broadly consistent with findings from similar country-level studies conducted for Switzerland and other industrialized countries, including Finland, Canada, and the Netherlands.

Distribution of Responsibilities for Net-Negative Emissions

The report further examines how the efforts necessary for achieving net-negative GHG emissions could be distributed among actors within Switzerland.

Rather than advocating a specific burden-sharing approach, the report explores how different principles relating to equity, principles embedded in Swiss law, general public policy principles and pragmatic considerations would align with the allocation of efforts across actors in the Swiss economy and society. The results illustrate the implications of alternative approaches and highlight key trade-offs that would ultimately need to be resolved through political decision-making.

A first set of principles derives from global equity considerations commonly used in international burden-sharing on climate change, such as those discussed above. Two principles are particularly relevant in this context: *responsibility* and *capability* (or *capacity*). Applied domestically, the responsibility logic would imply that actors

[†] Note that this differs from the confidence level associated with achieving a specific temperature target; here, the confidence level refers to the distribution of global removal requirements across a range of 1.5°C-compatible scenarios.

who have contributed most to warming – either through historically large cumulative emissions of long-lived GHGs or ongoing emissions of short-lived GHGs – would bear the greatest responsibility for delivering net-negative outcomes. A key question in such an approach concerns the time horizon over which responsibility is assessed, since the choice of start date for historical emissions can significantly influence which actors are considered responsible for climate change.

The capacity principle applied domestically would imply that actors with the greatest financial (or technological) capacity should make the greatest effort, regardless of their direct contribution to emissions. In practice, this could mean that entities with higher income or greater economic resources would either implement or finance carbon removal activities, including potentially outside Switzerland, regardless of their emissions.

A further perspective arises from principles embedded in Swiss law and climate policy. In particular, the constitution of Switzerland embeds the *polluter-pays principle* (PPP) in environmental policy, which assigns responsibility for preventing or remedying environmental harm to those who cause it. A possible interpretation of the PPP could require that the costs of achieving net-negative emissions are borne by those who continue to emit GHGs – i.e., residual emitters after 2050 – rather than by the general public. Such an approach would be similar to a levy on waste deposits being used to remediate existing landfills, i.e., where polluters are asked to cover not only the costs of their current pollution but also to contribute to the broader system costs.

Domestic burden-sharing choices are constrained by the principle of *avoidance of retroactive liability*, a widely recognized legal principle that prevents actors from being held responsible for actions that were legal at the time they occurred. This principle can limit the extent to which historical emissions are used to assign responsibility for future mitigation obligations. Another consideration concerns the *use of established policy mechanisms*. Extending existing instruments – such as emissions reporting systems, carbon pricing mechanisms, or general taxation frameworks – may be more feasible and politically acceptable than creating entirely new regulatory structures. Finally, policies designed to support net-negative emissions should rely on a sufficiently *broad base* of contributors to ensure financial stability and political legitimacy over time.

Taken together, the analysis shows that different weighting given to these policy principles leads to different conclusions regarding who should bear the burden of achieving net-negative emissions. No single approach is fully consistent with all equity considerations, public policy principles and legal requirements. Responsibility-based approaches align closely with the PPP but may conflict with the avoidance of retroactive liability if they rely on historical emissions. Conversely, capacity-based approaches generally align well with public policy principles but may not reflect the PPP.

Across the different perspectives considered, two broad approaches appear particularly compatible with the combination of legal, equity, and general public policy principles examined. One approach would allocate responsibility for the provision of net-negative GHG emissions based on those causing emissions from a defined future starting point well before net-zero – e.g., 2030 – in order to avoid retroactive liability issues. Another approach would distribute the necessary efforts according to the capacity to pay of companies or taxpayers through financial contributions used to fund carbon dioxide removal, either from 2030 or from 2050 onwards.

Implementing relevant policies as soon as possible – well before net-negative emissions are required at national level under existing law – suggests an intertemporal approach to policy design. Under such an approach, emitters, companies, and taxpayers would contribute cumulatively from, e.g., 2030 onwards toward meeting the burden of achieving net-negative emissions after 2050. Both approaches suggest an increasing role of federal government not only as market regulator to enable the private sector to achieve net-negative emission goals, but as active market participant to coordinate investments and manage risks.

Furthermore, the report highlights that the choice of domestic burden-sharing mechanisms and policies for net-negative emissions cannot be considered independently of the policies used to reach net-zero emissions. Existing sectoral targets under Swiss climate law imply that most sectors are expected to reach zero emissions by 2050, with agriculture remaining the largest source of residual emissions. If responsibility for net-negative emissions were allocated solely based on residual emissions remaining in 2050, this would concentrate the burden largely on the agricultural sector.

However, an important determinant of the required scale of carbon removal is the level of residual emissions that remain after abatement and capture at the source. Reducing residual emissions lowers the amount of removals required to achieve a given net-negative target and, for a given volume of removals, would allow for a more ambitious net-negative outcome. In this light, it may be more logical to support sectors expected to continue emitting after 2050 – such as agriculture – in further reducing these emissions rather than relying on them, or the taxpayer, to finance large-scale carbon removals.

At the company level, the requirement under Swiss climate law that all companies (excluding farms) reach net-zero emissions by 2050 implies that net emissions themselves can no longer serve as a metric for assigning additional obligations to remove CO_2 after 2050. Any company-level allocation would therefore require an alternative yardstick to allocate efforts to contribute to net-negative emissions, such as financial capacity or a formula based on earlier emissions trajectories.

Overall, the analysis suggests that reaching net-negative emissions requires deliberate policy choices in the near future about how efforts may be distributed across actors in the Swiss economy, and to enable such choices to inform strategic private sector investments. These choices involve balancing principles of historical responsibility, financial capacity, legal feasibility, and political practicality.

Financing Net-Negative Emissions

The report further examines how the provision of net-negative emissions could be financed through economic policy instruments. Because real-world experience with large-scale carbon dioxide removal remains largely nonexistent, the analysis is necessarily conceptual and exploratory. However, the report draws parallels to radioactive waste management and nuclear decommissioning, for which a substantial empirical base of governance structures already exists.

Economic approaches to carbon policy are usually evaluated against the benchmark of economic efficiency – that is, in the context of this report, achieving a given climate objective at the lowest possible cost. Such approaches typically seek to provide appropriate incentives for both emission reductions and carbon removals by aligning these activities within a coherent price-based framework. These instruments are therefore based on polluter-financed carbon removals and aim to internalize the expected costs of achieving net-negative emissions, ensuring that the cost of present and/or future carbon removal is reflected in present emission and abatement decisions.

A central conceptual distinction in economic instruments concerns whether emissions and removals are linked within the same period or across time. *Contemporaneous* instruments finance removals at the time emissions occur, for example by recycling carbon pricing revenues into carbon removal procurement or by requiring emitters to offset emissions through removals in the same period. *Intertemporal* instruments, by contrast, link emissions released today to removals delivered in the future. These approaches can involve accumulating financial resources over time – for example through a carbon tax – or assigning emitters forward obligations to finance or deliver removals at a later stage. Hence, both contemporaneous and intertemporal approaches may differ with respect to how prices are established – through markets or regulation – and whether an intermediary institution manages the financing of removals.

The analysis first considers the prospects for financing net-negative emissions through contemporaneous instruments. Integrating carbon removals into existing carbon pricing systems – such as emissions trading schemes – could in principle lead to more cost-effective outcomes. As long as gross emissions exceed removals, such systems remain broadly consistent with a *strict interpretation of the PPP*, since emitters pay for each unit of emission and may thereby finance removals on a *ton-by-ton* basis.

However, this logic becomes increasingly difficult to sustain once emissions decline toward net-zero levels. At net-zero, residual GHG emissions are exactly balanced by carbon removals. Achieving net-negative emissions would therefore require each residual unit of emissions after 2050 to finance more than one unit of carbon removal. Such "one-to-many" relationships between emissions may raise both economic and legal challenges. Conceptual analysis suggests that contemporaneous polluter-financed arrangements may not yield cost-effective – or even feasible – outcomes for a given net-negative GHG target. In some circumstances, they could even create incentives to maintain higher levels of residual emissions in order to sustain the revenue base needed to finance removals. These limitations suggest that purely contemporaneous polluter-financed instruments are unlikely to support sustained net-negative emissions at scale.

An alternative would be to finance net-negative emissions through public budgets. However, such an approach would require significant preparation well before 2050, as large-scale funding mechanisms would need to be established in advance. Moreover, climate-related public expenditures are likely to increase substantially in the coming decades, including spending on adaptation, international climate finance, and loss-and-damage mechanisms. Financing net-negative emissions through public budgets could therefore raise fiscal sustainability concerns and intensify competition for limited public resources.

The analysis therefore examines intertemporal instruments, which link present emissions to removals that occur later in time. When implemented well before net-zero emissions are reached, such systems can maintain a broad financing base and remain consistent with a strict, ton-by-ton interpretation of the PPP. Conceptually, intertemporal designs can lead to cost-effective outcomes under any net-negative target, provided that a national carbon budget has not yet been depleted at the time the policy is introduced.

In practice, however, implementing intertemporal instruments faces significant challenges. Market-based approaches require firms to compare the costs of reducing emissions today with the expected discounted cost of future carbon removal. This presupposes that firms can form reasonably reliable expectations about future removal costs as well as technological and regulatory developments. Given the early stage of the carbon removal ecosystem and the limited empirical information available on future removal costs and scalability, these informational requirements are difficult to satisfy. In addition, long-term obligations raise questions of commitment and enforcement, as firms may not exist decades after the emissions occur or may expect that regulatory requirements will be relaxed over time. Addressing these risks requires additional mechanisms – such as collateral requirements or other forms of financial assurance – to ensure that removal obligations remain credible.

Against this background, the report discusses three stylized intertemporal design approaches that have emerged in the literature: a government-led *tax-fund* approach, an emission trading system-based *removal obligation* approach with a collateral requirement, and an approach that treats carbon removal obligations as a form of *environmental liability* supported by financial assurance mechanisms. While these approaches differ in some implementation details, they share the core principle that emissions today should be priced at least at the discounted cost of removing carbon in the future – implying that future removal costs and deployment scales must at least be estimable to some extent, which in turn requires a carbon removal ecosystem that is more mature than the current one.

Beyond the design of financing instruments themselves, the affordability of large-scale carbon removal depends on both demand- and supply-side factors. The compliance costs paid for removals faced by regulated entities will depend not only on technological progress but also on how rents in carbon removal markets are managed. Moreover, the costs of ambitious net-negative targets will depend partly on the availability of international carbon removal opportunities. Switzerland's climate strategy already anticipates sourcing part of its removals abroad under Article 6 of the Paris Agreement. Access to comparatively abundant and lower-cost removal potential outside Switzerland could therefore play an important role in achieving net-zero emissions and net-negative thereafter at manageable cost, although significant uncertainty remains regarding the future scale and governance of international carbon removal markets.

Furthermore, important lessons can be drawn from the governance of *nuclear decommissioning* and *radioactive waste management*. Unlike carbon removal, these policy domains provide a rich empirical record of how societies manage long-term environmental liabilities and intergenerational obligations. Existing governance systems typically combine the PPP with safeguards designed to prevent unfunded liabilities from being transferred to future generations. In practice, a *subsidiarity principle* often applies: the most local or decentralized entity capable of managing a task should carry it out. Responsibility for decommissioning is therefore frequently decentralized to operators, while the management of radioactive waste – characterized by longer time horizons as well as greater uncertainty and non-diversifiable risks – tends to involve stronger public coordination and oversight.

Carbon removal currently appears more similar to radioactive waste management, which can be understood as a problem of maintaining *cumulative funding adequacy*. Under such an approach, the focus is not on pricing each ton of emissions to reflect its future removal cost, but on ensuring that sufficient funding is accumulated over time to finance the total volume of required removals. This typically involves periodically updating cost estimates, identifying potential funding shortfalls, and adjusting contributions – primarily from polluters but potentially also from other sources – to maintain funding adequacy as knowledge about removal costs and deployment evolves. In practice, this requires linking fund management closely to the operational deployment of carbon removal in order to improve cost estimates over time. Over time, however, carbon removal could evolve toward more market-based arrangements as technologies mature and risks become better understood.

Experience from radioactive waste management also shows that many jurisdictions anchor liability with operators while employing multiple *lines of defense* – such as financial guarantees, shareholder liabilities or shared operator liabilities – to ensure that funding shortfalls are borne primarily by operators rather than by the general public. These governance principles may provide useful reference points for future carbon removal policy.

Taken together, the analysis suggests that purely contemporaneous financing mechanisms are unlikely to support sustained net-negative emissions. Intertemporal policy designs are therefore likely to play an important role in linking present emissions to future removals. At the same time, the current state of the carbon removal ecosystem and the substantial uncertainties surrounding future costs and delivery imply that fully market-based solutions may be difficult to implement in the near term. Public institutions will likely need to play a central role in managing the financial and governance challenges associated with large-scale net carbon removal, extending beyond their roles as regulators to include a more mission-oriented role in enabling and coordinating CDR delivery. Since intertemporal instruments would need to be implemented as early as 2030, hence well before a mature CDR ecosystem will be established, near-term policy efforts may initially focus on ensuring cumulative funding adequacy and fiscal sustainability by establishing a potentially broad base of contributors to atmospheric clean-up. As the carbon removal ecosystem matures, policy frameworks could gradually transition toward more decentralized and market-based approaches with the aim of improving efficiency.

Zusammenfassung

Derzeitige Trends bei den Treibhausgasemissionen und der globalen Mitteltemperatur machen es praktisch sicher, dass die globale Erwärmung 1,5 °C innerhalb der nächsten zehn Jahre überschritten wird. Die Begrenzung der globalen Erwärmung auf 1,5 °C auf lange Sicht wird daher mit nahezu vollständiger Sicherheit auf globalen Entwicklungspfaden beruhen, in denen die Erwärmung diesen Wert zunächst überschreitet und anschliessend durch anhaltende globale Netto-Negativemissionen von CO_2 und möglicherweise sogar Netto-Negativemissionen bei allen Treibhausgasen wieder auf 1,5 °C zurückgeführt wird.†

Vor diesem Hintergrund wird allgemein erwartet, dass Länder mit hohem Einkommen, starker technologischer, institutioneller und wirtschaftlicher Leistungsfähigkeit sowie erheblichen historischen Beiträgen zur globalen Erwärmung über Netto-Null-Ziele hinausgehen und zur globalen Netto-Entnahme von Kohlenstoff aus der Atmosphäre beitragen. Grob kalkuliert impliziert der Beitrag der Schweiz zur globalen Erwärmung – unter Berücksichtigung von territorialen CO_2 und anderer Treibhausgasemissionen sowie ihres heutigen Anteils an der Weltbevölkerung –, dass der Anstieg der globalen Median-Temperatur bereits bei ungefähr 1,8 °C läge. Obwohl die territorialen CO_2-Emissionen pro Kopf in der Schweiz um 2015 unter den globalen Durchschnitt fielen, übersteigen die in Importen enthaltenen Emissionen die inländischen Emissionen deutlich. Gleichzeitig verfügt die Schweiz über erhebliche wirtschaftliche Kapazitäten, um zu globalen Minderungsanstrengungen beizutragen. Zusammengenommen sprechen diese Faktoren dafür, dass der Schweizer Beitrag zur Erreichung globaler Temperaturziele durch CO_2-Entnahmen plausibel höher ausfallen könnte als der vieler anderer Länder.

Die Schweizer Klimagesetzgebung spiegelt diese Erwartung bereits wider, indem sie bis 2050 Netto-Null-Treibhausgasemissionen und anschliessend den Übergang zu negativen Netto-Treibhausgasemissionen vorschreibt. Dieser Bericht unterstützt die Operationalisierung des Schweizer Übergangs zu negativen Nettoemissionen nach 2050, indem er Orientierungsziele bereitstellt, mögliche nationale Verantwortungszuweisungen diskutiert und Überlegungen zur Ausgestaltung von klimapolitischen Steuerungsinstrumenten für die Bereitstellung netto-negativer Zukunftspfade skizziert.

Schweizer Netto-Negativ-Ziele nach 2050

Zunächst untersucht der Bericht, wie sich das Schweizer Ambitionsniveau für negative Netto-Treibhausgasemissionen nach 2050 ableiten lässt, und liefert indikative Bandbreiten für negative Nettoemissionen im Jahr 2060. Die Analyse berücksichtigt sowohl Gerechtigkeitsprinzipien welche der Lastenteilung zugrunde liegen, als auch praktische Umsetzbarkeitsaspekte.

Lastenteilungsmodelle bestimmen, wie globale Minderungsanforderungen – also Emissionsminderungen und Kohlenstoffentnahmen –, die mit einem bestimmten Temperaturziel vereinbar sind, auf Länder verteilt werden können. Solche Modelle hängen von mehreren zentralen Entscheidungen und Parametern ab, darunter die Grösse des verbleibenden globalen Kohlenstoffbudgets, die verwendeten Methoden zur

† Netto-negative CO_2-Emissionen liegen vor, wenn die Entnahme von Kohlendioxid die verbleibenden CO_2-Emissionen übersteigt, während netto-negative Treibhausgas-(THG-)Emissionen voraussetzen, dass die Entnahmen die verbleibenden THG-Emissionen übersteigen. Netto-negative THG-Emissionen stellen daher eine strengere Anforderung dar als netto-negative CO_2-Emissionen.

Zuordnung von Emissionen zu Ländern, die Gerechtigkeitsprinzipien für die Verteilung der Minderungsanstrengungen, der geplante künftige Pfad bis zur Erreichung des Netto-Null Ziels, sowie das Ausmass internationaler Kooperation bei der Zielerreichung. Diese technischen Parameter und ethischen Entscheidungen beeinflussen nationale Ergebnisse in Lastenteilungsrechnungen erheblich und erklären, weshalb veröffentlichte Schätzungen stark variieren.

Das verbleibende globale Kohlenstoffbudget beschreibt die kumulative Menge an CO_2, die noch ausgestossen werden kann, während die Erwärmung auf ein bestimmtes Temperaturniveau begrenzt wird. Schätzungen dieses Budgets hängen von methodischen Entscheidungen ab, etwa davon, ob vorübergehende Überschreitungspfade berücksichtigt werden, welche Annahmen zu Nicht-CO_2-Treibhausgasen getroffen werden und mit welchem Konfidenzniveau ein Temperaturziel erreicht werden soll. Daher unterscheiden sich die verfügbaren Schätzungen des Kohlenstoffbudgets selbst für dasselbe Temperaturziel erheblich. Kohlenstoffbudgets dienen häufig als Ausgangspunkt für Lastenteilungsrechnungen, mit denen zulässige Emissionen oder Entnahmeverpflichtungen auf Länder verteilt werden, während gesonderte Bilanzierungsansätze die tatsächlichen Emissionen von Ländern bestimmen. Die internationale Berichterstattung unter der UNFCCC basiert auf territorialen Emissionen innerhalb nationaler Grenzen. Alternative konsumbezogene Ansätze ordnen die im internationalen Handel verkörperten Emissionen den Endverbrauchern zu und können für ethische Überlegungen in Lastenteilungsdebatten relevant sein.

Gerechtigkeitsprinzipien bilden die normative Grundlage für die Zuweisung von Emissionsrechten und Minderungsanstrengungen zwischen Ländern. In der Literatur werden vor allem drei Prinzipien diskutiert. Verantwortungsbasierte Ansätze weisen Ländern mit höheren kumulierten historischen Emissionen grössere Minderungsanstrengungen zu. Fähigkeitsbasierte Ansätze verteilen grössere Anstrengungen auf Länder mit höherer wirtschaftlicher Leistungsfähigkeit und besserer Fähigkeit, Minderungs- und Anpassungskosten zu tragen. Gleichheitsbasierte Ansätze verteilen Emissionsrechte typischerweise pro Kopf und implizieren damit einen gleichen Zugang zum „atmosphärischen Gemeingut“. In der Praxis werden diese „reinen“ Prinzipien häufig kombiniert, angepasst, um grundlegende Entwicklungsbedürfnisse in Ländern mit niedrigerem Einkommen zu berücksichtigen, oder mit Übergangsphasen von heutigen Emissionsniveaus hin zu stärker gerechtigkeitsbasierten Zuteilungen umgesetzt.

Jedes Prinzip führt für die Schweiz zu qualitativ unterschiedlichen Konsequenzen.

Fähigkeitsbasierte Ansätze führen angesichts des hohen Pro-Kopf-Einkommens und der Pro-Kopf-Wirtschaftsleistung der Schweiz häufig zu den strengsten Anforderungen.

Verantwortungsbasierte Modelle weisen in der Regel etwas geringere, aber weiterhin erhebliche Minderungsanstrengungen zu, die die historischen Emissionen der Schweiz relativ zu ihrer Bevölkerung widerspiegeln. Da die territorialen CO_2-Emissionen pro Kopf in der Schweiz seit etwa 2015 unter dem globalen Durchschnitt liegen, werden verantwortungsbasierte Zuteilungen für die Schweiz im Allgemeinen umso strenger, je weiter der historische Bilanzierungszeitraum ausgedehnt wird. Neuere Studien zeigen jedoch, dass die Schweiz aufgrund unterdurchschnittlicher Pro-Kopf-Emissionen aus Landnutzung, Landnutzungsänderung und Forstwirtschaft (engl. LULUCF) zwischen 1850 und 1950 ein „Guthaben“ angesammelt hat. Daher verringern Zuteilungsansätze, die Emissionen aus Landnutzungsänderungen und sehr lange historische Zeiträume einbeziehen, tendenziell die aus dem Verantwortungsprinzip abgeleitete Minderungsbelastung der Schweiz. Werden jedoch konsumbezogene statt territorialer Emissionen verwendet, ist der Schweizer Verantwortungsanteil im Allgemeinen deutlich höher.

Gleichheitsorientierte Pro-Kopf-Ansätze führen tendenziell zu vergleichsweise grosszügigen Zuteilungen. Da die derzeitigen territorialen CO_2-Emissionen pro Kopf in der Schweiz unter dem globalen Durchschnitt liegen, könnte man das Land unter einem solchen Zuteilungsansatz als bereits übererfüllend einstufen. Allerdings deuten viele Berechnungen für die Schweiz darauf hin, dass der langfristige Pfad zu Netto-Null-Emissionen bis 2050 dennoch über den Emissionsniveaus liegen könnte, die sich aus einer strikt gleichen Pro-Kopf-Zuteilung ergeben würden.

Wendet man diese Lastenteilungsmodelle auf die Schweiz an, ergibt sich eine sehr breite Spanne möglicher Ziele für Netto-Negativ-Emissionen. Bestehende Online-Rechner zur Lastenteilung und Studien deuten für 2060 auf Ergebnisse hin, die von moderaten Netto-Positiv-Emissionen unter gleichheitsbasierten Ansätzen (rund 1 $MtCO_2$-eq) bis zu sehr hohen Netto-Negativ-Emissionen unter einigen fähigkeitsbasierten Modellen von rund 230 $MtCO_2$-eq reichen – also deutlich über den heutigen nationalen Emissionsniveaus der Schweiz. Insgesamt legt die Literatur jedoch nahe, dass Pfade, die aus gerechtigkeitsbasierten Lastenteilungsprinzipien abgeleitet werden, tendenziell ambitioniertere Minderungsanstrengungen implizieren als die derzeit gesetzlich verankerte Schweizer Entwicklung Richtung Netto-Null-Emissionen bis 2050. Das deutet darauf hin, dass zusätzliche Ambition über 2050 hinaus gerechtfertigt sein könnte.

Ein ergänzender Referenzwert für das potenzielle Schweizer Ambitionsniveau bei negativen Nettoemissionen lässt sich auf technischer Grundlage durch Extrapolation bestehender nationaler klimapolitischer Szenarien ableiten. Die aktuelle Modellierung für die langfristige Klimastrategie der Schweiz geht davon aus, dass Netto-Null-Emissionen im Jahr 2050 durch eine Kombination aus Emissionsminderungen (einschliesslich Carbon Capture and Storage) sowie inländischer und internationaler Kohlendioxidentnahme erreicht werden. Würde die in den Jahren 2040 bis 2050 vorgesehene Skalierung von Emissionsvermeidung und Entnahmetechnologien im Folgejahrzehnt 2050 bis 2060 fortgesetzt, könnte die Schweiz plausibel negative Netto-Treibhausgasemissionen von mehr als 10 $MtCO_2$-eq pro Jahr bis 2060 erreichen.

Schliesslich wird ein einfacher und transparenter Benchmarking-Ansatz eingeführt, der die potenziellen Bruttoentnahmeziele der Schweiz mit dem globalen Entnahmebedarf unter 1,5-°C-Minderungspfaden verknüpft. Die Methode nimmt an, dass entwickelte Länder innerhalb einer Koalition proportional zu ihren jeweiligen wirtschaftlichen Leistungsfähigkeiten zur Kohlendioxidentnahme beitragen. In diesem Rahmen hängen das Schweizer Entnahmeziel – und die entsprechenden Ziele anderer Länder in der Koalition – sowohl von der Grösse der betrachteten Koalition als auch vom geforderten Konfidenzniveau ab, mit dem der globale Entnahmebedarf gedeckt werden soll. Unter diesen Annahmen würde ein Schweizer Ziel negativer Netto-Treibhausgasemissionen von ungefähr 20 $MtCO_2$-eq bis 2060 – unter der Annahme, dass die verbleibenden Treibhausgasemissionen auf rund 6 $MtCO_2$-eq gesenkt werden können – bei einem Konfidenzniveau von 50 % einen ausreichenden Beitrag darstellen. Zudem könnte das potenzielle Schweizer Ziel von rund 20 $MtCO_2$-eq bis 2060 als Spiegelung des dänischen Ambitionsniveaus interpretiert werden. Dänemark ist eines der wenigen Länder mit relativ konkreten Negativemissionszielen und kann daher als möglicher Referenzpunkt dienen.

Insgesamt legen gerechtigkeitsbasierte Lastenteilungsrahmen konsistent nahe, dass einkommensstarke Industrieländer wie die Schweiz über Netto-Null-Emissionen hinausgehen sollten, um zur Stabilisierung der globalen Temperatur und möglicherweise zur Umkehr der Erwärmung beizutragen. Diese Schlussfolgerung stimmt weitgehend mit Ergebnissen ähnlicher Länderstudien für die Schweiz und andere Industrieländer überein, darunter Finnland, Kanada und die Niederlande.

Verteilung der Verantwortlichkeiten für Netto-Negativ-Emissionen

Der Bericht untersucht ferner, wie die für negative Netto-Treibhausgasemissionen notwendigen Anstrengungen innerhalb der Schweiz auf verschiedene Akteure verteilt werden könnten.

Anstatt einen bestimmten Lastenteilungsansatz zu empfehlen, untersucht der Bericht, wie unterschiedliche Prinzipien in Bezug auf Gerechtigkeit, im Schweizer Recht verankerte Grundsätze, allgemeine Prinzipien öffentlicher Politik und pragmatische Erwägungen mit der Verteilung von Anstrengungen auf Akteure in der Schweizer Wirtschaft und Gesellschaft zusammenpassen würden. Die Ergebnisse verdeutlichen die Implikationen alternativer Ansätze und heben zentrale Zielkonflikte hervor, die letztlich politisch entschieden werden müssten.

Eine erste Gruppe von Prinzipien leitet sich aus globalen Gerechtigkeitsüberlegungen ab, die in der internationalen Lastenteilung im Klimabereich häufig verwendet werden, etwa die zuvor diskutierten. Zwei Prinzipien sind in diesem Kontext besonders relevant: Verantwortung und Fähigkeit (oder Kapazität). Auf die nationale Ebene übertragen würde die Verantwortungslogik bedeuten, dass Akteure, die am stärksten zur Erwärmung beigetragen haben – entweder durch historisch hohe kumulierte Emissionen langlebiger Treibhausgase oder durch laufende Emissionen kurzlebiger Treibhausgase –, die grösste Verantwortung für die Bereitstellung negativer Nettoergebnisse tragen würden. Eine zentrale Frage eines solchen Ansatzes betrifft den Zeitraum, über den Verantwortung bewertet wird, da die Wahl des Startdatums für historische Emissionen erheblich beeinflussen kann, welche Akteure als für den Klimawandel verantwortlich gelten.

Das auf die nationale Ebene angewandte Kapazitätsprinzip würde bedeuten, dass Akteure mit der grössten finanziellen (oder technologischen) Leistungsfähigkeit die grössten Anstrengungen unternehmen sollten – unabhängig von ihrem direkten Beitrag zu Emissionen. In der Praxis könnte dies bedeuten, dass Akteure mit höherem Einkommen oder grösseren wirtschaftlichen Ressourcen CO_2-Entnahmeaktivitäten umsetzen oder finanzieren, gegebenenfalls auch ausserhalb der Schweiz, unabhängig von ihren Emissionen.

Eine weitere Perspektive ergibt sich aus Grundsätzen, die im Schweizer Recht und in der Schweizer Klimapolitik verankert sind. Insbesondere ist in der Schweizer Bundesverfassung das Verursacherprinzip in der Umweltpolitik verankert, das die Verantwortung für die Vermeidung oder Behebung von Umweltschäden denjenigen zuweist, die sie verursachen. Eine mögliche Auslegung dieses Prinzips könnte verlangen, dass die Kosten zur Erreichung negativer Nettoemissionen von jenen getragen werden, die weiterhin Treibhausgase ausstossen – also von den verbleibenden Emittenten nach 2050 – und nicht von der Allgemeinheit. Ein solcher Ansatz wäre vergleichbar mit einer Abgabe auf Deponieeinlagerungen zur Sanierung bestehender Altlasten: Verursacher werden dabei nicht nur aufgefordert, die Kosten ihrer aktuellen Verschmutzung zu tragen, sondern auch zu den breiteren Systemkosten beizutragen.

Nationale Lastenteilungsentscheidungen werden durch das Prinzip der Vermeidung rückwirkender Haftung begrenzt – einen weithin anerkannten Rechtsgrundsatz, der verhindert, dass Akteure für Handlungen verantwortlich gemacht werden, die zum Zeitpunkt ihres Vollzugs rechtmässig waren. Dieses Prinzip kann einschränken, in welchem Umfang historische

Emissionen zur Zuweisung künftiger Minderungsverpflichtungen herangezogen werden. Ein weiterer Gesichtspunkt betrifft die Nutzung bestehender Steuerungsinstrumente. Die Ausweitung bestehender Instrumente – etwa Emissionsberichtssysteme, CO_2-Bepreisungsmechanismen oder allgemeiner Steuerrahmen – könnte praktikabler und politisch akzeptabler sein als die Schaffung völlig neuer Regulierungsstrukturen. Schliesslich sollten Politiken zur Unterstützung negativer Nettoemissionen auf einer ausreichend breiten Basis von Beitragszahlern beruhen, um finanzielle Stabilität und politische Legitimität langfristig sicherzustellen.

Insgesamt zeigt die Analyse, dass eine unterschiedliche Gewichtung dieser Prinzipien zu unterschiedlichen Schlussfolgerungen darüber führt, wer die Last zur Erreichung von Netto-Negativ-Emissionen tragen sollte. Kein einzelner Ansatz ist vollständig mit allen Gerechtigkeitsüberlegungen, politischen Grundsätzen und rechtlichen Anforderungen vereinbar. Verantwortungsbasierte Ansätze stimmen eng mit dem Verursacherprinzip überein, können jedoch mit der Vermeidung rückwirkender Haftung kollidieren, wenn sie sich auf historische Emissionen stützen. Kapazitätsbasierte Ansätze hingegen passen im Allgemeinen gut zu den Grundsätzen der Politikgestaltung, spiegeln das Verursacherprinzip aber nicht zwingend wider.

Über die unterschiedlichen betrachteten Perspektiven hinweg erscheinen zwei breite Ansätze besonders gut mit der Kombination aus rechtlichen, gerechtigkeitsbezogenen und allgemeinen politischen Grundsätzen vereinbar. Ein Ansatz würde die Verantwortung für die Bereitstellung negativer Netto-Treibhausgasemissionen jenen zuweisen, die Emissionen ab einem definierten zukünftigen Startpunkt deutlich vor 2050 verursachen – etwa ab 2030 –, um Probleme rückwirkender Haftung zu vermeiden. Ein anderer Ansatz würde die erforderlichen Anstrengungen entsprechend der Zahlungsfähigkeit von Unternehmen oder Steuerzahlern über finanzielle Beiträge verteilen, die zur Finanzierung von Kohlendioxidentnahmen verwendet werden, entweder ab 2030 oder erst ab 2050.

Die möglichst frühe Umsetzung relevanter Politiken – also deutlich bevor Netto-Negativ-Emissionen nach geltendem Recht auf nationaler Ebene erforderlich werden – spricht für einen intertemporalen Ansatz der Politikgestaltung. In einem solchen Ansatz würden Emittenten, Unternehmen und Steuerzahler beispielsweise ab 2030 kumulativ dazu beitragen, die Last zur Erreichung von Netto-Negativ-Emissionen nach 2050 zu tragen. Beide Ansätze deuten auf eine wachsende Rolle des Bundes hin – nicht nur als Marktregulator, der dem Privatsektor das Erreichen negativer Nettoemissionsziele ermöglicht, sondern auch als aktiver Marktteilnehmer zur Koordination von Investitionen und zum Management von Risiken.

Ferner hebt der Bericht hervor, dass die Wahl inländischer Lastenteilungsmechanismen und Politiken für Netto-Negativ-Emissionen nicht unabhängig von den Politiken betrachtet werden kann, die zum Erreichen von Netto-Null-Emissionen eingesetzt werden. Bestehende Sektorziele im Schweizer Klimarecht implizieren, dass die meisten Sektoren bis 2050 Null-Emissionen erreichen sollen, während die Landwirtschaft die grösste Quelle verbleibender Emissionen bleibt. Würde die Verantwortung für Netto-Negativ-Emissionen ausschliesslich auf Basis der nach dem Jahr 2050 verbleibenden Emissionen zugewiesen, würde sich die Last daher weitgehend auf den Landwirtschaftssektor konzentrieren.

Ein wichtiger Bestimmungsfaktor für das erforderliche Ausmass an CO_2-Entnahmen ist jedoch das Niveau der Residualemissionen nach Vermeidung, Minderung und Abscheidung an der Quelle. Die Verringerung von Residualemissionen senkt die Menge an Entnahmen, die erforderlich ist, um ein bestimmtes Negativziel zu erreichen, und würde bei einem gegebenen Entnahmevolumen ein ambitionierteres Netto-

Negativ-Ergebnis erlauben. Vor diesem Hintergrund könnte es sinnvoller sein, jene Sektoren, die voraussichtlich auch nach 2050 weiter emittieren – wie etwa die Landwirtschaft –, bei der weiteren Senkung dieser Emissionen zu unterstützen, anstatt sich darauf zu verlassen, dass sie oder die Steuerzahler grossskalige CO_2-Entnahmen finanzieren.

Auf Unternehmensebene bedeutet die Vorgabe des Schweizer Klimarechts, dass alle Unternehmen (mit Ausnahme landwirtschaftlicher Betriebe) bis 2050 Netto-Null-Emissionen erreichen müssen, dass Netto-Emissionen selbst danach nicht mehr als Massstab für zusätzliche Verpflichtungen zur CO_2-Entnahme nach 2050 dienen können. Jede unternehmensbezogene Zuteilung würde daher einen alternativen Massstab erfordern, um Beiträge zu Netto-Negativ-Emissionen zu bestimmen, etwa die finanzielle Leistungsfähigkeit oder eine Formel auf Basis früherer Emissionspfade.

Insgesamt legt die Analyse nahe, dass das Erreichen Netto-Negativ-Emissionen bewusste politische Entscheidungen in naher Zukunft darüber erfordert, wie die Anstrengungen auf Akteure in der Schweizer Wirtschaft verteilt werden können, damit diese Entscheidungen strategische Investitionen des Privatsektors rechtzeitig leiten können. Diese Entscheidungen erfordern eine Abwägung zwischen historischer Verantwortung, finanzieller Leistungsfähigkeit, rechtlicher Umsetzbarkeit und politischer Praktikabilität.

Finanzierung von Netto-Negativ-Emissionen

Der Bericht untersucht ferner, wie die Bereitstellung von Netto-Negativ-Emissionen durch wirtschaftspolitische Instrumente finanziert werden könnte. Da praktische Erfahrungen mit grossskaliger Kohlendioxidentnahme bislang weitgehend fehlen, ist die Analyse notwendigerweise konzeptionell und explorativ. Der Bericht zieht jedoch Parallelen zur Entsorgung radioaktiver Abfälle und zur Stilllegung von Kernkraftwerken, für die bereits eine umfangreiche empirische Grundlage zu Governance-Strukturen existiert.

Wirtschaftspolitische Ansätze der Klimapolitik werden üblicherweise am Massstab wirtschaftlicher Effizienz bewertet – also im Kontext dieses Berichts daran, ein bestimmtes Klimaziel zu den geringstmöglichen Kosten zu erreichen. Solche Ansätze zielen typischerweise darauf ab, sowohl Emissionsminderungen als auch Kohlenstoffentnahmen geeignete Anreize zu geben, indem beide Aktivitäten in einen kohärenten preisgestützten Rahmen eingebettet werden. Diese Instrumente beruhen daher auf vom Verursacher finanzierten Kohlenstoffentnahmen und sollen die erwarteten Kosten zur Erreichung von Netto-Negativ-Emissionen internalisieren, sodass die Kosten gegenwärtiger und/oder zukünftiger CO_2-Entnahmen bereits in gegenwärtigen Emissions- und Minderungsentscheidungen berücksichtigt werden.

Eine zentrale konzeptionelle Unterscheidung bei wirtschaftspolitischen Instrumenten betrifft die Frage, ob Emissionen und Entnahmen innerhalb desselben Zeitraums oder über einen grösseren Zeitraum hinweg verknüpft werden. *Zeitgleiche* Instrumente finanzieren Kohlenstoffentnahmen in dem Zeitraum, in dem Emissionen entstehen – zum Beispiel durch die Verwendung von Einnahmen aus CO_2-Bepreisung für die Beschaffung von CO_2-Entnahmen oder durch die Verpflichtung von Emittenten, Emissionen im selben Zeitraum durch Entnahmen auszugleichen. *Intertemporale* Instrumente hingegen verknüpfen heute freigesetzte Emissionen mit Entnahmen, die erst in der Zukunft erbracht werden. Solche Ansätze können den Aufbau finanzieller Mittel über die Zeit beinhalten – beispielsweise über eine CO_2-Steuer – oder Emittenten zukünftige Verpflichtungen zuweisen, Entnahmen zu finanzieren oder zu liefern. Sowohl zeitgleiche als auch intertemporale Ansätze können sich darin unterscheiden, wie Preise festgelegt werden – über Märkte oder Regulierung – und ob eine vermittelnde Institution die Finanzierung von Entnahmen verwaltet.

Die Analyse betrachtet zunächst die Aussichten, Netto-Negativ-Emissionen über zeitgleiche Instrumente zu finanzieren. Die Integration von Kohlenstoffentnahmen in bestehende CO_2-Bepreisungssysteme – etwa Emissionshandelssysteme – könnte prinzipiell zu kosteneffizienteren Ergebnissen führen. Solange die Bruttoemissionen die Entnahmen übersteigen, bleiben solche Systeme weitgehend mit einer strikten Auslegung des Verursacherprinzips vereinbar, da Emittenten für jede Emissionseinheit zahlen und damit Entnahmen auf Tonne-für-Tonne-Basis finanzieren können.

Diese Logik wird jedoch zunehmend schwieriger aufrechtzuerhalten, sobald die Emissionen in Richtung Netto-Null sinken. Bei Netto-Null werden verbleibende Treibhausgasemissionen exakt durch Kohlenstoffentnahmen ausgeglichen. Um negative Nettoemissionen zu erreichen, müsste daher jede verbleibende Emissionseinheit nach 2050 mehr als eine Einheit Kohlenstoffentnahme finanzieren. Solche „1:n“-Beziehungen können sowohl wirtschaftliche als auch rechtliche Herausforderungen aufwerfen. Konzeptionelle Analysen legen etwa nahe, dass zeitgleiche, vom Verursacher finanzierte Instrumente in der Regel weniger kosteneffizient sind und den verfügbaren Lösungsraum einschränken. Dadurch kann es sein, dass ein vorgegebenes Netto-Negativ-Ziel mit einem solchen Politikansatz gar nicht erreicht werden kann. Unter bestimmten Umständen könnte ein solcher Ansatz sogar Anreize schaffen, höhere Residualmissionen aufrechtzuerhalten, um die Einnahmenbasis zur Finanzierung von Entnahmen zu sichern. Das spricht dafür, dass rein zeitgleiche, vom Verursacher finanzierte Instrumente Netto-Negativ-Emissionen in grossem Massstab kaum aufrechterhalten können.

Eine Alternative bestünde darin, Netto-Negativ-Emissionen aus öffentlichen Haushalten zu finanzieren. Ein solcher Ansatz würde jedoch erhebliche Vorbereitungen deutlich vor 2050 erfordern, da gross angelegte Finanzierungsmechanismen im Voraus aufgebaut werden müssten. Ausserdem dürften klimabezogene öffentliche Ausgaben in den kommenden Jahrzehnten stark steigen, einschliesslich Ausgaben für Anpassung, internationale Klimafinanzierung sowie Mechanismen für Verluste und Schäden. Die Finanzierung von Netto-Negativ-Emissionen aus öffentlichen Haushalten könnte daher fiskalische Nachhaltigkeitsfragen aufwerfen und den Wettbewerb um begrenzte öffentliche Mittel verschärfen.

Die Analyse widmet sich daher intertemporalen Instrumenten, die heutige Emissionen mit späteren Entnahmen verknüpfen. Werden solche Systeme deutlich vor Erreichen von Netto-Null-Emissionen eingeführt, können sie eine breite Finanzierungsbasis erhalten und zugleich mit einer strikten Tonne-für-Tonne-Auslegung des Verursacherprinzips vereinbar bleiben. Konzeptionell können intertemporale Ausgestaltungen unter jedem Net-Negativ-Ziel zu kosteneffizienten Ergebnissen führen, vorausgesetzt, ein nationales Kohlenstoffbudget ist zum Zeitpunkt der Einführung der Politik noch nicht erschöpft.

In der Praxis ist die Umsetzung intertemporaler Instrumente jedoch mit erheblichen Herausforderungen verbunden. Marktbasierte Ansätze setzen voraus, dass Unternehmen die Kosten heutiger Emissionsminderung mit den erwarteten diskontierten Kosten zukünftiger Kohlenstoffentnahme vergleichen. Das setzt wiederum voraus, dass Unternehmen hinreichend verlässliche Erwartungen über zukünftige Entnahmekosten sowie technologische und regulatorische Entwicklungen bilden können. Angesichts des frühen Entwicklungsstands des CO_2-Entnahme-Ökosystems und der begrenzten empirischen Informationen über künftige Kosten und Skalierbarkeit sind diese Informationsanforderungen schwer zu erfüllen. Hinzu kommt, dass langfristige Verpflichtungen Fragen der Verbindlichkeit und Durchsetzung aufwerfen, weil

Unternehmen Jahrzehnte nach dem Emissionszeitpunkt möglicherweise nicht mehr existieren oder darauf setzen könnten, dass regulatorische Anforderungen mit der Zeit gelockert werden. Zur Bewältigung dieser Risiken bedarf es zusätzlicher Mechanismen finanzieller Absicherung um die Glaubwürdigkeit von Entnahmeverpflichtungen zu gewährleisten.

Vor diesem Hintergrund diskutiert der Bericht drei stilisierte intertemporale Gestaltungsansätze, die in der Literatur aufgekommen sind: einen staatlich geführten Steuer-Fonds-Ansatz, einen auf dem Emissionshandelssystem basierenden Entnahmeverpflichtungsansatz gestützt durch Besicherung sowie einen Ansatz, der Verpflichtungen zur Kohlenstoffentnahme als Form umweltbezogener Haftung behandelt, die durch Mechanismen der finanziellen Absicherung gestützt wird. Diese Ansätze unterscheiden sich zwar in einigen Umsetzungsdetails, teilen jedoch das Kernprinzip, dass heutige Emissionen mindestens mit den diskontierten Kosten künftiger Kohlenstoffentnahme bepreist werden sollten. Daraus folgt, dass künftige Entnahmekosten und Einsatzmengen zumindest in gewissem Mass abschätzbar sein müssen – was wiederum ein deutlich reiferes CO_2-Entnahme-Ökosystem voraussetzt als das heutige.

Über die Ausgestaltung der Finanzierungsinstrumente hinaus hängt die Bezahlbarkeit grossskaliger Kohlenstoffentnahme sowohl von Nachfrage- als auch von Angebotsfaktoren ab. Die von regulierten Akteuren getragenen Erfüllungskosten für Entnahmen werden nicht nur vom technologischen Fortschritt abhängen, sondern auch davon, wie Renten in CO_2-Entnahmemärkten gesteuert werden. Zudem werden die Kosten ambitionierter Negativziele teilweise von der Verfügbarkeit internationaler CO_2-Entnahmemöglichkeiten abhängen. Die Schweizer Klimastrategie geht bereits davon aus, einen Teil ihrer Entnahmen im Rahmen von Artikel 6 des Pariser Abkommens im Ausland zu beschaffen. Der Zugang zu vergleichsweise umfangreichen und kostengünstigeren Entnahmepotenzialen ausserhalb der Schweiz könnte daher eine wichtige Rolle spielen, um Netto-Null-Emissionen und danach Netto-Negativ-Emissionen zu tragbaren Kosten zu erreichen; zugleich bestehen weiterhin erhebliche Unsicherheiten über das zukünftige Volumen und die Governance internationaler CO_2-Entnahmemärkte.

Darüber hinaus lassen sich wichtige Lehren aus der Governance der Stilllegung von Kernkraftwerken und der Entsorgung radioaktiver Abfälle ziehen. Anders als bei der Kohlenstoffentnahme gibt es hier einen reichen empirischen Erfahrungsschatz darüber, wie Gesellschaften langfristige Umweltverbindlichkeiten und intergenerationelle Verpflichtungen bewältigen. Bestehende Governance-Systeme kombinieren typischerweise das Verursacherprinzip mit Schutzvorkehrungen, die verhindern sollen, dass ungedeckte Verbindlichkeiten auf künftige Generationen übertragen werden. In der Praxis gilt häufig ein Subsidiaritätsprinzip: Die jeweils lokalste oder dezentralste Einheit, die eine Aufgabe bewältigen kann, sollte sie übernehmen. Die Verantwortung für die Stilllegung wird daher oft dezentral den Betreibern zugewiesen, während die Entsorgung radioaktiver Abfälle – charakterisiert durch längere Zeithorizonte sowie grössere Unsicherheit und nicht diversifizierbare Risiken – tendenziell stärkere öffentliche Koordination und Aufsicht erfordert.

Die Kohlenstoffentnahme erscheint derzeit der Entsorgung radioaktiver Abfälle ähnlicher, die sich als Problem der Sicherstellung der Angemessenheit der Finanzierung verstehen lässt. In einem solchen Ansatz liegt der Schwerpunkt nicht darauf, jede Tonne Emission so zu bepreisen, dass ihre künftigen Entnahmekosten vollständig widergespiegelt werden, sondern darauf, im Zeitverlauf ausreichend Mittel anzusammeln, um das insgesamt erforderliche Entnahmevolumen zu finanzieren. Dies erfordert typischerweise eine regelmässige Aktualisierung von Kostenschätzungen, die Identifizierung potenzieller Finanzierungslücken und die

Anpassung von Beiträgen – primär von Verursachern, gegebenenfalls aber auch aus anderen Quellen –, um die Angemessenheit der Finanzierung angesichts fortschreitender Erkenntnisse über Entnahmekosten und Skalierung aufrechtzuerhalten. In der Praxis erfordert dies eine enge Verknüpfung des Fondsmanagements mit der operativen Bereitstellung von Kohlenstoffentnahmen, um Kostenschätzungen im Zeitverlauf zu verbessern. Langfristig könnte sich die Kohlenstoffentnahme jedoch stärker in Richtung marktbasierten Arrangements entwickeln, wenn Technologien reifen und Risiken besser verstanden werden.

Erfahrungen aus der Entsorgung radioaktiver Abfälle zeigen zudem, dass viele Rechtsordnungen die Haftung bei den Betreibern verankern und mehrere „Verteidigungslinien" einsetzen – etwa finanzielle Garantien, Aktionärshaftung oder geteilte Betreiberhaftung –, um sicherzustellen, dass Finanzierungslücken in erster Linie von den Betreibern und nicht von der Allgemeinheit getragen werden. Diese Governance-Prinzipien könnten nützliche Referenzpunkte für die zukünftige Politik zur Kohlenstoffentnahme bieten.

Zusammengenommen legt die Analyse nahe, dass rein zeitgleiche Finanzierungsmechanismen anhaltende Netto-Negativ-Emissionen kaum unterstützen können. Intertemporale Politikansätze werden daher wahrscheinlich eine wichtige Rolle dabei spielen, welche heutige Emissionen mit künftigen Entnahmen zu verknüpfen. Zugleich machen der aktuelle Entwicklungsstand des CO_2-Entnahme-Ökosystems und die erheblichen Unsicherheiten hinsichtlich künftiger Kosten und Skalierbarkeit deutlich, dass vollständig marktbasierte Lösungen kurzfristig schwer umsetzbar sein dürften. Öffentliche Institutionen werden daher voraussichtlich eine zentrale Rolle bei der Bewältigung der finanziellen und Governance-Herausforderungen grossskaliger Netto-Kohlenstoffentnahme spielen müssen – über ihre Rolle als Regulatoren hinaus in einer stärker missionsorientierten Funktion zur Ermöglichung und Koordination der Bereitstellung von Kohlenstoffentnahmen. Da intertemporale Instrumente bereits ab 2030 eingeführt werden müssten und damit deutlich vor dem Entstehen eines ausgereiften Kohlenstoffentnahme-Ökosystems, könnten kurzfristige Politikbemühungen zunächst darauf ausgerichtet sein, durch den Aufbau einer möglichst breiten Beitragsbasis die Angemessenheit der Finanzierung und fiskalische Nachhaltigkeit sicherzustellen. Mit zunehmendem Entwicklungsstand des CO_2-Entnahme-Ökosystems könnten die Politikansätze schrittweise in Richtung stärker dezentraler und marktbasierten Ansätze übergehen, um die wirtschaftliche Effizienz zu erhöhen.

Résumé

Les tendances récentes des émissions de gaz à effet de serre (GES) et de la température moyenne mondiale rendent pratiquement certain le dépassement du seuil de 1,5 °C de réchauffement global au cours des dix prochaines années. Limiter à long terme le réchauffement mondial à 1,5 °C reposera donc presque certainement sur des trajectoires mondiales dans lesquelles le réchauffement dépasse d'abord ce niveau avant de revenir ensuite à 1,5 °C grâce à des émissions mondiales nettes négatives durables de CO_2 et, potentiellement, même à des émissions nettes négatives de GES.[†]

Dans ce contexte, on s'attend largement à ce que les pays à revenu élevé, disposant de fortes capacités technologiques, institutionnelles et économiques, et ayant contribué de manière substantielle au réchauffement mondial historique, aillent au-delà des objectifs de neutralité nette et contribuent à l'élimination nette mondiale du carbone atmosphérique. En termes généraux, si l'on rapporte la contribution de la Suisse au réchauffement mondial — en tenant compte du CO_2 territorial et des autres GES ainsi que de sa part actuelle de la population mondiale —, l'augmentation médiane de la température mondiale serait déjà d'environ 1,8 °C. Bien que les émissions territoriales suisses de CO_2 par habitant soient passées sous la moyenne mondiale vers 2015, les émissions incorporées dans les importations dépassent largement les émissions domestiques. Dans le même temps, la Suisse dispose d'une capacité économique considérable pour contribuer aux efforts mondiaux d'atténuation. Pris ensemble, ces facteurs suggèrent que la contribution de la Suisse à l'atteinte des objectifs mondiaux de température par le biais des absorptions de carbone pourrait raisonnablement dépasser celle de nombreux autres pays.

La législation climatique suisse reflète déjà cette attente en prescrivant des émissions nettes nulles de GES d'ici 2050, puis une transition vers des émissions nettes négatives de GES par la suite. Le présent rapport vise à opérationnaliser la transition de la Suisse vers des émissions nettes négatives après 2050 en proposant des objectifs de référence, en examinant les modalités possibles de répartition des responsabilités au niveau national et en présentant des considérations de conception des politiques publiques pour produire des résultats nets négatifs à grande échelle.

Objectifs suisses d'émissions nettes négatives après 2050

Le rapport examine d'abord comment l'ambition climatique de la Suisse en matière d'émissions nettes négatives de GES après 2050 pourrait être dérivée et fournit des fourchettes indicatives pour les émissions nettes négatives en 2060. L'analyse tient compte à la fois des approches de partage de l'effort fondées sur l'équité et des contraintes de faisabilité pratique.

Les cadres de partage de l'effort déterminent comment les exigences mondiales d'atténuation — c'est-à-dire les réductions d'émissions et les absorptions de carbone — compatibles avec un objectif de température donné peuvent être réparties entre les pays. De tels cadres dépendent de plusieurs choix et paramètres clés, notamment la taille du budget carbone mondial

[†] Des émissions nettes négatives de CO_2 se produisent lorsque les absorptions de dioxyde de carbone dépassent les émissions résiduelles de CO_2, tandis que des émissions nettes négatives de gaz à effet de serre (GES) exigent que les absorptions dépassent les émissions résiduelles de GES. Les émissions nettes négatives de GES constituent donc une exigence plus stricte que les émissions nettes négatives de CO_2.

restant, les méthodes comptables utilisées pour attribuer les émissions aux pays, les principes d'équité guidant la répartition de l'effort d'atténuation, la trajectoire future prévue vers la neutralité nette et le degré de coopération internationale autorisé pour atteindre les objectifs. Ces paramètres techniques et ces choix éthiques influencent fortement les résultats nationaux dans les calculs de partage de l'effort et expliquent pourquoi les estimations publiées varient considérablement.

Le budget carbone mondial restant décrit la quantité cumulée de CO_2 qui peut encore être émise tout en limitant le réchauffement à un niveau de température donné. Les estimations de ce budget dépendent de choix méthodologiques, notamment de la prise en compte ou non de trajectoires de dépassement temporaire, des hypothèses relatives aux GES non-CO_2 et du niveau de confiance associé à l'atteinte d'un objectif de température donné. En conséquence, même pour une même cible de température, les estimations disponibles du budget carbone varient sensiblement. Les budgets carbone constituent souvent le point de départ des calculs de partage de l'effort qui répartissent les émissions admissibles ou les obligations d'absorption entre les pays, tandis que des approches comptables distinctes déterminent les émissions effectives des pays. La notification internationale au titre de la CCNUCC repose sur les émissions territoriales produites à l'intérieur des frontières nationales. D'autres approches fondées sur la consommation attribuent aux consommateurs finaux les émissions incorporées dans le commerce international et peuvent être pertinentes pour les considérations éthiques dans les débats sur le partage de l'effort.

Les principes d'équité constituent la base normative de la répartition des droits d'émission et des efforts d'atténuation entre pays. Trois principes sont les plus fréquemment discutés dans la littérature. Les approches fondées sur la responsabilité attribuent des efforts plus importants aux pays ayant les émissions historiques cumulées les plus élevées. Les approches fondées sur la capacité allouent un effort plus important aux pays disposant d'une plus grande capacité économique et d'une meilleure aptitude à absorber les coûts de l'atténuation. Les approches fondées sur l'égalité répartissent généralement les droits d'émission sur une base par habitant, impliquant un accès égal au « bien commun atmosphérique ». En pratique, ces principes « purs » sont souvent combinés, ajustés pour tenir compte des besoins élémentaires de développement dans les pays à plus faible revenu, ou mis en œuvre avec des périodes de transition à partir des niveaux d'émissions actuels vers des répartitions davantage fondées sur l'équité.

Chaque principe a des implications qualitativement différentes pour la Suisse.

Les approches fondées sur la capacité produisent souvent les exigences les plus strictes compte tenu du revenu par habitant élevé de la Suisse et de sa forte production économique.

Les cadres fondés sur la responsabilité attribuent généralement des efforts d'atténuation un peu moins importants, mais toujours substantiels, reflétant les émissions historiques de la Suisse au regard de sa population. Comme les émissions territoriales suisses de CO_2 par habitant sont inférieures à la moyenne mondiale depuis environ 2015, les allocations fondées sur la responsabilité deviennent généralement plus exigeantes pour la Suisse à mesure que la période historique comptabilisée s'allonge. Toutefois, des études récentes indiquent que la Suisse a accumulé un « crédit » partiel en raison d'émissions de UTCATF par habitant inférieures à la moyenne entre 1850 et 1950. Par conséquent, les approches d'allocation qui incluent les émissions liées aux changements d'affectation des terres et des horizons historiques très longs tendent à réduire la charge d'atténuation de la Suisse dérivée de la responsabilité. En revanche, si l'on utilise des émissions fondées sur la consommation plutôt que territoriales, la part de responsabilité de la

Suisse est généralement nettement plus élevée, en particulier lorsque l'année de départ retenue est plus récente.

Les approches d'égalité par habitant tendent à conduire à des allocations relativement généreuses. Comme les émissions territoriales actuelles de CO_2 par habitant en Suisse sont inférieures à la moyenne mondiale, on pourrait considérer que le pays surperforme déjà dans un tel cadre d'allocation. Toutefois, de nombreux calculs d'égalité par habitant pour la Suisse suggèrent que la trajectoire de long terme vers la neutralité nette d'ici 2050 pourrait malgré tout dépasser les niveaux d'émissions impliqués par une allocation strictement égale par habitant.

L'application de ces cadres à la Suisse conduit à une très large gamme d'objectifs possibles d'émissions nettes négatives. Les calculateurs en ligne existants et les études consacrés au partage de l'effort suggèrent, pour 2060, des résultats allant d'émissions nettes encore légèrement positives dans les approches fondées sur l'égalité (environ 1 $MtCO_2$-eq) à des émissions nettes négatives très élevées dans certains cadres fondés sur la capacité, de l'ordre de 230 $MtCO_2$-eq, soit bien au-delà du niveau actuel des émissions nationales suisses. Dans l'ensemble, la littérature indique toutefois que les trajectoires dérivées de principes de partage de l'effort fondés sur l'équité tendent à impliquer des efforts plus ambitieux que la trajectoire actuellement inscrite dans la législation suisse vers la neutralité nette d'ici 2050, ce qui laisse penser qu'une ambition supplémentaire au-delà de 2050 pourrait être justifiée.

Un point de référence complémentaire pour l'ambition nette négative potentielle de la Suisse peut être établi sur une base technique en extrapolant les scénarios nationaux de politique climatique existants. La modélisation actuelle de la stratégie climatique de long terme de la Suisse suppose que la neutralité nette est atteinte en 2050 grâce à une combinaison de réductions d'émissions (y compris le captage et stockage du carbone) et d'absorptions de dioxyde de carbone domestiques et internationales. Si la montée en puissance des technologies d'évitement des émissions et d'absorption envisagée pendant la décennie 2040-2050 se poursuivait durant la décennie suivante 2050-2060, la Suisse pourrait plausiblement atteindre en 2060 des émissions nettes négatives de GES supérieures à 10 $MtCO_2$-eq par an.

Enfin, le rapport présente une méthode de référence simple et transparente reliant les objectifs potentiels suisses d'absorptions brutes aux besoins mondiaux d'absorption dans les trajectoires d'atténuation compatibles avec 1,5 °C. La méthode suppose qu'une coalition de pays économiquement développés contribue à l'absorption de dioxyde de carbone proportionnellement à sa capacité économique. Dans ce cadre, l'objectif suisse d'absorption — et les objectifs correspondants des autres pays de la coalition — dépendent à la fois de la taille de la coalition considérée et du niveau de confiance requis pour que les besoins mondiaux d'absorption soient couverts. Selon ces hypothèses, un objectif suisse d'émissions nettes négatives de GES d'environ 20 $MtCO_2$-eq d'ici 2060 — en supposant que les émissions résiduelles de GES puissent être réduites à environ 6 $MtCO_2$-eq — représenterait une contribution suffisante avec un niveau de confiance de 50 %. En outre, un objectif suisse potentiel d'environ 20 $MtCO_2$-eq d'ici 2060 pourrait être interprété comme reflétant le niveau d'ambition du Danemark. Le Danemark est l'un des rares pays à disposer d'objectifs relativement concrets en matière d'émissions nettes négatives et peut donc constituer un point de référence utile.

Pris dans leur ensemble, les cadres de partage de l'effort fondés sur l'équité suggèrent de manière cohérente que des pays industrialisés à haut revenu comme la Suisse devraient aller au-delà de la neutralité nette afin de contribuer à la stabilisation de la température mondiale et, potentiellement, à l'inversion du réchauffement. Cette conclusion est globalement cohérente avec les résultats d'études nationales similaires menées pour la Suisse et d'autres pays industrialisés, notamment la Finlande, le Canada et les Pays-Bas.

Répartition des responsabilités pour les émissions nettes négatives

Le rapport examine ensuite comment les efforts nécessaires à l'obtention d'émissions nettes négatives de GES pourraient être répartis entre les acteurs en Suisse.

Plutôt que de préconiser une approche spécifique de partage de l'effort, le rapport analyse dans quelle mesure différents principes relatifs à l'équité, des principes inscrits dans le droit suisse, des principes généraux de politique publique et des considérations pragmatiques convergent quant à la répartition des efforts entre les acteurs de l'économie et de la société suisses. Les résultats illustrent les implications d'approches alternatives et mettent en évidence les principaux arbitrages qu'il faudrait, en définitive, trancher par une décision politique.

Un premier ensemble de principes dérive de considérations d'équité globale couramment utilisées dans le partage international de l'effort climatique, comme celles évoquées ci-dessus. Deux principes sont particulièrement pertinents ici : la responsabilité et la capacité. Appliquée au niveau national, la logique de responsabilité impliquerait que les acteurs ayant le plus contribué au réchauffement — soit par des émissions cumulées historiquement élevées de GES à longue durée de vie, soit par des émissions actuelles de GES à courte durée de vie — portent la plus grande responsabilité dans la fourniture de résultats nets négatifs. Une question centrale dans une telle approche concerne l'horizon temporel sur lequel la responsabilité est évaluée, puisque le choix de la date de départ pour les émissions historiques peut influencer de manière significative les acteurs considérés comme responsables du changement climatique.

Le principe de capacité, appliqué au niveau national, impliquerait que les acteurs disposant de la plus grande capacité financière (ou technologique) fournissent l'effort le plus important, indépendamment de leur contribution directe aux émissions. En pratique, cela pourrait signifier que des entités ayant des revenus plus élevés ou des ressources économiques plus importantes mettent en œuvre ou financent des activités d'absorption de carbone, y compris potentiellement hors de Suisse, indépendamment de leurs émissions.

Une autre perspective découle des principes ancrés dans le droit suisse et la politique climatique suisse. En particulier, la Constitution suisse consacre en matière environnementale le principe du pollueur-payeur, qui attribue la responsabilité de prévenir ou de réparer les atteintes à l'environnement à ceux qui les causent. Une interprétation possible de ce principe pourrait exiger que les coûts liés à l'atteinte d'émissions nettes négatives soient supportés par ceux qui continuent à émettre des GES — c'est-à-dire les émetteurs résiduels après 2050 — plutôt que par le grand public. Une telle approche s'apparenterait à l'utilisation d'une redevance sur les dépôts de déchets pour assainir des décharges existantes, où les pollueurs sont tenus de couvrir non seulement les coûts de leur pollution actuelle, mais aussi de contribuer aux coûts plus larges du système.

Les choix nationaux en matière de partage de l'effort sont limités par le principe d'évitement de la responsabilité rétroactive, principe juridique largement reconnu qui empêche de tenir des acteurs responsables d'actions qui étaient légales au moment où elles ont été commises. Ce principe peut limiter la mesure dans laquelle les émissions historiques sont utilisées pour attribuer des obligations futures d'atténuation. Une autre considération concerne le recours à des mécanismes d'action publique déjà établis. Étendre des instruments existants — tels que les systèmes de déclaration des émissions, les mécanismes de tarification du carbone ou les cadres généraux de taxation — peut être plus faisable et politiquement plus acceptable que de créer des structures réglementaires entièrement nouvelles. Enfin, les politiques destinées à soutenir les émissions nettes négatives devraient reposer sur une base suffisamment large de contributeurs afin d'assurer dans le temps la stabilité financière et la légitimité politique.

Pris ensemble, les résultats de l'analyse montrent que l'importance relative accordée à ces principes conduit à des conclusions différentes quant à ceux qui devraient supporter la charge liée à l'atteinte d'émissions nettes négatives. Aucune approche unique n'est pleinement compatible avec l'ensemble des considérations d'équité, des principes de politique publique et des exigences juridiques. Les approches fondées sur la responsabilité s'alignent étroitement sur le principe du pollueur-payeur, mais peuvent entrer en conflit avec l'évitement de la responsabilité rétroactive lorsqu'elles reposent sur les émissions historiques. À l'inverse, les approches fondées sur la capacité s'accordent généralement bien avec les principes de politique publique, mais peuvent moins bien refléter le principe du pollueur-payeur.

Parmi les différentes perspectives examinées, deux grandes approches apparaissent particulièrement compatibles avec la combinaison des principes juridiques, d'équité et de politique publique générale considérés. Une première approche consisterait à attribuer la responsabilité de la fourniture d'émissions nettes négatives de GES aux acteurs à l'origine d'émissions à partir d'un point de départ futur défini bien avant la neutralité nette — par exemple 2030 — afin d'éviter les problèmes de responsabilité rétroactive. Une autre approche consisterait à répartir les efforts nécessaires en fonction de la capacité contributive des entreprises ou des contribuables, au moyen de contributions financières destinées à financer les absorptions de dioxyde de carbone, soit à partir de 2030, soit à partir de 2050.

La mise en œuvre des politiques pertinentes dès que possible — bien avant que les émissions nettes négatives ne soient requises au niveau national en vertu du droit en vigueur — plaide pour une approche intertemporelle de conception des politiques. Dans une telle approche, les émetteurs, les entreprises et les contribuables contribueraient de manière cumulative à partir, par exemple, de 2030, afin de répondre à la charge liée à l'obtention d'émissions nettes négatives après 2050. Les deux approches suggèrent un rôle croissant de la Confédération, non seulement comme régulateur de marché permettant au secteur privé d'atteindre des objectifs d'émissions nettes négatives, mais aussi comme participant actif au marché, chargé de coordonner les investissements et de gérer les risques.

Le rapport souligne en outre que le choix des mécanismes nationaux de partage de l'effort et des politiques en matière d'émissions nettes négatives ne peut être considéré indépendamment des politiques utilisées pour atteindre la neutralité nette. Les objectifs sectoriels existants dans le droit climatique suisse impliquent que la plupart des secteurs devraient atteindre zéro émission d'ici 2050, l'agriculture demeurant la principale source d'émissions résiduelles. Si la responsabilité des émissions nettes négatives était attribuée exclusivement sur la base des émissions résiduelles restant en 2050, la charge se concentrerait donc largement sur le secteur agricole.

Or, un déterminant majeur du volume d'absorptions de carbone nécessaire est le niveau des émissions résiduelles subsistant après réduction et captage à la source. Réduire les émissions résiduelles diminue la quantité d'absorptions nécessaire pour atteindre un objectif net négatif donné et, à volume d'absorptions constant, permettrait d'obtenir un résultat net négatif plus ambitieux. Dans cette perspective, il peut être plus logique de soutenir les secteurs qui devraient continuer à émettre après 2050 — comme l'agriculture — dans la réduction supplémentaire de ces émissions, plutôt que de compter sur eux, ou sur le contribuable, pour financer des absorptions de carbone à grande échelle.

Au niveau des entreprises, l'exigence du droit climatique suisse selon laquelle toutes les entreprises (à l'exception des exploitations agricoles) doivent atteindre des émissions nettes nulles d'ici 2050 implique que les émissions nettes elles-mêmes ne peuvent plus servir d'indicateur pour attribuer, après 2050, des obligations supplémentaires d'absorption de CO_2. Toute allocation au niveau des entreprises nécessiterait donc un autre critère de répartition pour contribuer aux émissions nettes négatives, tel que la capacité financière ou une formule fondée sur des trajectoires d'émissions antérieures.

Dans l'ensemble, l'analyse suggère que l'atteinte d'émissions nettes négatives requiert, dans un avenir proche, des choix politiques délibérés sur la manière de répartir les efforts entre les acteurs de l'économie suisse, afin que ces choix puissent orienter les investissements stratégiques du secteur privé. Ces choix impliquent de concilier responsabilité historique, capacité financière, faisabilité juridique et praticabilité politique.

Financement des émissions nettes négatives

Le rapport examine enfin comment l'obtention d'émissions nettes négatives pourrait être financée au moyen d'instruments économiques de la politique climatique. Étant donné que l'expérience concrète en matière d'absorption de dioxyde de carbone à grande échelle demeure largement inexistante, l'analyse est nécessairement conceptuelle et exploratoire. Le rapport établit toutefois des parallèles avec la gestion des déchets radioactifs et le démantèlement nucléaire, pour lesquels il existe déjà une base empirique substantielle en matière de structures de gouvernance.

Les approches de politique économique en matière de carbone sont généralement évaluées à l'aune de l'efficience économique, c'est-à-dire, dans le contexte du présent rapport, de l'atteinte d'un objectif climatique donné au coût le plus faible possible. De telles approches cherchent généralement à fournir des incitations appropriées à la fois pour les réductions d'émissions et pour les absorptions de carbone, en intégrant ces activités dans un cadre cohérent fondé sur les prix. Ces instruments reposent donc sur des absorptions de carbone financées par les pollueurs et visent à internaliser les coûts attendus de l'atteinte d'émissions nettes négatives, de sorte que le coût des absorptions de carbone présentes et/ou futures soit déjà reflété dans les décisions actuelles d'émission et de réduction.

Une distinction conceptuelle centrale entre les instruments économiques concerne le point de savoir si les émissions et les absorptions sont liées sur une même période ou dans le temps. Les instruments liant émissions et absorptions sur une même période financent les absorptions au moment où les émissions se produisent, par exemple en réaffectant les recettes de la tarification du carbone à l'achat d'absorptions de carbone, ou en imposant aux émetteurs de compenser leurs émissions par des absorptions sur la même période. Les instruments intertemporels, en revanche, relient les émissions libérées aujourd'hui à des absorptions fournies dans le futur. Ces approches peuvent impliquer l'accumulation de ressources financières au fil du temps — par exemple via une taxe carbone — ou l'attribution aux émetteurs d'obligations futures de financer ou de fournir des absorptions à un stade ultérieur. Les approches sur une même période et les approches intertemporelles peuvent donc différer quant au mode de formation des prix — par le marché ou par la réglementation — et quant à l'existence d'une institution intermédiaire chargée de gérer le financement des absorptions.

L'analyse examine d'abord les perspectives de financement des émissions nettes négatives au moyen d'instruments liant émissions et absorptions sur une même période. L'intégration des absorptions de carbone dans les systèmes existants de tarification du carbone — tels que les systèmes d'échange de quotas d'émission — pourrait en principe conduire à des résultats plus efficients en termes de coûts. Tant que les émissions brutes restent supérieures aux absorptions, de tels systèmes demeurent globalement compatibles avec une interprétation stricte du principe du pollueur-payeur, puisque les émetteurs paient pour chaque unité d'émission et peuvent ainsi financer les absorptions sur une base tonne pour tonne.

Toutefois, cette logique devient de plus en plus difficile à maintenir à mesure que les émissions diminuent vers des niveaux de neutralité nette. À la neutralité nette, les émissions résiduelles de GES sont exactement compensées par les absorptions de carbone. Atteindre des émissions nettes négatives exigerait donc que chaque unité résiduelle d'émissions après 2050 finance plus d'une unité d'absorption de carbone. De telles situations, dans lesquelles une unité d'émission doit financer plusieurs unités d'absorption, peuvent soulever des défis économiques et juridiques. L'analyse conceptuelle suggère que des instruments liant émissions et absorptions sur une même période et financés par les pollueurs risquent de ne pas produire, pour un objectif donné d'émissions nettes négatives de GES, des résultats efficients en coûts — voire même réalisables. Dans certaines circonstances, ils pourraient même créer des incitations à maintenir des niveaux plus élevés d'émissions résiduelles afin de préserver l'assiette de financement nécessaire aux absorptions. Ces limites suggèrent que des instruments purement contemporains et financés par les pollueurs sont peu susceptibles de permettre durablement des émissions nettes négatives à grande échelle.

Une autre possibilité serait de financer les émissions nettes négatives au moyen des budgets publics. Une telle approche exigerait toutefois une préparation substantielle bien avant 2050, puisque des mécanismes de financement à grande échelle devraient être mis en place à l'avance. En outre, les dépenses publiques liées au climat devraient augmenter fortement dans les décennies à venir, notamment pour l'adaptation, le financement international du climat et les mécanismes relatifs aux pertes et préjudices. Financer les émissions nettes négatives à partir des budgets publics pourrait donc soulever des préoccupations de soutenabilité budgétaire et accentuer la concurrence pour des ressources publiques limitées.

L'analyse se concentre donc sur les instruments intertemporels, qui relient les émissions actuelles à des absorptions qui n'interviennent que plus tard. Lorsqu'ils sont mis en œuvre bien avant l'atteinte de la neutralité nette, de tels systèmes peuvent maintenir une large base de financement tout en restant compatibles avec une interprétation stricte, tonne pour tonne, du principe du pollueur-payeur. D'un point de vue conceptuel, des conceptions intertemporelles peuvent produire des résultats efficients en coûts pour tout objectif net négatif, à condition qu'un budget carbone national n'ait pas encore été épuisé au moment de l'introduction de la politique.

En pratique, toutefois, la mise en œuvre d'instruments intertemporels se heurte à des difficultés importantes. Les approches fondées sur le marché exigent que les entreprises comparent le coût de la réduction des émissions aujourd'hui au coût actualisé anticipé de l'absorption future de carbone. Cela suppose que les entreprises puissent former des anticipations raisonnablement fiables quant aux coûts futurs des absorptions, ainsi qu'aux évolutions technologiques et réglementaires. Compte tenu du stade encore précoce de l'écosystème de l'absorption de carbone et des informations empiriques limitées disponibles sur les coûts futurs et la capacité de déploiement, ces exigences informationnelles sont difficiles à satisfaire. En outre, les obligations de long terme soulèvent des questions de crédibilité et d'exécution, dans la mesure où les entreprises pourraient ne plus exister plusieurs décennies après la survenance des émissions ou pourraient anticiper un assouplissement des exigences réglementaires avec le temps. La maîtrise de ces risques nécessite des mécanismes supplémentaires — tels que des exigences de garantie ou d'autres formes de garantie financière — afin d'assurer la crédibilité des obligations d'absorption.

Dans ce contexte, le rapport examine trois approches stylisées de conception intertemporelle apparues dans la littérature : une approche de fonds alimenté par une taxe pilotée par l'État, une approche d'obligation d'absorption fondée sur un système d'échange de quotas d'émission assortie d'une obligation de constituer des garanties financières, et une approche qui traite les obligations d'absorption de carbone comme une forme de responsabilité environnementale soutenue par des mécanismes de garantie financière. Si ces approches diffèrent sur certains détails de mise en œuvre, elles partagent un principe fondamental : les émissions d'aujourd'hui devraient être tarifées au moins au niveau du coût actualisé d'élimination du carbone dans le futur. Cela implique que les coûts futurs des absorptions et les volumes de déploiement doivent être, dans une certaine mesure, estimables, ce qui suppose à son tour un écosystème d'absorption de carbone plus développé qu'aujourd'hui.

Au-delà de la conception des instruments de financement eux-mêmes, l'accessibilité économique du déploiement à grande échelle des absorptions de carbone dépend à la fois de facteurs liés à la demande et à l'offre. Les coûts de conformité supportés pour les absorptions par les entités réglementées dépendront non seulement du progrès technologique, mais aussi de la manière dont les rentes sur les marchés de l'absorption de carbone sont gérées. En outre, le coût d'objectifs ambitieux d'émissions nettes négatives dépendra en partie de la disponibilité d'opportunités internationales d'absorption de carbone. La stratégie climatique suisse anticipe déjà qu'une partie des absorptions sera obtenue à l'étranger dans le cadre de l'article 6 de l'Accord de Paris. L'accès à des potentiels d'absorption relativement abondants et moins coûteux hors de Suisse pourrait donc jouer un rôle important pour atteindre la neutralité nette puis des émissions nettes négatives à un coût maîtrisable, même si des incertitudes importantes subsistent quant à l'ampleur future et à la gouvernance des marchés internationaux de l'absorption de carbone.

En outre, des enseignements importants peuvent être tirés de la gouvernance du démantèlement nucléaire et de la gestion des déchets radioactifs. Contrairement à l'absorption de carbone, ces domaines de politique publique offrent un riche retour d'expérience empirique sur la manière dont les sociétés gèrent des passifs environnementaux de long terme et des obligations intergénérationnelles. Les systèmes de gouvernance existants combinent généralement le principe du pollueur-payeur avec des garde-fous destinés à empêcher le transfert de passifs non financés vers les générations futures. En pratique, un principe de subsidiarité s'applique souvent : l'entité la plus locale ou la plus décentralisée capable d'assumer une tâche devrait s'en charger. La responsabilité du démantèlement est donc fréquemment décentralisée au niveau des exploitants, tandis que la gestion des déchets radioactifs — caractérisée par des horizons plus longs ainsi que par une plus grande incertitude et des risques non diversifiables — tend à impliquer une coordination et une surveillance publiques plus fortes.

À l'heure actuelle, l'absorption de carbone ressemble davantage à la gestion des déchets radioactifs, que l'on peut comprendre comme un problème consistant à maintenir dans la durée un financement suffisant. Dans une telle approche, l'enjeu n'est pas de fixer un prix pour chaque tonne d'émission de manière à refléter son coût futur d'absorption, mais de veiller à ce qu'un financement suffisant soit accumulé au fil du temps pour couvrir le volume total d'absorptions requis. Cela implique généralement une mise à jour périodique des estimations de coûts, l'identification d'éventuels déficits de financement et l'ajustement des contributions — principalement des pollueurs, mais potentiellement aussi d'autres sources — afin de préserver un financement suffisant à mesure que les connaissances progressent sur les coûts d'absorption et les capacités de déploiement. En pratique, cela suppose d'articuler étroitement la gestion du fonds avec le déploiement opérationnel des absorptions de carbone afin d'améliorer les estimations de coûts au fil du temps. Avec le temps, toutefois, l'absorption de carbone pourrait évoluer vers des dispositifs davantage fondés sur le marché, à mesure que les technologies progresseront et que les risques seront mieux compris.

L'expérience tirée de la gestion des déchets radioactifs montre également que de nombreuses juridictions ancrent la responsabilité au niveau des exploitants tout en mobilisant plusieurs lignes de défense — telles que des garanties financières, la responsabilité des actionnaires ou des responsabilités partagées entre exploitants — afin que les déficits de financement soient supportés prioritairement par les exploitants plutôt que par le grand public. Ces principes de gouvernance peuvent constituer des points de référence utiles pour l'élaboration future de politiques d'absorption de carbone.

Pris ensemble, les résultats de l'analyse suggèrent que des mécanismes de financement purement contemporains sont peu susceptibles de permettre durablement des émissions nettes négatives. Les conceptions intertemporelles des politiques devraient donc jouer un rôle important pour relier les émissions actuelles aux absorptions futures. Dans le même temps, l'état actuel de l'écosystème de l'absorption de carbone et les incertitudes considérables entourant les coûts futurs et la réalisation effective des absorptions laissent penser que des solutions entièrement fondées sur le marché pourraient être difficiles à mettre en œuvre à court terme. Les institutions publiques devront probablement jouer un rôle central dans la gestion des défis financiers et de gouvernance associés au déploiement à grande échelle des absorptions nettes de carbone, au-delà de leur rôle de régulateur, dans une fonction davantage orientée vers la mission consistant à rendre possible et à coordonner la réalisation de l'absorption de dioxyde de carbone. Comme les instruments intertemporels devraient être mis en œuvre dès 2030, donc bien avant qu'un écosystème mature d'absorption de carbone n'existe, les efforts de politique à court terme pourraient d'abord se concentrer sur la garantie, dans la durée, d'un financement suffisant et de la soutenabilité budgétaire, grâce à l'établissement d'une base potentiellement large de contributeurs au nettoyage de l'atmosphère. À mesure que l'écosystème de l'absorption de carbone progressera, les cadres de politique publique pourraient évoluer progressivement vers des approches plus décentralisées et davantage fondées sur le marché, dans l'objectif d'améliorer l'efficience.

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1 Introduction

Most mitigation pathways compatible with limiting global warming to 1.5°C rely on exceeding this threshold, followed by a return to the target later in the century. This was already the case in scenarios assessed around the adoption of the Paris Agreement, including those underlying the Special Report on 1.5°C. Since then, two developments have sharpened the relevance of overshoot pathways. First, global emissions have not declined at the pace implied by early Paris-aligned scenarios, making near-term exceedance of 1.5°C increasingly likely. Second, the evidence base on climate impacts has continued to strengthen, underscoring the need to limit warming to 1.5°C at most – and potentially lower – given growing damages and risks. As a result, the question is not whether overshoot pathways are part of 1.5°C-consistent mitigation, but how temperature reversal can be achieved credibly (*1*).

Reversing warming after having exceeded a temperature level like 1.5°C requires sustained net-negative CO_2 emissions, achieved through durable reductions in emissions of CO_2 and non-CO_2 greenhouse gases (GHGs) combined with large-scale deployment of carbon dioxide removal (CDR), to minimize ongoing radiative forcing. However, returning to 1.5°C by 2100 requires that peak warming remains well below 2°C. Higher and longer exceedance increases climate risks, reduces the likelihood of returning to 1.5°C, and heightens the potential for irreversible impacts and tipping points (*2*).

The allocation of these efforts among signatory countries of the Paris Agreement raises well-established questions of burden-sharing under the principle of common but differentiated responsibilities and respective capabilities. In this context, countries with high incomes, advanced technological and financial capacity, and large historical contributions to cumulative emissions are widely expected to move beyond net-zero targets and to lead the transition towards net-negative GHG emissions (*3*, *4*).

For Switzerland, the case for engaging with net-negative emissions might not only be grounded in responsibility and capability, but also in its direct exposure to climate risks. Switzerland's warming rate already exceeds the global average (*5*), with temperatures in the Alps rising at approximately twice the global mean (*6*). This accelerated warming drives cascading impacts across multiple systems, including more frequent heatwaves and droughts interspersed with intense precipitation events, declining snow cover, shifts in vegetation phenology and species distributions, and rising natural hazards such as rockfalls, debris flows, and permafrost degradation (*5*–*7*). Hydrological impacts are particularly severe: without strong climate protection, river discharge patterns are projected to shift markedly, with around 30% more runoff in winter and 40% less in summer by the end of the century, fundamentally altering water availability for hydropower, agriculture, and urban supply. These risks are comprehensively synthesized in assessments such as the 2025 Climate Risk Analysis for Switzerland (*7*).

Importantly, some climate impacts unfold with long time lags; they might continue evolving even after temperatures stabilize at 1.5°C. An example is glacier retreat, which reflects systematic delays between climate forcing and cryospheric response (*8*), with substantial losses unavoidable even in ambitious mitigation scenarios (*9*). Alpine permafrost shows similar delayed responses (*10*), increasing the likelihood of rock avalanches and debris flows (*11*). Comparable multi-decadal lags are observed globally, including in boreal permafrost thaw (*12*) and sea-level rise, suggesting that meeting Paris-aligned temperature targets may be insufficient to prevent certain impacts (*13*). Stabilizing climate impacts may therefore require temperatures to decline below 1.5°C implying sustained net-negative emissions over extended periods (*14*).

Against this background, Switzerland's climate policy framework already embeds an obligation to move into net-negative territory after mid-century. Switzerland's climate policy is anchored in the Climate and Innovation Act (CIA) and the CO_2 Act. The CIA enshrines in law the objective of achieving net-zero GHG emissions by 2050, with residual emissions to be balanced through "negative emission technologies", i.e., carbon dioxide removals, in Switzerland and abroad. Article 3(2) further requires Switzerland to achieve a "*net-negative emissions balance after 2050*"[1]. The Federal Office for the Environment (FOEN/BAFU) is responsible for coordinating Swiss climate policy, implementing climate protection instruments, and facilitating effective solutions in line with these statutory objectives.

This report responds to the practical need to operationalize the direction towards *net-negative after 2050*: it provides benchmark values and framing for post-2050 net-negative ambition (Chapter 2), clarifies options for distributing responsibilities across domestic actors (Chapter 3), and outlines policy design considerations – particularly financing architectures – for delivering net-negative GHG outcomes at scale (Chapter 4). The key insights from Chapters 2-4 are brought together in Chapter 5, which synthesizes the main conclusions and policy implications.

[1] For the legal text in English see: https://unfccc.int/sites/default/files/resource/Supplement_Switzerland_Long_Term_Climate_Strategy_for_NDC_2031-2035_en.pdf

2 Swiss net-negative targets after 2050

2.1 Introduction

This chapter aims to derive indicative net-negative emissions target ranges for Switzerland for 2060. The objective is to assess how such targets can be aligned with basic burden-sharing considerations, notably, taking into account the principle of Common but Differentiated Responsibilities and Respective Capabilities (CBDR-RC) embedded in the United Nations Framework Convention on Climate Change (UNFCCC) and reaffirmed in the Paris Agreement.

Similar analyses have been conducted for other industrialized countries. For Canada, Finland and the Netherlands, recent studies show that even under conservative assumptions, achieving net-zero GHG emissions by 2050 is not compatible with standard burden-sharing frameworks. A related assessment was carried out for Switzerland in the context of the *KlimaSeniorinnen case*. Under a deliberately conservative allocation method, the assessment concluded that Switzerland would need to reach net-zero GHG emissions by 2040. It further noted that approaches grounded purely in equity principles – such as responsibility-based or capability-based allocations – would assign Switzerland substantially smaller emission allowances, or "fair carbon budgets".

The chapter is structured into two main parts. Section 2.2 provides a broad review of burden-sharing approaches and examines the key parameters relevant for deriving national efforts. Section 2.3 then derives indicative ranges for possible net-negative targets from three perspectives. First, it draws on the literature review, which shows that the range of net-negative targets implied by equity-based burden-sharing arrangements is very wide and, in many cases, suggests emission reductions more ambitious than Switzerland's current net-zero-by-2050 target. Second, it qualitatively extrapolates Switzerland's current long-term climate strategy into net-negative territory. Third, it develops a benchmarking approach to assess Switzerland's potential contribution to the global carbon removal requirements implied by 1.5°C pathways.

2.2 Key parameters and design choices in burden-sharing frameworks

In simplified terms, burden-sharing involves estimating the difference between emissions that can be attributed to a country (for example, under production-based or consumption-based accounting; or with varying sectoral or GHG coverage) and the emissions that the country is eligible to generate given a specified temperature goal (for example, under alternative equity principles or least-cost[2] allocation approaches). This difference then forms the basis for deriving a future emissions trajectory, or a related metric such as required abatement.

The literature on burden-sharing is extensive, with several recent reviews of previous studies (*15–18*). Studies attempt to classify these approaches using recognized equity principles, most importantly *capability*, *responsibility*, and *equality*. In practice, many approaches are hybrids, and they differ not only in their underlying ethical framing, including the relative weighting given to individual equity principles, but also in *what* they allocate across countries (for example, carbon budgets, annual net emissions, abatement with respect to a

[2] Mitigation efforts are distributed among countries reflecting the most cost-effective allocation, typically given by equal marginal abatement costs across countries (*15*).

baseline, removals, or abatement costs). Depending on the variable which is distributed between countries, burden-sharing might also require assumptions about past and future emissions, baseline emission assumptions, future GDP and population trajectories, abatement cost curves, and so on.

Early burden-sharing proposals concentrated primarily on distributing the remaining global carbon budget. The introduction of CDR in scenario modelling significantly expanded the way in which burden-sharing could be operationalized because of the additional temporal and spatial flexibilities, notably the option to exceed carbon budgets and replenish them later on through net-negative emissions. Some more recent burden-sharing exercises distribute removal quotas between countries, without directly addressing emissions.

Approaches also vary in how they treat convergence from current observed emissions to targeted levels, they might vary in climate projections, the role of non-CO_2 GHGs, and in the socioeconomic and technological assumptions that underpin scenario modelling. Consequently, estimates cover an extremely broad range. To provide context for the results that follow, we outline a basic set of commonly used parameters and options from which various burden-sharing approaches can be constructed.

The points below illustrate some of the most critical sets of assumptions underlying burden-sharing calculations:

- **Remaining carbon budget** as basis to compute global and national CO_2 emission trajectories. This reflects the global temperature goal (typically, 1.5°C) and the probability of staying within it (typically 50%).

- **Accounting principles** used to attribute emissions to countries – such as production-based, consumption-based, or hybrid supply-chain approaches – as well as the treatment of internationally unallocated emissions (e.g., aviation and maritime bunker fuels) and land use, land-use change and forestry (LULUCF).

- **Equity principles** guiding the distribution of effort, for example responsibility, capability, or hybrid formulations combining several principles.

- **Calculation method** translating these principles into quantitative emissions allowances, abatement or removal burdens for each country.

- **International cooperation** determining whether derived targets must be met solely through domestic action or whether mitigation outcomes generated abroad (e.g., through emission reductions or CDR) can be counted toward compliance. This affects the cost of achieving climate targets and may therefore influence burden-sharing arrangements in which mitigation costs are taken into account. The Paris Agreement (Article 6) explicitly permits such cooperative approaches, which can significantly affect both the feasibility and the cost of meeting derived targets.

2.2.1 Remaining carbon budget

Determining a remaining carbon budget translates a global temperature goal into a cumulative emissions constraint (*19*). The process specifies a global temperature limit (such as 1.5°C or 2°C above pre-industrial levels) and a probability of staying below it (for example, 50, 67, or 83 percent). A higher probability of meeting the temperature target implies a smaller remaining carbon budget. Several protocols exist for calculating budgets, including those that prohibit exceedance of the temperature threshold and those that allow a overshoot followed by a return below the target.

Carbon budgets are computed conditional on assumed trajectories for non-CO_2 GHGs: higher projected non-CO_2 radiative forcing reduces the allowable CO_2 budget, whereas more ambitious non-CO_2 mitigation increases it (*20*). For countries with large shares of non-CO_2 emissions, assumptions about non-CO_2 mitigation and the distribution of those efforts can significantly alter the allocated CO_2 budget and the overall effort needed to meet national (CO_2 and non-CO_2) emission targets.

Given the range of parameters, remaining carbon budget estimates on a global scale vary widely. The remaining carbon budget for limiting warming to 1.5°C starting after 2022 is estimated to 250 $GtCO_2$ (50% chance), with uncertainty arising mainly from the CO_2-temperature response and future non-CO_2 warming, yielding a combined uncertainty range of roughly −200 to 830 $GtCO_2$ (*20*). Standard reference estimates are regularly provided in the IPCC's Assessment Reports.

2.2.2 Accounting Principle

Several approaches exist in the literature for attributing GHG emissions to countries, including production-based (territorial), consumption-based (footprint), and extraction-based accounting. For physical integrity it would generally be desirable that all countries follow a consistent methodology for both target setting and accounting (*21*), although this is challenging to achieve in practice given the nationally-driven, bottom-up nature of national targets under the Paris Agreement. The current standard for national reporting under the UNFCCC is based on territorial emissions as defined in the IPCC 2006 Guidelines for National Greenhouse Gas Inventories. While the Paris Agreement requires methodological consistency and comprehensive coverage in accounting for Nationally Determined Contributions (NDCs), the design and scope of national targets remain nationally determined.

For many high-income countries, consumption-based emissions exceed territorial emissions, reflecting the carbon intensity of imported goods. To the extent that domestic consumption drives emissions embodied in imported products, responsibility can be attributed to final consumers as well as to producers and other actors along the value chain, raising the question of how embodied emissions should be allocated across jurisdictions. From a regulatory feasibility perspective, however, territorial emissions remain more directly governable, as they occur within a country's jurisdiction and can be addressed through domestic policy instruments. A related concern is carbon leakage: if mitigation policies reduce territorial emissions without affecting consumption, emissions may shift abroad. In the worst case, relocation to jurisdictions with weaker climate policies could even increase global emissions.

In response to these concerns, there has been some advocacy for reducing consumption-based emissions (*21*, *22*) and even for setting binding targets (*23*), notably in the past Swedish policy debate. For Switzerland, the fraction of net CO_2 imports relative to production-based emissions is pronounced, significantly exceeding the average ratio observed across the EU and Sweden (see Figure 1). While Switzerland's national GHG inventory follows a territorial accounting approach, it is noteworthy that Article 10 of the Climate and Innovation Act requires the federal administration to achieve net-zero emissions by 2040 including Scope 3 emissions, thereby extending responsibility to indirect emissions at the institutional level.

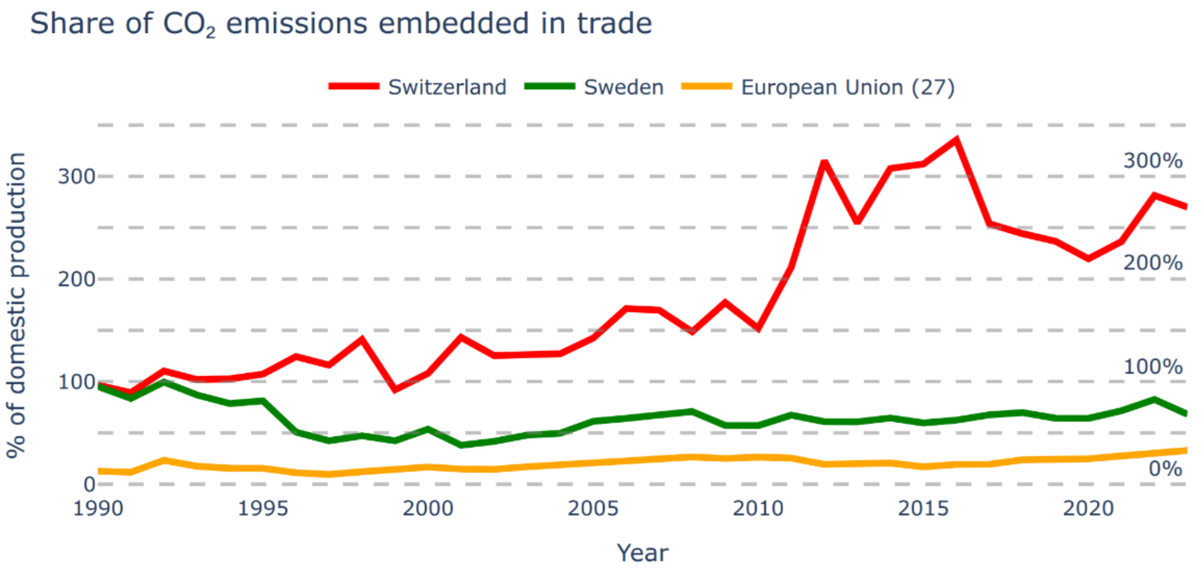

Figure 1. Carbon emissions embedded in trade. Ratio of net CO_2 imports (i.e., imports minus exports) to production-based (territorial) emissions for Switzerland, Sweden, and EU (27). Source: Our World in Data (https://ourworldindata.org/grapher/share-co2-embedded-in-trade).

2.2.3 Equity principles and other factors shaping country-level allocations

Equity principles specify how a remaining global carbon budget consistent with a given temperature limit (or an alternative metric such as a global mitigation burden, as discussed before) should be distributed among countries and on what grounds. Several preliminary observations are worth noting:

- First, the UNFCCC articulates the principle of common but differentiated responsibilities and respective capabilities (CBDR-RC), which provides a legally binding but only broadly framed basis for differentiating mitigation efforts according to countries' *capabilities* and historical *responsibilities* for global warming, without prescribing a specific quantitative allocation formula.
- Second, empirical analyses suggest that the burden-sharing pattern emerging from the global stocktake process and embodied in countries' NDCs aligns most closely with a capability-based logic (*24*). Among several allocation principles (including responsibility and equality), capability – proxied by the Human Development Index – is most consistently associated with the relative ambition of national mitigation commitments. However, this association is qualitative and does not imply that current NDCs reflect the full quantitative reductions that strict adherence to a capability metric (e.g., based on GDP or income) would entail for individual countries.
- Third, terminology is often used inconsistently across disciplines – including law, ethics, political science, and climate science – and sometimes even within them. Terms such as *capability, capacity,* and *ability-to-pay* are frequently used interchangeably, while concepts such as *responsibility*, *polluter-pays*, or *beneficiary-pays* can lead to similar implications in burden-sharing contexts. Furthermore, there is doubt about whether the *equality principle* for burden-sharing rests on any fundamental principle of justice (see discussion in ref (*25*) and references therein). A precise delineation between these principles lies beyond the

scope of this study. Notably, however, a conceptual link can be drawn between *responsibility* and *capability*: to the extent that wealth in industrialized countries is partly related to the historical and ongoing use of fossil fuels, their ability to finance climate mitigation may itself reflect benefits derived from past emissions.

- Fourth, global mitigation scenarios – such as those assessed by the IPCC – are typically constructed based on an *cost-effectiveness* (or *least-cost*) objective. Emission reductions and CDR deployment are modelled to occur where they are technologically feasible and economically least expensive, given physical potentials and energy system characteristics, among other things. Cost-effectiveness is an efficiency criterion rather than a distributive principle: it determines where mitigation occurs, but not who ultimately bears the associated costs. Equity considerations are therefore often layered on top of such least-cost pathways: burden-sharing rules may determine which countries ultimately bear the costs, but this need not imply that mitigation or CDR must occur domestically, as obligations can in principle be met through financial transfers and international cooperation.

2.2.3.1 Responsibility

Under the responsibility principle, countries with greater responsibility for climate change, including the effect of historical emissions, receive smaller future emissions allowances or larger obligations to reduce GHGs or remove CO_2. A central parameter is the start year for counting historical emissions. Common reference points include 1850, 1990, and 2015. Using 1850 reflects full historical responsibility of early industrializers such as the United Kingdom, the European Union, and the United States and reflecting the near-permanent warming caused by CO_2 emissions. A 1990 start date ties responsibility to the period in which scientific consensus and political awareness of climate change were increasingly well established, which is often considered as the most defensible approach (*25*). Choosing 2015 largely omits historical responsibility and aligns allocations with the situation at the time of the Paris Agreement.

For many developed countries, applying a responsibility-based approach would yield carbon budget allocations that are already exhausted or even negative. Switzerland is no exception. Its per-capita CO_2 emissions (incl. LULUCF) exceed the global average when averaged over a period from 1950 onward – capturing the period of rapid post-war industrial expansion – and as well as from 1990 (see Figure 2). Starting in 1850, however, yields a below-average outcome because of relatively low emissions from land use change from 1850 to 1950 (*26*).

Instead of averaging per-capita emissions over a historical period, we also evaluate responsibility for past cumulative emissions from 1850 onwards relative to the size of the *current* population. Scaling Switzerland's contribution to global warming – accounting for territorial CO_2 and other GHG emissions and scaling by its *current* share of the global population – implies that the median global temperature increase would already be approximately 1.8°C (Figure 3). This illustrates how subtle differences in methods can lead to qualitatively different conclusions.

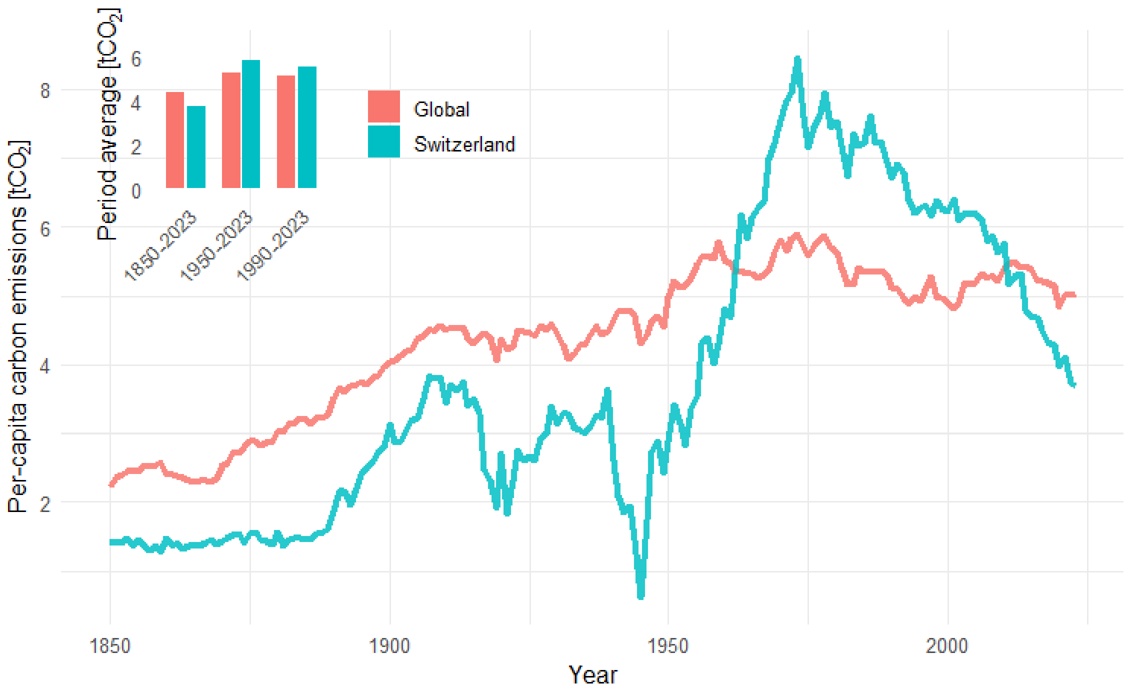

Figure 2. Per-capita CO_2 emissions for Switzerland and globally, including land-use, land-use change and forestry (LULUCF). The bar charts show average values over the periods starting in 1850, 1950, and 1990 and ending in 2023. For data sources see, see Annex 1.

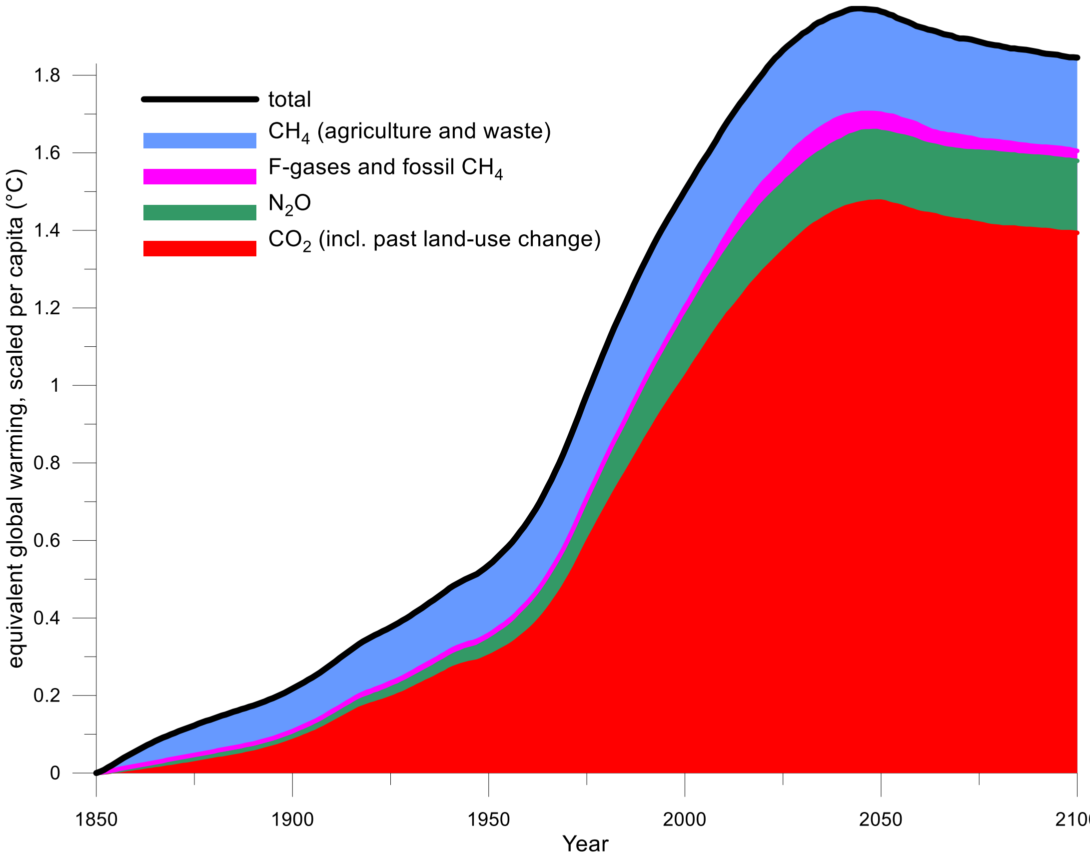

Figure 3. Hypothetical global temperature increase based on Switzerland's per-capita contribution to warming, accounting for CO_2 and other GHGs and using Switzerland's current share of the global population. The estimate shown corresponds to the median value of the underlying calculations. For details, see Annex 1.

2.2.3.2 Capability

Capability-based approaches allocate a larger share of mitigation effort to countries with greater economic and institutional resources. The underlying rationale is that countries with higher income levels and stronger institutional capacity are better positioned to absorb mitigation costs. In quantitative burden-sharing frameworks, this is often represented by allocating emissions allowances inversely to GDP per capita or by using composite indices intended to capture a country's ability-to-pay. Unlike responsibility-based approaches, capability-based allocation does not primarily depend on historical emissions and may therefore imply substantial obligations even for countries with comparatively low historical contributions.

2.2.3.3 Equality

The equality principle holds that every individual has an equal claim to global public resources, including the atmosphere. In many studies, this principle is operationalized as *equal-per-capita* emissions, meaning that emission pathways should be allocated across nations proportionally to population size. In contrast to responsibility- or capability-based approaches, this framing grants Switzerland relatively generous emission rights. A critical caveat of this approach is that "equal rights to the atmosphere" often translate into "equal obligations to restore the atmosphere" once global net-negative CO_2 emissions become necessary. In other words, net-negative emission requirements are allocated in the same way as emission rights, implying that each country must contribute equally on a per-capita basis to atmospheric clean-up. However, equality-based approaches can also be formulated to distribute required mitigation efforts rather than allocating net emissions.

2.2.3.4 Basic needs and minimum development opportunities

Country-level allocations based on responsibility, capability, or equality are often adjusted to account for addressing *basic needs* or *development opportunities*. A common distinction is made between subsistence emissions – associated with meeting essential needs – and luxury emissions, which can in principle be reduced without undermining basic welfare (*27*, *28*). For example, the Greenhouse Development Rights framework (*29*) applies a development threshold of roughly USD 7,000 per capita per year when calculating countries' responsibility and capability shares. By excluding income below this level from the burden-sharing calculus, a larger share of mitigation effort is effectively assigned to higher-income populations, thereby increasing the implied contributions of wealthier countries.

Related concerns have also been raised regarding strict equal-per-capita allocation rules (*30*): equal-per-capita emission rights may overlook large differences in development levels and basic needs. Because emissions are a means of achieving human well-being rather than an end in themselves, strict equal per-capita allocations may risk producing "equality for unequals." To address these concerns, some authors propose modified equal-per-capita approaches that incorporate adjustments for basic needs, historical responsibility, and benefits derived from past emissions (*31*).

2.2.3.5 Adjustment costs

The adjustment cost perspective focuses on how the economic costs of the transition to low- or negative-emission pathways are distributed across countries, including impacts on energy prices, stranded assets, and employment. Under this view, an allocation is considered equitable if it avoids imposing abrupt or economically destabilizing adjustment burdens on particular countries. Accounting for adjustment costs might constitute a legitimate dimension of equity (*28*): future allocations should recognize the substantial economic and social challenges faced by countries with currently high emissions. In this spirit, policy continuity considerations may implicitly account for adjustment costs by allowing gradual transitions from the status quo.

An extreme case of adjustment costs is the principle of *grandfathering*, which implies that future emission rights depend, at least for some period of time, on the level of past or present emissions. In this sense, present emission levels are often used as starting point to model smooth transitions towards other equity-based allocations (*16*). This approach, which is prevalent primarily in allocations using the equal-per-capita principle, implicitly favors current high emitters regardless of actual adjustment costs (*32*, *33*).

2.2.3.6 Hybrid allocation methods

Most recent studies – including those used to derive the net-negative target range for Switzerland in Section 2.3.1 below – combine multiple equity principles by applying hybrids of single-principle allocation rules. Illustrative examples include the contraction-and-convergence or per-capita-converge rules (*16*, *34*) which broadly combine elements of grandfathering (or adjustment costs) and equality, with national emissions gradually converging toward equal-per-capita levels over time. As noted before, similar approaches exist which adjust equal-per-capita allocations for basic needs, historical responsibility, and the benefits derived from past emissions (*31*). Other approaches blend responsibility- and capability-based principles in an attempt to operationalize the CBDR-RC principle of the Paris Agreement, including the Greenhouse Development Rights framework (*29*).

2.2.4 International cooperation

Another constraint is the assumed level of international cooperation, which influences how mitigation efforts can be shared and whether efficiency gains from cross-border emissions trading are feasible. Under a high-cooperation scenario (e.g., the shared socioeconomic pathway, SSP1 (*35*)), countries can make use of well-functioning carbon markets and international mitigation opportunities, allowing those with higher obligations to reduce costs by financing emissions reductions or removals elsewhere. In contrast, a low-cooperation scenario (e.g., SSP3) assumes reduced international engagement, requiring countries to meet targets largely through domestic action and increasing overall mitigation costs. Intermediate configurations include club arrangements in which groups of countries, such as the EU, cooperate internally while implementing measures such as carbon border adjustments to limit leakage.

For high-income countries with a strong ability to pay but constrained land, ocean, or energy resources for large-scale domestic CDR – such as Switzerland – the degree to which CDR can be sourced internationally in a manner that delivers genuine additional removals is a critical determinant of cost and feasibility.

2.3 Determining a net-negative target range for Switzerland

2.3.1 Literature estimates for net-negative emissions

Given the large number of modelling parameters and choices involved, potential net-negative emission targets derived from equity-based burden-sharing approaches vary widely. For Switzerland, capability-based approaches generally imply the highest mitigation and removal efforts, followed by responsibility-based approaches, whose results depend strongly on the chosen start date for accounting historical emissions (as illustrated in Figure 2). Both capability- and responsibility-based approaches tend to assign Switzerland a mitigation burden above the global per-capita average, that is, above what would result from equal per-capita allocations. As a result, equality-based approaches typically imply comparatively less ambitious targets for Switzerland and similar industrialized countries. Because Switzerland's per-capita territorial emissions are already below the global average, the country could currently be interpreted as overachieving under an equal-per-capita allocation. However, while this may hold at present, Switzerland's NDC-aligned trajectory to net-zero greenhouse gas emissions by 2050 could still exceed even such a relatively generous allocation.

Various online burden-sharing calculators exist, differing in their underlying assumptions and in the number of parameters that can be adjusted through their interfaces. Most of these tools are based on peer-reviewed studies. Below, we present indicative ranges for net emissions in 2060. Where possible, parameter choices were harmonized to enhance comparability – notably, by selecting settings consistent with global 1.5°C scenarios that provide a 50% probability of meeting the temperature target by 2100. Although the resulting estimates remain imperfectly comparable, they provide an indication of the range of outcomes implied by different allocation approaches. Values reported for years earlier than 2060 should be interpreted as lower bounds for that year.

Moreover, it should be noted that such aggregated ranges combine results derived from different allocation principles and modelling assumptions, which may reflect distinct and sometimes incompatible ethical perspectives. Consequently, while these estimates provide a useful indication of the breadth of outcomes discussed in the literature, their interpretation in policy contexts requires careful consideration of the underlying normative assumptions (*30*).

The Climate Action Tracker reports a 1.5°C-compatible "fair-share" range of –38 to –95 $MtCO_2$-eq for Switzerland already by 2035[3] (no projection is provided for 2060). The Carbon Budget Explorer (*16*, *36*) reports a range of 1 to –228 $MtCO_2$-eq in 2060[4]. The lower bound reflects the Greenhouse Development Rights-based allocation method (see also Section 2.2.3.4).

The Climate Equity Reference Calculator (*37*), which focuses on responsibility- and capability-based allocations, reports a 2035 range from 5 $MtCO_2$-eq under a purely responsibility-based allocation to –231 $MtCO_2$-eq under a capability-based allocation[5]. Notably, the responsibility-based allocation is more ambitious than current Swiss NDC-compatible projections but remains net-positive. This relatively modest target in part reflects the assumption that historical

[3] The fair share range comprises approaches based on responsibility, capability, equality. For methods refer to: https://climateactiontracker.org/methodology/cat-rating-methodology/fair-share/; data has significant overlap with ref (*18*).
[4] To derive this range, we set the global warming parameter to 1.5°C, the acceptable risk of exceeding this limit to 0.5. All other parameters are left at mid-range (i.e., set to 0.5). We use data from all allocation methods (grandfathering, per capita, ability to pay, Greenhouse Development Rights, equal cumulative per capita). For Greenhouse Development Rights, we report the mid-range value, which appears to apply similar weights on capability and responsibility metrics. For methods see: https://www.carbonbudgetexplorer.eu/about#technology
[5] We select global mitigation compatible with a 1.5°C pathway, set the beginning of historical emission accounting to 1990, include non-CO2 emissions, exclude emissions embedded in trade, and set the responsibility weight to 1 (full responsibility-based allocation) and to 0 (full capability-based allocation). For methods see: https://climateequityreference.org/about-the-climate-equity-reference-project-effort-sharing-approach/

responsibility is calculated from 1990 onward – when the IPCC published its first assessment report – and the fact that Switzerland's per-capita territorial emissions fell below the global average around 2015 (see Figure 2).

Finally, the Coordinated Allocation of Removal Efforts (CARE) Calculator (*38*) yields an approximate range of 11 to 500 $MtCO_2$ of gross removals in 2060[6]. Crucially, these figures represent *gross* CDR allocations and reflect a strand of the literature (*39*, *40*) that applies equity principles to allocate global carbon removal quotas (instead of, e.g., remaining carbon budgets, net-emission pathways or mitigation targets). To obtain net-negative emissions, these values must be adjusted for projected residual emissions in 2060. The reported ranges are summarized in Table 1.

Table 1. Possible net-negative emission ranges for Switzerland in 2060. Values for 2030 and 2035 present a lower bound, as net-negative emissions are expected to grow over time. The values derived from the CARE calculator represent gross removals, rather than net-negative emissions. Data presented for global emission pathways which best align with a 1.5°C target (end-of-century warming below 1.5°C with a 50% chance in 2100).

	Climate Action Tracker	**Carbon Budget Explorer**	**Climate Equity Reference**	**Coordinated Allocation of Removal Efforts (CARE) Calculator**
Estimate of net emissions (or gross removals for the CARE Calculator), $MtCO_2$-eq/year	-38 to -95 in 2030	1 to -228 in 2060	5 to -231 in 2035	11-500 in 2060 *(gross removals)*
Online tool link	https://climateactiontracker.org/	https://www.carbonbudgetexplorer.eu/	https://calculator.climateequityreference.org/	https://tracker.carbongap.org/care-calculator/

To place the results from online calculators in context, it is useful to consider country-level case studies conducted for Switzerland and other countries.

In the case of *Verein KlimaSeniorinnen Schweiz and Others v. Switzerland* before the European Court of Human Rights, the Swiss government provided to the applicants a 2012

[6] The CARE Calculator enables interactive scenario analysis of national CDR contributions of EU countries to global climate goals by varying several critical parameters: (1) the global CDR requirement, specified through climate mitigation pathways with different annual removal volumes of 10.8 Gt CO_2e/yr (C1 scenario), 12.5 Gt CO_2e/yr (C2 scenario), or 9.8 Gt CO_2e/yr (C3 scenario) in 2060; (2) the participating country group, ranging from worldwide participation to participation limited to upper-income/Annex I countries; and (3) the allocation principle allows various weighted combinations of polluter-pays (historical responsibility), ability-to-pay (financial capacity), equality (population-based). The range reported in Table 1 for Switzerland is derived by comparison with other EU EU countries. The upper bound is derived by selecting the following parameters: only Annex I countries participate; C2 scenario; ability-to-pay by Gross National Income (GNI) per capita. We use Swiss current GNI per capita as reference, which places Switzerland between Denmark (452 Mt/yr) and Luxembourg (579 Mt/yr). We thus report an upper bound of 500 $MtCO_2$/yr in 2060. The lower bound is derived by selecting the following parameters: all countries participate; C3 scenario; equality-based using current population numbers. Since Austria and Switzerland have similar population sizes, we select Austria as proxy, resulting removal of ~11 $MtCO_2$/yr in 2060.

policy brief by L. Bretschger (*41*, *42*) [7]. The method underlying this policy brief was subsequently applied to updated data at the request of *Verein KlimaSeniorinnen* (*43*). Their analysis highlights two key points:

- Bretschger's framework combines initial grandfathering – under which countries with higher current emissions retain larger emission allowances – with a gradual transition toward an equality-based allocation. Under this structure, historical emissions do not directly reduce future allocations, and economic capability is not included as an explicit allocation parameter. To the extent that CBDR-RC is interpreted as requiring differentiation according to responsibility for historical emissions and capability to deliver mitigation, the approach does not operationalize these criteria directly.

- Applying Bretschger's allocation framework and assuming a linear reduction pathway to net-zero by 2050 implies that Switzerland's allocated emissions budget would be exhausted before the end of 2033, resulting in an overshoot of 181 $MtCO_2$-eq by 2050. Because this allocation does not explicitly adjust for historical responsibility or economic capability, it can be interpreted as relatively favorable to Switzerland compared with burden-sharing approaches that apply these criteria more strictly. The 181 $MtCO_2$-eq could therefore be understood as a lower-bound estimate (i.e., relative to more differentiated allocation rules) of Switzerland's excess emissions, which would need to be compensated through cumulative net-negative emissions until 2100.

The modified versions of equal-per-capita allocation for Switzerland (*31*) first discussed in Section 2.2.3.4 estimates that Switzerland has already accrued a carbon debt (i.e., a "negative carbon budget") between 30 and 300 $MtCO_2$ by 2017, whereas a simple equal-per-capita approach would have allocated a remaining budget of 530 $MtCO_2$.

Likewise, a recent study (*26*) finds that, assuming Switzerland follows an NDC-derived pathway to net zero, its remaining carbon budget for the second half of the century ranges from approximately zero to below –2 $GtCO_2$, depending on the allocation assumptions (see Supplementary Figure 12 in ref (*26*)). A negative budget can be interpreted as implying a cumulative net-negative emissions requirement for the period from 2050 to 2100. Only allocation methods that account for historical responsibility since 1850 assign Switzerland a slightly larger remaining carbon budget than its NDC-consistent emissions, due to a net CO_2 credit from historically below-average LULUCF emissions between 1850 and 1950 (see also Figure 2.)

An analysis for the Finnish Climate Change Panel (*44*) informed Finland's decision to adopt targets of net-zero emissions by 2035 and net-negative emissions by 2040. The Finnish targets correspond closely to the report's ability-to-pay (capability-based) framework, while equal-per-capita or historical responsibility approaches would imply less or more stringent timelines, respectively. However, the Finnish assessment is based on a limited set of model estimates (*45*). A broader meta-analysis (*18*) indicates that a fully 1.5°C-compatible pathway for Finland would require achieving net-negative emissions as early as 2030.

Similar studies have derived "fair carbon budgets" for the Netherlands (*45*) and Canada (*46*) using capability- and/or responsibility-

[7] "Respondent submitted … material in support, including a Policy Brief by Prof. Dr. Lucas Bretschger from 2012 ("Policy Brief") at Annex 1…", source: https://en.klimaseniorinnen.ch/wp-content/uploads/2023/04/230427_53600_20_Response_to_Governments_written_answers_to_questions_posed_by_GG.pdf

based allocation methods. For the Netherlands, the analysis finds that the country has already exhausted its fair carbon budget, implying that national net emissions would need to fall below zero by 2030 and remain net-negative thereafter to align with global climate goals in an equitable manner. For Canada, under a 1.5°C target, the study finds that the fair carbon budget was already exhausted by 2017, amounting to roughly –7 $GtCO_2$. If Canada were to follow a linear emission reduction pathway to net-zero by 2050, it would accumulate a carbon debt of more than 16 $GtCO_2$, equivalent to nearly 30 years of emissions at 2024 levels.

Together, these assessments illustrate that when standard burden-sharing principles are applied consistently, they tend to produce pathways for high-income industrialized countries that may be considerably more demanding than current national targets.

2.3.2 Up-scaling from net-zero into net-negative

One benchmark of minimal net-negative GHG emissions can be derived based purely on how Switzerland is currently planning to reach the point of net-zero emissions.

Under current plans (*47*), Switzerland is aiming to reach net-zero emissions in 2050, including emissions from domestic refueling of international aviation. Based on current estimates, this will entail residual domestic emissions of about 12 Mt CO_2-eq plus 1-2 Mt CO_2 from international aviation, prior to the use of any carbon capture and storage (CCS) or CDR (*48*). CCS is estimated to avoid about 5 Mt of those emissions to the atmosphere, with about 8-9 Mt CO_2-eq remaining.[8] These *true residual emissions* of about 8-9 Mt CO_2-eq would be counterbalanced by domestic CDR of about 2 Mt CO_2 and the remainder of 6-7 Mt CO_2 CDR financed internationally (*49*).

Existing modelling in EP2050+ scenarios (*49*) for domestic emissions essentially treats net-zero as an end-point that merely needs to be maintained post-2050. The analysis provides no information on what further domestic reductions or increased domestic or international removals might be possible if policy efforts continue to reach and sustain an increasing scale of net-negative emissions. Modelling in EP2050+ scenarios envisages residual emissions (prior to use of CCS for emissions avoidance) to drop further from 11.8 to 10.7 Mt CO_2-eq by 2060, and current EP2050+ scenarios accordingly reduce the amount of CDR financed internationally by 1.1 Mt CO_2 in 2060 to maintain net-zero GHG emissions.

If, hypothetically, Switzerland instead were to maintain the volume of CDR financed internationally beyond 2050 and achieve the further reduction in domestic gross emissions, this would achieve net-negative emissions of 1.1 Mt CO_2-eq by 2060 (or a reduction of about 102% relative to 1990). It is noteworthy that the pathways for domestic gross emissions (prior to use of CCS or CDR) are dropping much more rapidly before 2050 than after 2050, and similarly, the use of CCS and CDR domestically is upscaled rapidly leading up to 2050 but in the current modelled pathways then kept sufficient only to maintain net-zero emissions. This is illustrated in Figure 4.

If the increased use of CCS and CDR were continued to grow into the decade 2050-2060 at a similar rate as they are envisaged to grow leading up to 2050 (i.e., here a simple extrapolation), the total volume of emission avoidance (via CCS applied to fossil emission sources) and removals (CDR) could be increased from 11.7 Mt CO_2 in 2050 up to about

[8] The exact remaining emissions are difficult to quantify precisely since the modelling groups CCS applied to emissions from fossil sources together with CDR that requires capture of CO_2 from the atmosphere, or avoidance of emissions from biogenic sources where the CO_2 removal occurs through prior growth of plant material.

20 Mt CO_2 in 2060. Note that the relative contributions from CCS (avoidance of emissions to the atmosphere) and CDR (removal of CO_2 from the atmosphere) is not specified in detail in the EP2050+ scenarios, and therefore their relative contributions to avoid or counterbalance residual emissions in 2050 or their further upscaling to 2060 are indicative only.

Assuming true residual emissions (i.e. after CCS to avoid emissions to the atmosphere, and including emissions from international aviation) of 8-9 Mt CO_2-eq in 2050 (*48*), this would imply an equivalent amount of CDR of 8-9 Mt CO_2 reached in 2050, which by extrapolation could be upscaled to about twice that amount of more than 15 Mt CO_2 in 2060.[9]

Another question is whether residual emissions have reached a more or less stable plateau in 2050 (as suggested in the EP2050+ scenario), or whether further reductions beyond those currently modelled would be possible. It is beyond the scope of this study to estimate further abatement potential for those remaining "hard-to-abate" emissions as this would require sector-specific technology assessments and possibly also consideration of systemic changes in material efficiency and demand-side management. Here we only note that the largest share of residual emissions in 2050 is envisaged to come from agriculture. In this area, significant advances are being made to develop novel abatement technologies that to our knowledge were not included in the modelled emission pathways (*50*). If further reduction of residual emissions were a dedicated policy focus, it would appear not implausible for residual emissions in agriculture to drop below the 4.1 Mt CO_2-eq in 2060 as currently modelled. It would require a dedicated analysis to assess the potential of such technologies in the Swiss context, but the wide range of emerging technologies and dedicated investments internationally to address emissions from grazing livestock (*51*, *52*) suggests a potential to reduce residual emissions (before CCS and CDR) to less than 10 Mt CO_2-eq in 2060.

Combined with upscaled international and domestic CCS and CDR, this would imply a potential for net-negative emissions to reach more than 10 Mt CO_2 in 2060 (or a reduction of about 118% relative to 1990 emission levels).

We emphasize that such an estimate does not reflect any detailed feasibility assessment and is based purely on an extension of pre-2050 efforts in emission reductions, emission avoidance through CCS, and domestic and international CDR. Nonetheless, such estimates could perhaps serve as benchmark of what continued climate policy effort beyond 2050 could achieve if net-zero GHG emissions is not treated as the end-point of climate policy but merely as a steppingstone into net-negative emissions territory.

[9] The amount of removals from CDR financed internationally is in principle limited only by Switzerland's financial resources, but will also depend on credible sources of CDR and buying arrangements. For this reason we here make a conservative, illustrative assumption that internationally financed CDR together with extended efforts to further upscale the use of CCS and CDR domestically could reach 20 Mt CO_2 (of which 15-18 Mt CO_2 could be CDR), but note that in particular any further upscaling of CCS and CDR domestically would require a detailed, sector-by-sector technical feasibility assessment that is outside the scope of this report.

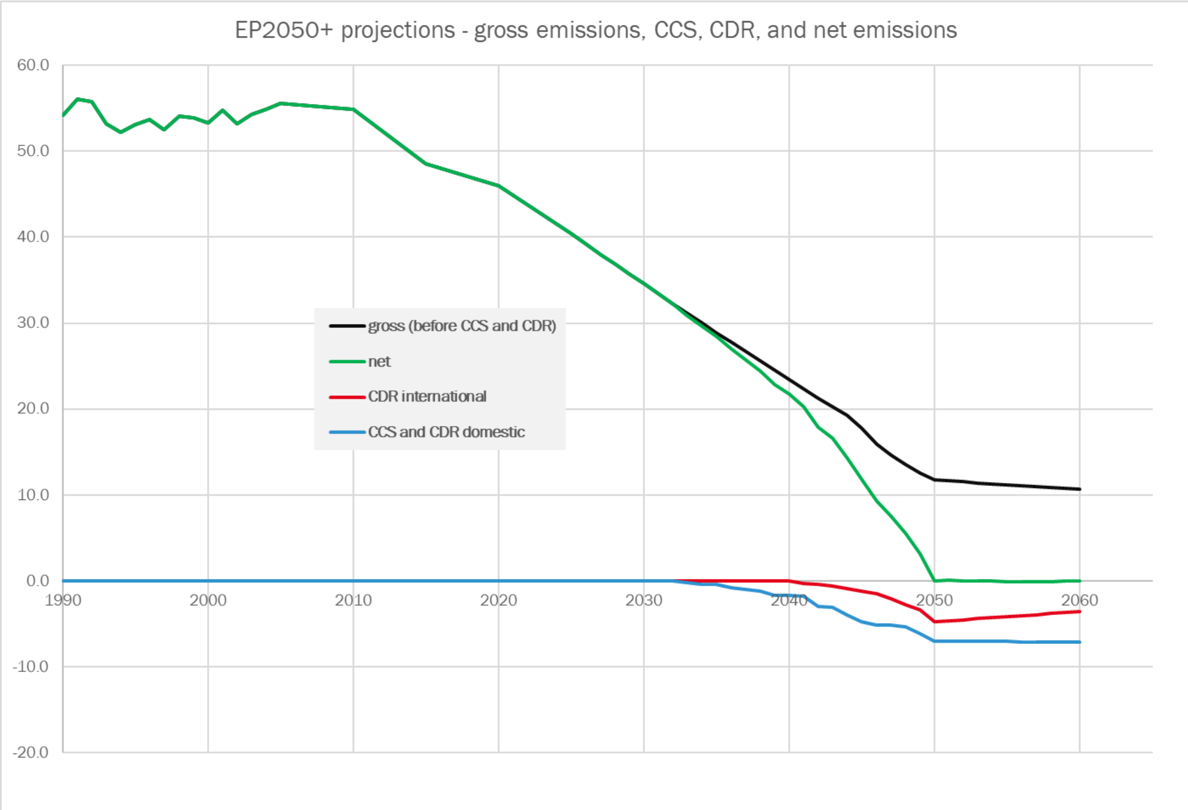

Figure 4. Emission and removal components of the Swiss EP2050+ scenario. Note that the relative contributions from CCS (avoidance of emissions to the atmosphere) and CDR (removal of CO_2 from the atmosphere) is not specified in detail in the EP2050+ scenarios, and therefore their relative contributions to avoid or counterbalance residual emissions are indicative only.

2.3.3 Within-coalition reciprocation of removal targets

In addition to the extrapolation in Section 2.3.2, we propose a simple framework to assess whether any given Swiss removals target may be consistent with the global CDR requirement implied by 1.5°C scenarios. The framework rests on two core elements:

1. Coalition assumption: We assume Switzerland is part of a group of countries that advances CDR in a broadly comparable way.

2. Capability-to-pay scaling: Within that coalition, we assume that removals scale with national GDP – i.e., each country's CDR contribution is proportional to its economic capacity, and this share is equivalent across coalition members.

Under these two assumptions[10] the national removal target can be benchmarked against the coalition's implied share of the global CDR requirement, providing a check to what degree a national target is aligned with a globally

[10] These assumptions for reciprocal climate action can be derived from principles established in ref (*27*). First, when multiple parties voluntarily commit to a shared endeavor, those with the greatest resources can reasonably contribute proportionally more, enabling others to participate meaningfully without overextending their capacity. Second, to the extent the collective endeavor is feasible, one may not expect any party to fall below a decent human standard of living; sacrifice of this threshold may only be considered if the endeavor cannot otherwise be achieved.

adequate outcome[11]. For more details, see Annex 2. Note that this approach is conceptually similar to the *Oxford Approach* (*53*), which derives national capability shares from GDP-based indicators adjusted for domestic development needs.

A natural reference group for this purpose would be OECD countries, which generally possess comparable institutional and financial capacity to absorb the costs of scaling CDR while maintaining high levels of economic welfare and macroeconomic stability. In addition, Table 2 and Figure 5 show results for an OECD + China and India grouping (a large coalition), as well as for a Switzerland + Euro Area (EA-17)[12] grouping (a small coalition).

Table 2. Possible Swiss gross removal targets for 2060 (Mt CO_2). The table reports Swiss gross removal targets consistent with alternative coalition assumptions (OECD + China + India; OECD; or Switzerland + EA-17), assuming coalition members adopt comparable targets scaled by GDP. For each row, the percentage indicates the share of 1.5°C scenarios in which the global CDR requirement would be at or below the global value implied by scaling the corresponding Swiss target ("scaled value"). The coalition columns therefore report the Swiss removal levels associated with each scenario quantile under the respective coalition assumption. For example, 67% indicates that scaling the reported Swiss target within the specified coalition would yield a global removal level ("scaled value") that is greater than or equal to the global CDR requirement in 67% of the underlying scenarios. In other words, the global removals requirement would be lower than or equal to the scaled value in 67% of scenarios. See Annex 2 for more information.

Quantile (=share of scenarios with global gross removals ≤ scaled value)	Swiss gross removals for a collation of OECD countries + India + China	Swiss gross removals for a collation of OECD countries	Swiss gross removals for a collation of Switzerland + EA17 countries
83%	40.5 Mt CO_2	77.1 Mt CO_2	322 Mt CO_2
67%	28.8 Mt CO_2	54.9 Mt CO_2	229 Mt CO_2
50%	25.9 Mt CO_2	49.4 Mt CO_2	206 Mt CO_2
33%	24.5 Mt CO_2	46.8 Mt CO_2	195 Mt CO_2
17%	18.7 Mt CO_2	35.7 Mt CO_2	149 Mt CO_2

[11] Note that we focus here on gross removals only, and assess whether a Swiss gross-removals target can constitute a defensible contribution to global gross removal efforts. Achieving the Paris Agreement objectives, however, ultimately depends on net-negative emissions. Net-negative outcomes are a function of residual emissions, and – holding gross removals constant – a country's contribution to the Paris goals can be increased through deeper reductions in residual emissions (see Sections 2.3.2 and 4.1.3). Due to data limitations, global removals are estimated by aggregating BECCS, DACCS, and net removals from AFOLU (for which gross emissions are not reported). This introduces a downward bias: total global gross removals are likely higher than reported here.
[12] The EA-17 includes Austria, Belgium, Finland, France, Germany, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Greece, Slovenia, Cyprus, Malta, Slovakia, Estonia.

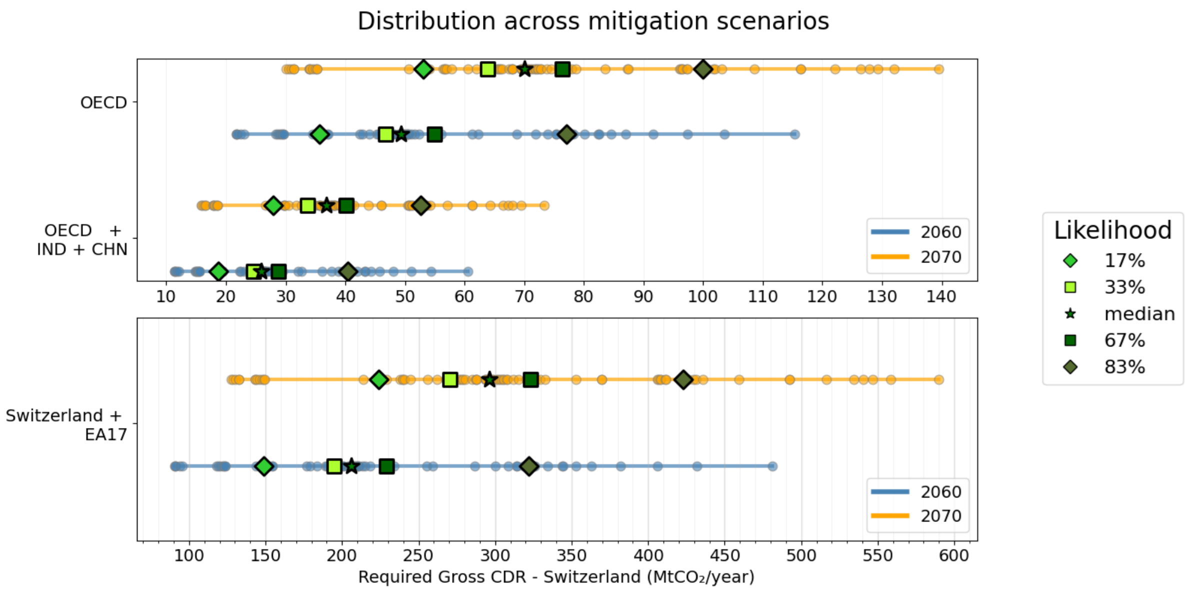

Figure 5. Distribution of possible gross removal targets for Switzerland. Each dot represents one global mitigation scenario, in which the global gross removals requirement has been scaled down to a gross removals value for Switzerland under the assumption that all countries in the selected coalition (OECD; OECD plus India and China; Switzerland plus EA-17 countries, see Footnote 12) contribute proportionally according to their GDP. The figure also illustrates quantiles across all scenarios. A given quantile (e.g., the median) indicates that, if Switzerland were to implement the corresponding target and other coalition members reciprocated by scaling their contributions according to GDP, the coalition would collectively meet or exceed the global CDR requirement in 50% of the underlying scenarios. Higher quantiles therefore correspond to more ambitious targets. Note the caveat regarding the computation of global gross removals in Footnote 11.

When the conservative 16-18 Mt CO_2 removal range for 2060 derived in Section 2.3.2 (i.e., twice the amount of 8 to 9 Mt CO_2 in 2050) is scaled to a global level under the assumption of a large coalition comprising OECD countries plus China and India, the implied global gross removals are relatively modest: fewer than 17% of the underlying 1.5°C scenarios exhibit global CDR requirements at or below this level (see Table 2, OECD + China + India column, 17% row, corresponding to 18.7 $MtCO_2$). In other words, in 83% of scenarios global removals are larger than those implied by scaling the potential Swiss target range of 16-18 Mt CO_2 to a global level even within a large coalition.

Under a Switzerland + EA-17 coalition – and possibly even under an OECD coalition – the implied removal volumes as shown in Figure 5 exceed what any individual country in the group could realistically deliver.

Furthermore, the proposed framework allows a national removals target set by another country to be translated into an equivalent Swiss target, ensuring consistency in terms of the implied contribution to global removal requirements. Denmark has proposed a quantitative net-negative target of a 110% cut in GHG emissions below 1990 levels by 2050, implying ~8 Mt CO_2e net removals. As detailed in Annex 2, replicating Denmark's ambition in Switzerland yields ~26 Mt CO_2 gross removals, corresponding to a net-negative emissions target of roughly 20 Mt CO_2-eq (i.e., under the assumption that residual emissions are brought down to roughly 6 $MtCO_2$-eq in 2060). This would be a sufficient contribution to global CDR efforts in more than 50% of scenarios under a OECD + China + India coalition, as indicated in Table 2 (OECD + China + India column, 50% row, corresponding to 25.9 $MtCO_2$).

Following this approach, Switzerland could commit to a specific quantity of CDR without formally conditioning its pledge on the actions of others. Such an unconditional commitment can signal willingness to contribute and invite reciprocal participation. However, the framework could be extended through "matching-commitment" mechanisms, under which countries condition part of their contribution on equivalent effort by others. In such arrangements, increases in one country's CDR target are triggered by comparable increases from coalition partners. This conditional cooperation logic can strengthen incentives to participate, enhance coalition stability, and raise aggregate mitigation ambition beyond what isolated unilateral commitments would achieve (*54*, *55*).

3 Distribution of responsibilities for net-negative emissions

3.1 Introduction

This chapter of the report addresses the fundamental question of which entities within the Swiss economy and society could be required to bear the burden of reaching net-negative emissions. We do so by considering the consistency of a range of burden-sharing choices with fundamental principles relating to global equity, to principles already embedded in Swiss climate law, and general principles of public policy.

Note that the discussion that follows does not advocate that any of those principles *should* be adopted as principles for sharing the burden of net-negative emissions within Switzerland, it only sets out the consequences *if* any of those principles were followed. Determining which principles to use will entail the weighing up of a wide range of considerations and competing priorities that ultimately require political judgements and that are well beyond the scope of this initial *if/then* analysis.

We take as an underlying assumption that there will indeed be an additional burden to be borne for reaching net-negative emissions after 2050, as compared to simply remaining at net-zero emissions from 2050; we then consider how different principles would lead to different choices about who should bear this additional burden.

We take the achievement of net-zero emissions by 2050 via some burden-sharing mechanism and associated policy choices as a given and out of scope of this study, and consider only the incremental burden to move from net-zero to net-negative emissions. However, policy choices of how net-zero emissions are reached, and the underlying narrative and policy principles that assign responsibility for reaching net-zero emissions could both constrain and enable subsequent choices for how to move from there to net-negative emissions. Section 3.4 briefly discusses relevant considerations.

3.2 A taxonomy of relevant actors/entities and policy principles

3.2.1 Global equity principles as guides for domestic burden-sharing

One set of principles for domestic burden-sharing could flow from the global equity principles that motivate Switzerland to reach net-negative emissions as a country (see Chapter 2), and asking what those principles would imply if their logic were applied also at a domestic level. We note that there is no requirement that global equity principles should necessarily flow directly into domestic burden-sharing mechanisms. This is because national-level emission targets represent commitments made at country-level to other countries, considering collective national responsibility, capacity and other geopolitical aspects. It does not necessarily follow that the same principles that guide country-level commitments would necessarily also determine which entities within a given country then bear the burden of delivering this collective commitment. E.g., a country could decide to reach net-negative emissions for a wide range of reasons related to its geopolitical relationships and how it views its role among the community of nations; this does not imply that this country then has to (or even can) apply those same principles and considerations to allocate the burden of reaching net-negative emissions among its citizens or companies. Nonetheless, consistency between principles could provide for a more coherent narrative about why Switzerland as a country should reach not only net-zero but net-negative emissions and "therefore" who should bear that additional burden within Switzerland.

As discussed in Chapter 2, one principle that is often invoked to inform burden-sharing among countries is the principle of *equality*, reflected e.g. in allocation of equal-per-capita emissions among countries (i.e. an equal right to pollute the atmosphere). Given that the world will exceed global warming of 1.5°C in the near future (by around 2030), and is projected to exceed 2°C under current policies, net-negative GHG may be required globally to bring global warming back to within the long-term temperature goal of the Paris Agreement, and in particular back to 1.5°C. The equality principle implies a consequent need for each individual country to reach net-negative GHG emissions (as invoked e.g. by the Kommission für Umwelt, Raumplanung und Energie des Nationalrates in support for of the Swiss climate law, BBl 2022 1536, Section 2.2.1.2)[13].

Applied at the domestic level, the equality principle would imply that every citizen has to deliver (i.e., is equally responsible for delivering) the same amount of net-negative emissions to ensure the nationally allocated amount of net-negative emissions is reached. However, governments generally accept that not all citizens or companies are equal, i.e. some have greater needs to emit, greater responsibility for warming or greater capacity to reduce emissions or deliver removals than others. Such differentiation is part of almost any distributional choice that governments must make. We therefore do not further pursue equality as potential principle for domestic burden-sharing.

The two other key principles which stand out from a global burden-sharing perspective, *responsibility* and *capacity*, are more readily used in some form for domestic burden-sharing choices.

3.2.1.1 Responsibility

Under this principle, the reason why Switzerland would seek to reach net-negative emissions is that Switzerland is currently responsible for a greater amount of global warming per person than the rest of the world, and therefore its contribution to global warming should shrink to support global efforts to meet the global long-term temperature goal set out in Article 2 of the Paris Agreement. Reaching net-negative emission would enable Switzerland to reduce its responsibility for global warming towards a more proportionate (and therefore equitable, under the responsibility principle) share.

If this global burden-sharing principle were applied also domestically, it would imply that those entities within Switzerland who have contributed most to global warming up to 2050 should also bear the greatest burden to reach net-negative emissions after 2050 and thereby undo part of their contribution. This would mean entities with the highest cumulative emissions of long-lived GHGs (especially CO_2 but also N_2O), and the highest on-going rate of emissions of short-lived gases (especially CH_4) should bear most of the burden of reaching net-negative emissions.

The distinction between short- and long-lived gases is relevant because for long-lived gases, their contribution to global warming is largely proportional to their cumulative emissions (i.e.

[13] "Langfristig, d.h. über 2050 hinaus, muss die weltweite Emissionsbilanz insgesamt negativ werden, so dass die Treibhausgaskonzentration in der Atmosphäre wieder sinkt. Nur dann kann die globale Erwärmung mit einer genügend hohen Wahrscheinlichkeit auf 1,5 Grad Celsius begrenzt werden. Die Vorlage präzisiert, dass die Schweiz hier einen Beitrag leisten muss."

both historical and current/future emissions), whereas for short-lived gases, historical emissions contribute little to future global warming and their main contribution comes from the on-going (current and future) rate of emissions.

The cumulative nature of long-lived gases implies that emitters that have had high historical emissions will have contributed a larger share to future global warming (even if their emissions decline by 2050) than entities who commenced their activities only recently or that may start their activities only in future even if they have the same future emissions up to and after 2050.

For the responsibility principle, the main question is when responsibility for emissions is assumed to start. This could be as early as 1850 (widely used in emissions allocations at country level in scientific climate change literature), or 1990 when the Intergovernmental Panel on Climate Change delivered its first assessment report and when reporting of emissions under the United Nations Framework Convention on Climate Change starts, or 2000 when the Swiss CO2-Act was enacted, or 2025 when the Swiss national climate and innovation law was enacted, or 2030 (e.g. if a new law is introduced at that point that sets out how individual companies and households are expected to contribute to the goal of net-negative emissions after 2050).

3.2.1.2 Capacity

Under this principle, the reason why Switzerland would seek to reach net-negative emissions is that even if the world as a whole only needs to reach net-zero emissions, at least some countries will need to reach net-negative emissions (given the principle of common but differentiated responsibilities and respective capabilities). Switzerland has one of the highest capacities to achieve net emission reductions given its relative wealth (see Section 2.3.1). Under this principle, Switzerland would use its resources to help address a global commons problem simply because it is in a position to do so, and because doing so would give other countries with lesser resources more development space to still reach a collective global goal. The logic of the capacity principle strongly implies that net emission reductions (i.e. reductions in emissions plus the scaling up of carbon dioxide removal) does not necessarily have to occur within Switzerland as the financial capacity of Switzerland to pay for emission reductions or removals could be cost-effectively applied anywhere.

If this global burden-sharing principle were applied also domestically, it would imply that those entities within Switzerland with the highest capacity (i.e. the largest financial and/or technological resources) should bear most of the burden to reach net-negative emissions. An important question is how "capacity to act" could be measured. In climate change literature applying this principle to countries, GDP is often used as a proxy for financial capacity. To the extent that countries are able to meet their NDCs also via international transferred mitigation outcomes under Article 6 of the Paris Agreement, domestic technological capacity is often given less consideration, given that countries with limited technical abatement potential but high financial capacity could meet their obligations at least in part through purchasing credits from other countries, and that this would often be more cost-effective (i.e. greater net emission reductions or removals could be achieved for a given cost if those reductions and removals occur where they are cheapest, which in many instances may not be within Switzerland).

If this principle is applied domestically, this would mean entities with the highest income levels, or the greatest ability to deploy technology, should either directly achieve or fund the achievement of net-negative emissions, including through investments in activities outside of Switzerland regardless of their own emissions. Similar considerations regarding the role of technological capacity apply at domestic level as at country level – if some form of trading is possible, then it does not matter if individual entities don't have high technical abatement potential themselves, since they could meet their obligations by funding other entities that are able to generate removals and at lower cost

3.2.2 Principles flowing from Swiss law and climate policy precedents

Another set of principles for domestic burden-sharing could flow from the principles embedded in Swiss law, either explicitly or established as precedent via climate policy. The key principle that can be identified here is the *polluter-pays-principle* (PPP; "Verursacher-prinzip") based in the Swiss constitution, which strongly underpins Swiss domestic climate policy.

The PPP is anchored in Art. 74 para. 2 of the Swiss Federal Constitution, which provides: *"[The Confederation] shall ensure that such damage or nuisance is avoided. The costs of avoiding or eliminating such damage or nuisance are borne by those responsible for causing it*".[14] In the context of GHG emissions, this wording points to the allocation of costs for the prevention and elimination of harm caused by those emissions, thereby conceptually aligning with mitigation measures and – where necessary – the removal of atmospheric CO_2 or the remediation of climate-related damage. While the constitutional text does not expressly refer to carbon pricing, its cost-allocation logic provides the normative basis for instruments that internalize the external costs of emissions, including pricing mechanisms that approximate the *social cost of carbon*.

In this report we discuss two plausible interpretations of the PPP. A *strict interpretation* requires full cost internalization on a *ton-by-ton* basis, such that each unit of emissions is matched by payment for its associated damages and/or removal. This is the logic usually applied in economic policy instruments, discussed in Chapter 4.

By contrast, a *broad interpretation* of the PPP, as adopted in this chapter, considers the principle satisfied as long as polluters, rather than the general public, bear some or all of the relevant costs. In other words, somebody has to pay for the cost of net-negative emissions, and under the PPP, this "somebody" is whoever is still causing net GHG emissions from 2050 onwards, regardless of whether those entities are compensating for their on-going emissions in other ways or not.

The broad PPP faces clear limitations in that in theory, Switzerland could reach net-zero emissions not by counterbalancing residual emissions with removals but by reaching zero gross emissions. In this case, there would be no polluters left after 2050 to carry the burden to reach net-negative emissions. Note that, according to current plans, the only polluter that remains in 2050 would be agriculture.[15]

The principle could be extended backwards in time, to apply not only to those who are still emitters after 2050, but to those who are emitters from now on. Selecting even earlier starting points to define "polluters" would make the polluter-pays principle more and more similar to the "responsibility" principle set out earlier.

[14] German: „[Der Bund] sorgt dafür, dass solche Einwirkungen vermieden werden. Die Kosten der Vermeidung und Beseitigung tragen die Verursacher".

[15] The Swiss climate law Art. 5 requires all companies to reach net-zero emissions by 2050, but we understand that this excludes farms. Current policy settings do not envisage agriculture to compensate for its remaining (mostly CH_4 and N_2O) emissions in 2050. Other minor polluters could remain depending on the detailed allocation of indirect emissions between companies and the public.

3.2.3 Principles flowing from general public policy and implementation

A third set of principles for domestic burden-sharing could flow from general good public policy principles. A key principle is the *avoidance of retroactive liability*, which provides for legal certainty ("Rechts-sicherheit").

Further general considerations include (although these may not be considered "principles" and more questions of feasibility and political economy) are the *use of established mechanisms* where possible (i.e. avoiding the need to develop and implement fundamentally new mechanisms), and to ensure policies have a sufficiently *broad base* to provide stability and predictability even if individual entities cease to exist or enter the market.

3.2.3.1 Avoidance of retroactive liability

This principle requires that entities are not held responsible at a later date for actions that were legal and permitted at the time the action occurred. We understand that the Swiss Federal Council ruled considered "true" retroactive liability as unconstitutional (Stellungnahme des Bundesrates vom 18. 02. 2015 bzgl Verbot der Rückwirkung von Erlassen; Postulat 14.4240); however, we do not have the expertise to advise on the narrow conditions under which this principle might be overruled by other considerations that are flagged by the Federal Council.

This principle is therefore in potential conflict with or at least constrains the responsibility principle: actors with high historical emissions carry considerable responsibility for future warming and could therefore be considered polluters that are required to compensate for the effect of their pollution (even if the polluting act lies in the past), but avoidance of retroactive liability implies that individual emitters could not be held responsible for emissions that occurred only in the past when there was no requirement to reduce or avoid such emissions (i.e. that were not considered to be a "pollution" at the time).

The Swiss national climate law, as currently formulated, does not set out liabilities for individual companies or individuals to reach net-negative emissions even though the law sets a national requirement for net-negative emissions after 2050. This implies that current emitters could argue that invoking the polluter-pays or responsibility principle to compel them to go beyond net-zero and reach net-negative emissions after 2050 cannot be derived from the current law which requires them only to reach net-zero emissions by 2050 following sectoral pathways.

The avoidance of retroactive liability would seem to imply that the earliest start date for operationalizing the "responsibility" principle would be the time when supplementary Federal law sets out in-principle obligations for reaching net-negative emissions for individual entities.

3.2.3.2 Use of established mechanisms

While the preceding principles are largely grounded in various forms of ethics that underpin public policy, using established mechanisms, where available, is more pragmatic and based more on efficiency and political economy considerations. It means simply that policies that can draw on existing mechanisms (using existing data gathering or existing incentives or obligations) are generally more efficient and may encounter less opposition than if new information and enforcement mechanisms and institutions need to be created.

For net-negative emissions, residual emissions and/or carbon dioxide removal performance may be gathered already under Swiss climate policy for the purpose of reaching net-zero emissions via obligations on companies to report their emissions and eventually to demonstrate their compliance with the net-zero emissions requirement by 2050, or via surrender obligations under the Emissions Trading Scheme. Regarding existing incentives or obligations, relevant aspects include emissions pricing or trading mechanisms that may be applied to emitters up to 2050 based on their already reported emissions and that could be extended beyond 2050; or under the capacity principle, existing general taxation mechanisms that already rely on companies and citizens declaring their revenue and net profits or personal income could be extended to also raise revenue for further net emission reductions and upscaling of carbon dioxide removal, including outside of Switzerland.

Reaching net-negative emissions does not necessarily rely on increased carbon dioxide removals but can (to some extent) also be achieved by further reducing residual emissions beyond their levels in 2050 while keeping removals at a constant level. Emission pathways developed for the Swiss climate law imply residual emissions of about 12 Mt CO_2-eq in 2050 (prior to the use of CCS to avoid emissions from some fossil CO_2 sources), plus emissions from international aviation of 1-2 Mt CO_2-eq. Net-zero emissions in 2050 are reached by a combination of domestic CCS and CDR, and international CDR activities. True residual emissions (after CCS to avoid emissions from fossil CO_2 sources) can be estimated at 8-9 Mt CO_2-eq in 2050 (see Section 2.3.2)

These same pathways envisage domestic gross emissions falling only moderately by another 1.1 Mt CO_2-eq in 2060, with about 0.5 Mt CO_2-eq further reductions in agriculture (from 4.6 to 4.1 Mt CO_2-eq) and the remainder from energy and industrial processes. The successful development of novel abatement technologies for remaining emissions, combined with improved material efficiency and demand-side measures, could potentially reduce residual emissions further. This implies that net-negative emissions of several Mt CO_2-eq per year could potentially be reached without further upscaling CDR.

A range of mechanisms and policy instruments will be in place to achieve emission reductions up to 2050 consistent with published long-term emission pathways. Such mechanisms do not necessarily have to come to a halt in 2050, but could be highly relevant for reaching net-negative emissions by incentivizing further reductions where feasible beyond 2050. Such policy instruments could remain in place in addition to mechanisms to establish and upscale CO_2 removal, or development of other GHG removal technologies such as the active destruction of CH_4.

3.2.3.3 Broad base

Ensuring a sufficiently broad base for policies as noted earlier, if policy to reduce gross emissions (rather than to counterbalance remaining emissions with removals) is highly successful, this could leave Switzerland with too few remaining polluters after 2050 to pay for additional carbon dioxide removals at scale. This could result in a situation that even if there were societal consensus that those who still emit GHGs after 2050 should carry (all of) the burden to not only counterbalance their remissions (i.e. achieve net-zero) but to reach net-negative emissions, those remaining emitters simply might not have the financial capacity or market stability to achieve that goal.

A broad and diverse base of emitters reduces the political risk of lobbying and special interests carving out exemptions (e.g. if the only polluter remaining in 2050 is agriculture, there may not be widespread public and political support that agriculture should carry the sole burden of reaching national-scale net-negative emissions even if there is general agreement in principle to a polluter-pays approach for net-negative emissions). There is no simple rule of what base is broad enough for stable and predictable policy, as it depends on the intended focus of the policy and whether the policy seeks to reduce emissions or incentivize action directly among those it targets, or whether the purpose of the policy is to raise revenue from as broad a base as possible and then use that revenue in a targeted way.

3.2.4 Mapping burden-sharing principles to actors in the Swiss economy

Table 3 overleaf provides a qualitative summary of how different entities that could be asked to share the burden of reaching net-negative emissions would relate to the principles set out above. We note that this is only a qualitative score and the table is best read as a pairwise comparison of options; i.e. from a responsibility perspective, emitters since 1850 clearly carry a higher responsibility for (have contributed more to) global warming than emitters since 1990, but the number of "+" and "-" symbols assigned to each option relies on somewhat subjective judgements. We again emphasize that we do not advocate for any of those principles, but intend for this table to merely summarize the degree to which certain burden-sharing approaches would be more or less consistent with the equity and public policy principles and implementation considerations discussed so far.

Table 3. Qualitative summary of potential domestic burden-sharing entities and consistency of selection of that entity with various policy principles.

Burden-bearing entity	Domestic burden-sharing principle	Distributional metric for burden-sharing		Consistency with global equity principles		Consistency with Swiss climate law for net-zero	Consistency with general public policy principles		
		Long-lived gases (e.g. CO_2)	Short-lived gases (e.g. CH_4)	Responsibility	Capacity	Polluter-Pays	Avoid retroactive liability	Established mechanisms	Broad base
Net-emitters post-2050	responsibility	annual net emissions from 2050		o	– –	+++	+++	+++	– –
Net-emitters at any time from 2030		annual net emissions from 2030		+	++	++	+++	+++	+++
Net-emitters at any time since 1990		cumulative net emissions since 1990	annual emissions from 2030	++	+	+	– –	o	++
Net-emitters at any time since 1850		cumulative net emissions since 1850	annual emissions from 2030	+++	–	+	– – –	– – –	+
Swiss companies (from 2030, or from 2050)	capacity	capacity to pay (e.g. annual company revenue or profit)		o	+++	o	+++	+++	+++
Swiss taxpayers (from 2030, or from 2050)		capacity to pay (e.g. annual income)		++	+++	++	+++	+++	+++
		additional distributive considerations		o ↔ +++	+ ↔ +++	o ↔ +++	+++	+ ↔ ++	+ ↔ +++

Notes and explanations:

- Column 1, "Burden-bearing entity" lists a range of potential choices of groups of entities that should bear the burden of reaching net-negative emissions, over and above any burden for Switzerland to reach net-zero emissions. Entities are separated either by their emissions from different times onwards, or by their financial capacity to support mitigation.
- Column 2, "Domestic burden-sharing principle" sets out the fundamental principle by which the burden of reaching net-negative emissions would be shared domestically; this is either "responsibility" (for causing climate change through net GHG emissions) or "capacity" (to pay for additional efforts either to remove additional carbon dioxide or to further reduce residual emissions remaining after 2050, regardless of whether the entity is causing or in other ways responsible for those emissions).
- Columns 3 and 4 illustrate potential metrics to determine the relative share of the total burden any given entity should bear, based either on their net emissions (for burden-sharing based on responsibility for climate change) or on their financial capacity (under the capacity principle). Note that net emissions refers to emissions that are under the entity's direct control (scope 1 and 2), not including offsets. A possible separation of emissions could be made based on long-lived or short-lived gases; however, this distinction becomes relevant only if emissions prior to 2030 are considered, i.e. when the lifetime of short-lived gases, especially methane, is significantly shorter than the time since the beginning of the responsibility period, and hence historical (pre-2030) emitters of short-lived gases cannot be said to be responsible for global warming in 2050.

- Column 5, “responsibility”: this generally increases the further back in time the responsibility starts, given the cumulative warming from long-lived greenhouse gases. Assigning the burden to Swiss companies or taxpayers on the basis of their revenue or income only weakly correspond to the responsibility principle; income is not a useful predictor of emissions for companies given the vastly different emission profiles of companies (it would only be a predictor where two companies have the same production profile and differ only in their total revenue and, by implication, production volume). Income currently is a strong predictor of emissions at individual level but this may not continue to be the case as wealthier individuals e.g. might be more likely to adopt electric cars, and it would not recognize individual behavioural choices.
- Column 6, “capacity”: this is highest if burden-bearing entities are selected based on their revenue or income levels. It is likely lowest for emitters from 2050 onwards, assuming that some of many emitters will have reached zero emissions even without reliance on offsets by that point. It also reduces if emitters since 1990 let alone 1850 are considered since the entities that used to be emitters in the past may no longer exist.
- Column 7, “polluter pays”: this is highest for emitters post-2050 (in the broad interpretation of the principle, anybody still emitting GHGs after 2050 is a “polluter” that could be held liable for removals to reach net-negative emissions even if they already pay the cost of compensating for their remaining emissions). The definition of “polluter” becomes more and more stretched the further back in time the definition is applied, since an entity might have caused emissions in the past but is no longer a polluter in 2050. Under Swiss climate law, all companies other than agriculture are required to have reached net-zero emissions by 2050 and therefore are no longer polluters in 2050. Individual taxpayers could still be polluters in 2050 but to a limited extent, depending on detailed allocation of indirect emissions.
- Column 8, “avoiding retroactive liability”: this principle be met for any criterion that assigns a burden only after relevant law is passed (which we here illustratively put at 2030); and it is strongly negative (i.e. in violation of that principle) for responsibility for emissions prior to the present, especially since 1850. We weakly differentiate between emissions since 1990 and 1850 since one could argue that there was an established case that GHG emissions are harmful since 1990. This can be applied at country level but may be challenged legally when it comes to assigning responsibility to companies or individuals for their past actions (noting that earlier legislation in 2000 gave no indication of any requirement, nationally or individually, for net-negative emissions).
- Column 9, “established mechanisms”: we score this high for emitters after 2030, and for any of the income-based approaches, since we assume that mechanisms exist to incentivize emission reductions (or raise revenue from unabated emissions) in all sectors at least from 2030 onwards (with currently the weakest policies in place for agriculture); and well-established mechanisms exist to determine company revenue and personal income levels and assign and collect taxes accordingly.
- Column 10, “broad base”: we score this highest for emitters from 2030, or for companies or taxpayers from 2030. The score is lower for emitters from 2050 (since there may be far fewer remaining gross emitters if climate policy seeking to drive gross reductions is successful), and it is also lower for emitters from 1990 or 1850 since some of the entities that were emitters in the past may no longer exist.

Additional distributive considerations:

Any policy, regardless of whether it is based on emitters or on financial capacity, could potentially differentiate the burden based on additional considerations. For individual taxpayers and companies this could include minimum income thresholds, family considerations, and partial or full exemptions for specific sectors and sub-branches. Similarly for emissions-based selections, there could be differentiation based on specific sectors including trade considerations and EU policies. Consideration would also have to be given whether sectors with high residual (“Hard to abate”) emissions would nonetheless be expected to make the same contribution to net-negative emissions by achieving or paying for higher levels of carbon dioxide removals, or whether those hard-to-abate emissions are exempted from a proportional responsibility. Such considerations are the domain of detailed policy design and political economy and we are unable to systematically explore their consequences. Here we only note that additional distributional choices could substantially skew the consistency of choices away from the policy principles set out in this table, as indicated in the bottom row for individual tax payers. The range shown in the bottom row is indicative only and not a complete assessment of the possible range of outcomes, since specific additional distributional choices and exemptions could create almost any degree of (in)consistency with any given policy principle.

3.3 Insights from policy principles for net-negative burden-sharing

Table 3 presents a qualitative scoring of the consistency of various domestic burden-sharing approaches for net-negative emissions with a range of policy principles. None of those scores are binding on policy (i.e. any given burden-sharing mechanism could be adopted even if it is strongly inconsistent with a given and widely accepted policy principle; and/or a climate policy could be modified so that it becomes less inconsistent). Nonetheless, these scores can indicate potential landing zones for domestic burden-sharing approaches for net-negative emissions and the policy principles that motivate these burden-sharing approaches.

One fundamental insight is that different public policy principles favor different domestic burden-sharing principles for net-negative emissions and metrics to allocate the burden. There is no single burden-sharing approach that is fully consistent with all public policy principles used in Table 3.

The avoidance of retroactive liability is generally a strongly held principle in public policy. If this policy principle is seen as foundational at a constitutional level (or regarded as key even if it could be circumvented in some specific instances), it would generally constrain burden-sharing choices based on emissions or capacity to pay from 2030 onwards (when a legal framework for such an allocation might first have been established), not to historical emitters/polluters or taxpayers.

Out of the burden-sharing approaches based on responsibility, only an approach that is based on net emissions from 2030 onwards would be more or less consistent with all listed public policy principles, especially polluter-pays, avoidance of retroactive liability, and use of established mechanisms. Setting the responsibility date later (e.g. only from 2050 onwards), or starting it earlier (now or in the past, when no law yet exists to assign responsibility for net-negative emissions to any individual entity), would violate one or more of those policy principles. The reason why consistency scores decrease if the burden is allocated only to those sectors that remain net emitters in 2050, since this could result in too narrow a base to bear the financial burden or affect entities and sectors that are regarded as nationally significant; placing the burden only on those entities could therefore conflict with other societal values or political preferences (see also Section 3.4 below).

Burden-sharing approaches based on capacity (based on some measure of capacity to pay, using any date from 2030 onwards) tend to have high consistency scores across all policy principles, with one key exception. The capacity of companies to pay for net-negative efforts may have little correlation with the actual responsibility of those companies for climate change, given then widely varying carbon footprints. Such a burden-sharing approach therefore does not score well against the principle of responsibility or polluter pays, although detailed policy modifications could be applied to reduce potential inconsistencies by applying a sectoral differentiation within the ability to pay.

While Table 3 is only qualitative and the individual scores are not strictly comparable across columns, it is noteworthy that the highest consistency across different policy principles is reached for a burden-sharing allocation based either on net emissions from 2030 onwards, or based on capacity to pay based on 2030 onwards. This suggests an intertemporal approach to policy design for net-negative emissions, i.e. that emitters, companies and taxpayers from 2030 onwards cumulatively contribute to meet the burden of reaching net-negative emissions from 2050 onwards. Chapter 4 provides more detailed elaborations of relevant intertemporal policy designs.

A separate consideration is the degree to which the domestic burden-sharing principle should be consistent with the rationale that Switzerland provides as a country for reaching net-negative emissions at national level. This is a political choice and may be more related to the need to obtain broad-based support for entering net-negative territory, not a policy requirement. In principle, Switzerland could adopt a responsibility rationale internationally for reaching net-negative emissions as a country, but nonetheless use the capacity to pay for net-negative emissions to allocate burdens domestically.

3.4 The role of net-zero policy choices for approaches to net-negative emissions

Policy choices and underlying burden-sharing approaches for net-negative emissions are not independent of the policies and burden-sharing approach to reach net-zero emissions. This is because the latter are likely to create a strong path-dependency for both the policy tools and the underlying philosophy for entering net-negative emissions territory. This section provides a high-level summary of the key points in which the existing framework for reaching net-zero emissions might provide entry points but could also face limitations for moving into net-negative emissions.

We note that if it were considered as self-evident that nobody should have to compensate for more than at most their own residual emissions, then it would be impossible for Switzerland to reach net-negative emissions since the responsibility for achieving this state would rest with nobody once the country reaches net-zero emissions.

Any burden-allocation approach that supports reaching net-negative emissions therefore must rely *either* on responsibility based on emissions prior to the point when net-zero is reached (which can be justified by the lasting warming from those emissions), *or* a broader interpretation of polluter-pays where responsibility for removals goes beyond merely compensating for on-going residual emissions, *or* the capacity to pay for additional removals regardless of the responsibility of any given entity for global warming.

3.4.1 Net-zero requirements for sectors

Article 4 of the Swiss climate law specifies that the buildings and domestic transport sectors are required to reach zero by 2050. BFE (2025) further explains the expectation that there will be no hard-to-abate emissions in those sectors, i.e. that *gross* emissions reach zero in these sectors. We understand that from a sectoral perspective, emissions exclude emissions embedded in purchased electricity or heat as those would be counted as part of industry. The law further specifies that gross emissions from industry (which includes electricity and heat generation for export to other sectors, or internationally) would be reduced by 90% by 2050 relative to 1990, which would include the use of CCS to reduce emissions by to capturing CO_2 emissions at source and durably storing those emissions. Currently there are no sectoral reduction targets in law for agriculture or waste as a sector, but both sectors are envisaged to play a role in ensuring that Switzerland reaches the net-zero GHG emissions target in 2050, and waste incineration plants are included in the sectoral target for industry.

These existing provisions, combined with the EP2050+ scenarios developed in support of the Swiss climate law, imply that agriculture would be the largest remaining emitting sector in 2050 at 4.6 Mt CO_2-eq, followed by industry with about 1.3 Mt CO_2-eq (based on the legislated 90% reduction relative to 1990 levels including synthetic gases - we assume that this would include the use of CCS to avoid some fossil emissions where applicable). In addition, the

Swiss climate law includes emissions from international aviation (based on refueling in Swiss airports), estimated at 1-2 Mt CO_2-eq in 2050, in the net-zero goal. Remaining emissions from these sectors would need to be offset by additional carbon dioxide removal technologies either internationally or domestically (including in the waste sector which is expected to generate a significant share of domestic removals via waste combustion combined with CCS – this constitutes CDR if there is organic content in waste).

These existing settings imply that a responsibility-approach to domestic burden-sharing for net-negative emissions, if responsibility is interpreted based on residual emissions in 2050, would place the majority of costs to achieve net-negative emissions on the agriculture sector, simply because agriculture would be by far the largest net emitter and hence most "responsible" for remaining emissions after 2050.

If responsibility is allocated based on emissions from 2030 onwards, the burden would be distributed more widely across sectors given that 2040 reduction targets are only 50% for industry and 57% for transport, implying that these sectors would still have material emissions during the 2030-2050 period.

3.4.2 Net-zero requirements for companies

Article 5 of the Swiss climate law specifies that (all) companies must reach net-zero emissions by 2050. At the company level, this includes scope 1 (direct) emissions and scope 2 (indirect) emissions from the use of purchased electricity and heat. Companies are encouraged but not required to include scope 3 emissions arising from their supply chains. The federal government encourages, but does not require, the development of emission reduction roadmaps consistent with the net-zero requirement (apart from the financial sector and companies above a given size threshold; see Verordnung 221.434 über die Berichterstattung über Klimabelange).

This universal approach to reaching net-zero emissions cannot easily be extended to reaching net-negative emissions. The main reason is that while net-zero may be viewed as a self-evident end-goal for company-level actions, an additional metric would be needed to determine how much net-negative emissions each company must achieve after 2050. By definition, no company will be a net emitter by 2050, so a responsibility principle cannot be applied based on emissions after 2050. If emissions prior to 2050 were used for allocating the magnitude of net-negative emissions for each company after 2050, such an approach would need to be signalled early as it would change investment choices into early or later decarbonization leading up to 2050. However, such an approach would raise significant equity and economic efficiency concerns, since the rate of decarbonization leading up to 2050 will differ between companies depending on the sector in which they operate and the availability of technologies for deep emission reductions prior to 2050. In addition, there could be inconsistencies depending on how scope 2 emissions are accounted for (i.e. to what extent those emissions occur as scope 1 in the accounts of energy supply companies and/or as scope 2 in the accounts of energy next- and end-users). It is noteworthy that the current law makes no differentiation between companies depending on how costly it is for them to reach net-zero emissions (the costs are likely to be substantially greater for some companies than for others, depending on their emission profile and technical abatement options); this lack of differentiation therefore provides no guidance on whether all companies should reach the same level of net-negative emissions after 2050, and how such an equality would be measured (it would be implausible that a company with 3 employees and a turnover of 1 million Francs would need to deliver the same amount of net-negative emissions as a company with 100 employees and a turnover of 100 million Francs).

An alternative approach at the company level would be based on a capacity to pay; i.e. a requirement to at least remain at net-zero emissions beyond 2050, with an additional tax payment added beyond 2050 that could be used by the federal government to fund carbon dioxide removal both domestically and internationally. Such a tax payment could also be expressed as an additional removal quantity that each company has to deliver post-2050, but the quantity of removals would still be based on the company's capacity to pay rather than its emissions. Ultimately, any allocation method that assigns responsibility for net-negative emissions to companies needs some yardstick to determine the quantity of net-negative emissions that each company must deliver, and by definition, the emissions of companies do not work as yardstick since all companies will be net-zero emitters.

We understand that farms are not included in this definition of 'company', since a requirement for all farms to reach net-zero emissions would effectively set a net-zero emissions target for the agriculture sector. In the absence of major technological breakthroughs for the abatement of methane and nitrous oxide emissions from agricultural (especially livestock) activities, reaching net-zero emissions could be prohibitively expensive for farm companies as it would require a reduction in livestock numbers and therefore directly threaten their business model, and lead to major structural change in the agriculture sector that would require careful management beyond climate policies. In addition, an emission reduction approach in agriculture that relies on reduced production could suffer from emission leakage, depending on changes in dietary patterns and trade relationships.

3.4.3 Extension of net-zero policy mechanisms towards net-negative outcomes

Some policy mechanisms that are designed to drive towards net-zero emissions could potentially be extended to reach into net-negative territory (e.g. schemes already emerging in some other countries where the government acts directly as purchaser of removals). In contrast, market-based approaches could require significant modification or complementation as their ability to generate removals is often based on the concept that removals need to compensate for remaining emissions, but not more than that.

A key example of this are emissions trading schemes. Such schemes in principle can be used to fund carbon dioxide removals to compensate for unabated emissions, but such a scheme has a natural limit in net-zero emissions. There are currently no conceptual models for operating an emissions trading scheme with a negative emissions cap. Options exist to build on emissions trading schemes to make them stretch into net-negative outcomes, but such transitions take significant time and careful modifications. One example is a "2 for 1" obligation, i.e. the need to surrender two removal credits to compensate for one unit of emissions. Such an approach, implemented from 2050 onwards, could in principle be used to achieve net-negative emissions, but it implies shifting the burden solely to those who are still net emitters after 2050. Based on current legislation, this would imply that agriculture would have to be included in an emissions trading scheme and as main remaining emitter after 2050 would then bear a large part of the burden of reaching net-negative emissions.

Such considerations suggest a need for a strategic and active role of federal government in ensuring a durable and growing demand for removals that is not contingent on a shrinking and shifting pool of emitters that may not be able to, or that society does not wish to, bear the burden of paying for all of the removals required to reach national net-negative emissions.

4 Financing options for net-negative emissions

4.1 Introduction

This chapter introduces the core economic concepts underlying policy instruments to finance net-negative emissions. Given that real-world experience remains limited, the discussion is necessarily stylized and exploratory. To distinguish this analysis from the broader literature on integrating CDR into climate policy and enabling their large-scale deployment (*56*, *57*), the focus here is deliberately confined to the specific question of financing net-negative emissions[16].

Economic approaches to carbon policy typically seek to provide appropriate incentives for both emission reductions and carbon removals by aligning these activities within a coherent price-based framework. In economic terms, such instruments aim to internalize the expected costs of achieving net-negative emissions, ensuring that the cost of (future) carbon removal is reflected in emission decisions. As a result, private actors account for both present abatement opportunities and anticipated (future) removal requirements when determining their optimal level of emissions. In this way, economic approaches generally operationalize the *polluter-pays principle*.

This chapter adopts that economic perspective as its point of departure; accordingly, the approaches evaluated here are all, in one way or another, grounded in the responsibility principle outlined in Chapter 3. A capability-based approach – for example, financing CDR through general taxation that is not linked to emissions – would in principle also be conceivable. We briefly touch upon this perspective in Section 4.2 (public financing of net-negative emissions) and Section 4.4.1.1 (where we discuss the possibility of placing the funding of net-negative emissions on a broader base). However, a full assessment of such an approach lies beyond the expertise and scope of this study[17]. We nevertheless wish to flag that a capability-based framework may merit consideration, either as an alternative to, or in combination with, a responsibility-based approach.

The analysis further rests on several assumptions to simplify the discussion and establish (at least in theory) fungibility between emission reductions and removals:

- First, it is assumed that policy instruments attach at points where emissions are verifiable, non-overlapping, and enforceable – typically at the point of release (e.g., large point sources, although this may be different if applied to agriculture which typically deals with a large number of small point sources), at the upstream entry of fossil carbon into the economy (e.g., fuel suppliers), or at customs entry for imports. References to "emitters" should therefore be understood as referring to entities designated as compliance entities under a GHG

[16] This chapter does not address a range of important and well-studied issues – such as the management of durability and liability for reversals, environmental spillovers, early-stage technology support, or the development of measurement, reporting, and verification (MRV) systems – except where they are directly relevant to the arguments concerning the provision and financing of net-negative emissions. We acknowledge that CDR is highly heterogeneous with respect to technological maturity, costs, permanence, MRV complexity, and governance arrangements. Any policy framework aimed at net-negative emissions will ultimately need to account for this heterogeneity, as well as for institutional and policy path dependencies arising from earlier phases of climate policy and CDR support.

[17] Even under a capability-based financing model, responsibility does not disappear entirely. To the extent that the need for future net-negative emissions reflects insufficient mitigation or delayed regulatory action, there remains a responsibility to adopt appropriate legal and financing frameworks today to minimize future removal requirements and ensure their feasibility.

regulatory framework – that is, the actors to whom regulatory obligations are attached – rather than necessarily the physical point of emission.

- Second, this chapter abstracts from differences in permanence by treating all removals as permanent, or with governance mechanisms in place to replace any reversal with an additional removal. Temporary removals do not affect the welfare-maximizing long-run concentration target (*58*), but play a role in smoothing costs over time. In the long run, temporary removals must be replaced by permanent removals or continuously offset by additional temporary removals.

- Finally, the discussion assumes established equivalence metrics between CO_2 and other GHGs, based on the Global Warming Potential over 100 years (GWP-100) as mandated in the Paris rulebook for emissions reporting and economy-wide targets by countries. However, this universal choice is contested by some stakeholders, which the design of policies and their communication will need to take into account.

These simplifications are adopted solely to keep the focus on the financing problem and should not be interpreted as normative claims about preferred accounting or governance approaches.

Finally, we review national governance approaches to radioactive waste management and nuclear decommissioning in Section 4.5, as these policy domains confront structurally similar intergenerational challenges and offer a considerably richer empirical record. In doing so, the analysis necessarily departs from the strictly economic perspective on carbon policy adopted in the preceding sections.

4.1.1 Basic principles and definitions

Climate policy is often evaluated against the economic benchmark of *efficiency* (or *cost-effectiveness*), that is, achieving a given climate target at the lowest possible mitigation costs. The *least-cost benchmark* computed in *social planner models* provides an important hypothetical reference point for the discussion in this chapter[18]. Reproducing the benchmark using *idealized policy instruments*[19] in competitive markets requires strong assumptions to hold, especially if such instruments must work over time (i.e., *intertemporally*).

This chapter distinguishes between *contemporaneous* and *intertemporal* policy designs for financing and delivering net-negative emissions. Contemporaneous instruments link emissions and removals within the same period – for example, by raising funds through carbon pricing that are immediately used to pay for removals, or by imposing mandates that require emitters to balance a defined share of their emissions with removals in the same year. Intertemporal instruments, by contrast, link emissions released earlier to removals that occur later. This can take the form of saving current carbon pricing revenues for future use in procuring removals, or assigning emitters a forward obligation to finance or deliver removals at a later date. The distinction between contemporaneous and intertemporal instruments does not arise in the social planner problem itself, but becomes relevant when formalizing the assumptions required for policy instruments to deliver the

[18] In this context the least-cost benchmark is a trajectory of emissions and removals that minimizes total discounted abatement costs subject to a specified carbon budget.

[19] By idealized policy instruments we mean policy tools that decentralize the social planner allocation in a competitive market equilibrium under the standard assumptions of perfect information, enforcement, and complete markets, such as Pigouvian taxes or perfectly enforced emissions caps with frictionless permit trading.

benchmark in a competitive market equilibrium.

4.1.2 Polluter-pays-principle and fiscal sustainability

This section examines how the transition to net-negative emissions interacts with the PPP and *fiscal sustainability*. For the PPP and fiscal sustainability we use the following definitions:

- Contrary to Chapter 3 and in line with standard economic logic, this chapter generally adopts a *strict interpretation* of the PPP which requires full cost internalization on a *ton-by-ton* basis, such that each unit of emissions is matched by payment for its associated damages and/or removal (see Section 3.2.2). Moreover, it is assumed that the PPP is applied *prospectively*: emitters are held responsible from the moment a PPP-based policy is established, i.e., not for past emissions (see also the introduction of the *avoidance of retroactive liability* principle in Section 3.2.3.1)

- Fiscal sustainability, on the other hand, means that the financing of removals (and net-negative emissions) does not create unfunded liabilities for public budgets. A fiscally sustainable policy ensures that any public commitments to procure removals are matched by secure, dedicated funding sources (e.g., earmarked carbon pricing revenues) rather than relying on ad-hoc budget reallocations.

PPP and fiscal sustainability are closely linked in the context of net-negative emissions, but they are not the same. Policies can be fiscally sustainable without being PPP-based – for example, if removals are funded through contributions from a broad base, rather than directly by individual emitters (see discussion in Chapter 3). Conversely, even PPP-based schemes can create fiscal risks, particularly when large polluters are state-owned or when governments are expected to act as backstops or provide bailouts if private emitters fail to meet their obligations. This concern is particularly salient in the context of intertemporal instruments, where liabilities extend far into the future and enforcement risks accumulate over time (see Section 4.3.1.2).

4.1.3 Minimizing residual emissions

Net-negative emissions arise when removals exceed residual emissions. Residual emissions are the GHG emissions that enter the atmosphere after abatement and capture at the source (including CCS), but before being offset by CDR[20]. In long-term mitigation scenarios, residual emissions originate from sectors where reducing GHG emissions to zero is projected to remain difficult.

Until 2100, much more CDR will be needed globally to offset residual emissions than for net-negative emissions (*59*). Reducing residual emissions lowers the amount of CDR required to achieve a given net-negative target. Consequently, it limits overall reliance on CDR. At the same time, deeper reductions in residual emissions may reduce the revenues generated by a price on CO_2 – revenues that may be required, under contemporaneous policy instruments, to finance net-negative emissions (see Section 4.2.1)

It is commonly assumed that marginal cost curves of emission reductions rise sharply as emissions approach zero, which is known as the *Inada condition* (*60*). This reflects the assumption that reducing gross emission to zero is infeasible. Notwithstanding the Inada condition, the presence of residual emissions in mitigation scenarios does not mean these

[20] Note that the scenarios underlying the Swiss long term climate strategy have a different notion of residual emissions.

emissions cannot be reduced further. Rather, integrated assessment models (IAMs) suggest that it may be more cost-effective to remove CO_2 than to push residual emissions closer to zero. IAMs differ in which sectors they project to retain residual emissions, also reflecting modelling choices about what technologies to assume and what exogenous demand shifts are incorporated into the model, but residuals are commonly concentrated in industry, transport and agriculture (*61*, *62*).

Outside a modelling context, residual emissions are simply the emissions that remain at a given point in time (e.g., at or beyond net-zero) *for whatever reason* – including constraints that are institutional or political rather than purely technical or economic. This matters because some emissions treated as "residual" in national strategies may not be "hard-to-abate" in the IAM sense, but may persist due to policy and political-economy frictions (*63*).

Net-negative policy design should therefore be considered jointly with strategies for managing residual emissions.

4.2 Contemporaneous instruments for net-negative emissions

Contemporaneous economic instruments, which include CDR, provide emitters with the option to offset a part of their emissions through removals within the same period, rather than reducing those emissions directly or paying the corresponding emissions price. Integrating CDR into a cap-and-trade system, for instance, can in principle yield a cost-effective allocation in which the marginal costs of emissions reductions and removals are equalized[21]. Removal providers receive the ETS-derived carbon price for each ton, while emitters pay the same price when buying allowances or removals.

This structure reflects the *strict PPP*, as defined above, because emitters bear the costs associated with their GHG releases on a ton-by-ton basis. The ETS channels these payments either into removals, which directly compensate for emissions happening at the same time, or into allowances, which represent a paid-for level of permitted pollution and results in a stream of public revenue. The strict PPP logic holds as long as gross emissions exceed gross removals. At net-zero, when removals exactly compensate residual emissions, each ton emitted finances one ton removed, and public revenues (e.g., from auctioning allowances within an ETS) diminish.

Moving toward net-negative emissions erodes the broad-base principle (see Section 3.2.3.3), as the pool of polluters contributing to financing of removals erodes. At equal marginal costs, additional funds need to be injected into the ETS so that removal providers continue to be rewarded despite declining emissions. These funds can come from residual emitters or fossil fuel producers, implying that pricing one ton of CO_2 must finance more than one ton of removal. Such an approach is no longer consistent with the strict PPP, in the sense that polluters are required to overcompensate each ton of emission with more than one ton of removal, and it faces significant implementation and potential legal challenges, as discussed in Section 4.2.1.

In case a polluter-financed contemporaneous financing of net-negative emissions is infeasible, additional funds would need to come from governments, implying that general tax revenues or other public resources would be used to finance removals. Governments are

[21] This logic applies equally to carbon taxes. We focus on ETSs here because most of the existing literature on integrating CDR into carbon pricing frameworks has examined ETS-based approaches (*57*). Moreover, unconstrained CDR integration into ETSs is often viewed critically, because of concerns about mitigation deterrence, negative spillovers, etc. Addressing these broader concerns is beyond the scope of this chapter.

projected to finance substantial and growing climate-related commitments, including adaptation investments, domestic loss-and-damage expenditures, and international climate finance or compensation mechanisms in the case of industrialized countries (*64–66*). Adding large-scale net-negative financing to these obligations would place significant pressure on public budgets. From a fiscal sustainability perspective, such an expansion of liabilities appears challenging, although further research is required to assess its long-term feasibility in greater detail.

4.2.1 Extending contemporaneous, polluter-financed instruments

Here, we illustrate the key implications of extending contemporaneous polluter-financed carbon pricing instruments into net-negative territory on a conceptual level, which would require that each ton of emission finances more than one ton of removal.

Under standard competitive market logic, all suppliers of carbon removals are compensated at the marginal cost of removal. Suppliers with lower production costs earn a producer surplus, as they receive the market price while incurring lower costs. Against this background, there are two conceptual ways in which a *one-to-many* relationship between emissions and removals could be established.

1. **Decoupling the price of emitting from the price paid for removals.** The first option is to remunerate removals at their marginal cost while decoupling the price paid by emitters from the price received by removal providers. If the emissions price is set sufficiently above the removal price, then the revenue from one ton of emissions can finance more than one ton of removals.

2. **Financing removals at average cost.** A second option is to abandon marginal-cost pricing for removals and instead compensate removal providers at their actual production cost, possibly plus a regulated surplus to maintain basic investment incentives, requiring rent control mechanisms as discussed in Section 4.4.2. On a system level this means that CDR suppliers are remunerated at close to average removal costs. Note that this option also implies that marginal costs of emission reductions and removals are generally no longer aligned.

Note that, in principle and depending on additional design choices, both options could be implemented either through a "correctly calibrated" carbon tax (e.g., with an intermediary collecting revenues and procuring removals) or through an ETS or mandate (*67*), for example by allowing emissions to be offset only against removals at a ratio greater than one. Because marginal removal costs are higher than (or equal to) the average production cost across removal suppliers, the average-cost-based approach would be simpler to achieve than the alternative option from a pure cost-based angle.

4.2.2 Limitations of contemporaneous net-negative financing

Both marginal-cost-based and average-cost-based approaches to financing removals face fundamental limitations. A central conceptual issue is the assumed shape of marginal cost functions for emission reductions. These functions satisfy the Inada condition, i.e., marginal costs rise steeply and tend toward infinity as full decarbonization is approached.

Small changes in the curvature of such marginal cost functions can determine whether carbon pricing generates a bounded revenue stream (i.e., revenues follow a typical peak-and-decline Laffer curve, as in Figure 6) or unbounded revenue stream, in which higher carbon prices always increase revenue. This sensitivity can lead to large and discontinuous changes in policy outcomes:

From a social planner perspective, the least-cost benchmark pathway is generally derived without explicit constraints on how removals are financed. Introducing such *one-to-many* financing requirements into a social planner setting might reduce cost-effectiveness or eliminate feasible solutions altogether. That is, the climate target cannot be achieved within the intended policy design because available carbon pricing revenues are insufficient to support the required scale of net-negative emissions.

Compared with a policy that strongly prioritizes reducing residual emissions, as discussed in 4.1.3, a *one-to-many* policy can shift the allocation toward higher residual emissions. Depending on the shape of marginal abatement cost curves in the modelling framework, increasing carbon prices (compared to the benchmark) does not necessarily increase revenue. When revenue is bounded as in Figure 6, revenue maximization (compared to the least-cost benchmark) may require lowering the carbon price, which then increases residual emissions.

Conceptually, the feasibility of *one-to-many* financing of removals depends critically on poorly observable features of marginal costs of emission reductions near full decarbonization. As a result, policies that appear robust under stylized modelling assumptions may perform very differently when those assumptions are even slightly violated.

In addition to the conceptual arguments above, residual emitting sectors facing very high compliance costs may relocate or reduce output. While this decreases the revenue base for financing CDR, the first also increases the risk of carbon leakage, while the latter reflects the most expensive way to reduce emissions from a welfare perspective[22].

Furthermore, recent litigation suggests that future regimes that attribute net-negative financing to residual emitters or fossil-fuel producers may attract proportionality challenges, and – where they are justified on historical-responsibility grounds (i.e., past production or emissions) – arguments that the scheme has a retroactive effect[23].

In practical terms, relying on polluter-financed contemporaneous designs beyond compensation of residual emissions requires the continued existence of residual-emitting sectors that *cannot fully reduce emissions* while being *willing and able to pay high removal costs* without *passing costs on to the general public*. This requires a careful assessment of the available revenue base (including residual emitters and upstream fossil fuel producers or importers), their economic and legal responses to high compliance costs, and the likely incidence of those costs across consumers.

[22] Experience from welfare-optimizing models such as DICE suggests that reducing output to avoid emissions is typically the most costly form of "abatement", so such outcomes can be far from the intended optimum.

[23] Challenges brought in connection with implementation of the EU's Net-Zero Industry Act illustrate this risk: certain fossil-fuel producers contest obligations to provide CO_2 injection capacity where allocations are based on historic production, alleging (among other grounds) disproportionality and lack of an adequate legal basis, including in actions before the CJEU challenging Commission allocation decisions.

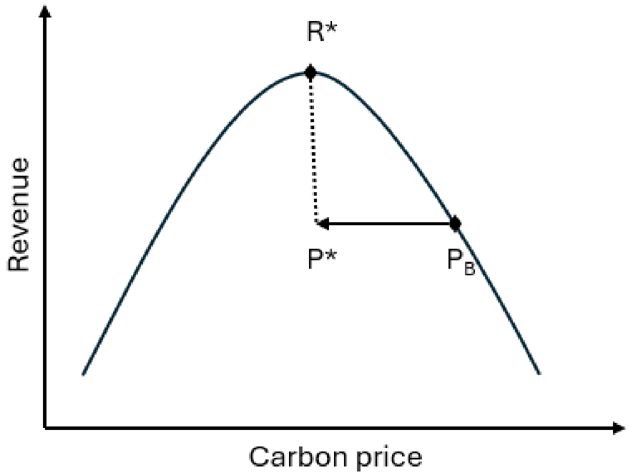

Figure 6. Stylized "Laffer-curve" for carbon pricing revenue. Whether carbon pricing revenues exhibit a peak-and-decline (Laffer-type) pattern, as illustrated here, or instead increase monotonically with the carbon price depends on the shape of marginal abatement cost curves. When revenues peak and decline as a function of the carbon price, maximum revenues R* are bounded. This upper bound limits the volume of removals that can be financed through revenue recycling, implying that some net-negative emissions targets may be unattainable under such financing schemes. Moreover, increasing revenues may then require lowering the carbon price from the benchmark level P_B to the revenue-maximizing level P*, thereby increasing residual emissions relative to the benchmark. Increased residual emissions in turn require further removals.

4.3 Intertemporal instruments for net-negative emissions

The standard logic behind intertemporal economic carbon policy instruments is to tie every ton of CO_2 emitted from today onwards to a ton removed in the future, on a strict ton-by-ton basis[24]. This implies that the marginal costs of reducing emissions should equal (at least) the discounted marginal cost of future carbon removal from the atmosphere. Accordingly, intertemporal economic instruments are typically designed to jointly incentivize emissions reductions and carbon removal, ensuring that both are undertaken at an economically efficient level.

Such intertemporal designs thus implement the *strict PPP* (see Section 4.1.2), and they can in principle deliver net-negative emissions in a *fiscally sustainable* way provided that future

[24] Note that instruments could also be designed to link each ton of emissions to an obligation to deliver X tons of removals.

- If X < 1, only a fraction of each ton would need to be compensated with removals. The remaining share, (1 − X), would effectively constitute free allocation (akin to grandfathering).
- If X > 1, the logic reverses: achieving a given net-negative target would require a sufficient volume of prior emissions to which the removal obligation can attach. For example, if compliance is defined such that an entity emitting 1 ton must later remove 2 tons, then the absence of that initial emission would prevent the required removals from being triggered – undermining delivery of the net-negative outcome as defined.

removals are credibly financed and delivered, and provided that instruments are implemented well before net-zero (see discussion below).

Thus, relative to contemporaneous financing approaches that rely on residual emitters, intertemporal instruments draw on a broader financing base, in line with the *broad base principle* established in Section 3.2.3.3. There are several ways to operationalize this link. Two illustrative policy options mark the ends of a broad spectrum of possible approaches:

- **Tax-fund approach.** A price is applied to CO_2 emissions today, generating revenue. These funds are invested by a centralized entity and earn interest over time. Later these funds are used to procure removals that compensate for the earlier emissions.

- **Obligation approach.** Emitters who release a ton of CO_2 today carry a binding obligation to demonstrate at specified point in the future that they have delivered or financed a corresponding ton of removal.

Under idealized assumptions, the two implementation archetypes yield equivalent outcomes: the mix and timing of emission reductions and removals is identical, even though the practical mechanics of when compliance payments are made, and how liabilities are distributed across decentralized and centralized/public entities differ. The obligation-based approach lends itself to implementation in intertemporal carbon markets, consistent with the view that decentralized market mechanisms allocate resources efficiently. By contrast, the tax-funded approach is more likely to rely on centralized decision-making and aligns with the perspective that governments are better positioned to manage deep uncertainty, coordinate long-term investments, and absorb systemic risks.

Three additional clarifications are important for intertemporal instruments:

- First, they are most naturally suited to long-lived gases like CO_2 where the physical impact of one ton emitted is similar to the impact of one ton removed 20 to 40 years later. Meaningful intertemporal implementations for short-lived GHGs would require further conceptual development.

- Second, the required timing of introducing such instruments is earlier than for contemporaneous financing of net-negative emissions, i.e., well before net-zero emissions are achieved. To avoid retroactive liabilities (see Section 3.2.3.1), an intertemporal instrument can only attach removal obligations to emissions that occur after it is introduced, and can therefore at best return cumulative net emissions to the level prevailing at the moment of implementation. It cannot compensate for earlier emissions under a *prospective* PPP definition. From a global perspective, a natural reference point for introducing such an instrument is the depletion of the remaining 1.5°C-consistent carbon budget, since once that budget is effectively exhausted, any additional ton of CO_2 must be balanced by a later removal. In light of Switzerland's net-zero target for 2050, the period from 2030 to 2050 remains as the critical window during which funds for net-negative emissions could be accumulated or corresponding obligations imposed.

- Third, making these intertemporal instruments work as intended relies on notably strong assumptions, in particular regarding long-term commitment and information requirements; these challenges are discussed in more detail in Section 4.3.1.

4.3.1 Limits of idealized implementation assumptions for intertemporal instruments

Literature on intertemporal emission trading with liberalized banking and borrowing (*68*, *69*) provides a useful entry point for discussing the assumptions that underpin idealized market-based approaches. The purpose here is not to offer a comprehensive review, but to highlight the central conceptual pitfalls. In the most stylized setting, emissions are treated as fully fungible with future removals. Rather than reducing a ton of emissions today, firms may choose to emit now and fulfil the resulting obligation later through CDR. Present emissions therefore become claims on future removals; from a marginal cost perspective, present emission reductions compete with discounted future removals.

However, for intertemporal carbon markets to reproduce the least-cost benchmark generated by a social planner model, stringent assumptions must hold – particularly regarding the treatment of information and uncertainty, as well as commitment and enforcement.

4.3.1.1 Information requirements

In general, intertemporal obligation systems require firms to optimize not only over present-period abatement options (i.e., emission reductions and removals) but over an entire future path of these options. Firms must compare the marginal cost of reducing emissions today with the expected discounted marginal cost of delivering removals years to decades into the future, and they must determine the optimal timing for delivering removals. Doing so requires forming expectations about future technological and market conditions, and the policy framework in which future removals will be certified. While uncertainty about future costs and policies is also relevant for investment decisions in a static ETS, here it becomes directly relevant for compliance decisions – and thus for whether an intertemporal system can credibly operate at all.

For an intertemporal carbon market to deliver the least-cost benchmark, firms must be able to form rational expectations about future removal prices. This requires that uncertainty about future removal prices is in principle estimable and sufficiently “well-behaved”. Enough observations must exist for firms to infer the relevant statistical properties and to form expectations that correctly reflect future outcomes. While individual agents may misjudge future prices in any given period, their forecasts should, on average, coincide with the true expected value of future realizations.[25] “Well-behaved” also implies that price shocks remain within a bounded range and do not routinely push the system into extreme states, such as persistent scarcity of removal opportunities.

In practice, the state of the current CDR ecosystem fundamentally violates these informational assumptions (*56*). There are no reliable empirical price distributions for removals, only early signals from the Voluntary Carbon Market and engineering estimates used in IAMs. This offers little guidance for forming expectations about how compliance markets might behave as they scale. The underlying uncertainty is difficult to formalize within probabilistic modelling frameworks, as it relies on too many unknown parameters and dynamic processes, including the future portfolio of CDR technologies, the pace and direction of innovation, constraints on deployment, and

[25] In competitive market equilibrium models, this is often expressed as two separate conditions: one on the existence of a stable probabilistic structure, and another on agents forming rational expectations consistent with that structure. When agents do not know an existing probabilistic structure, such as in bounded-rationality models with limited foresight or heuristic expectations, intertemporal decisions become distorted and no longer reproduce the least-cost benchmark.

potential technological spillovers. In addition, there is a prospect of major "structural breaks", ranging from technological breakthroughs to the failure of expected CDR options such as BECCS, or political and physical limits to large-scale deployment. Regulatory uncertainty further amplifies this challenge. MRV frameworks, approaches to managing removals with different durability profiles, and legal arrangements governing property rights questions of long-term carbon storage are still evolving and may change substantially as real-world experience accumulates.

Under these conditions, the assumptions required for an intertemporal obligation system cannot be satisfied without additional guardrails.

4.3.1.2 Commitment and enforcement

For intertemporal market-based systems to deliver the least-cost benchmark, obligations need to be perfectly enforceable, agents need to be homogeneous and fully rational, markets need to be competitive and frictionless, and regulators need to commit credibly to future policies. In practice, each of these assumptions is easily violated.

First, there is a moral hazard risk when firms can benefit from emitting today while expecting that future enforcement will be softened, and may even begin lobbying for such softening. In essence, this amounts to betting on time-inconsistent policymaking and future regulatory renegotiation. Governments inevitably face shifting political incentives, budget constraints, and lobbying pressures, all of which might create credible expectations that rules will be revised, and potentially relaxed, over time. When obligations extend far into the future, firms may reasonably anticipate that penalties will be weakened or requirements loosened if non-compliance becomes widespread or strict enforcement becomes politically costly.

Moreover, regulators cannot compel firms to exist in the future and thus deliver removals decades after emissions occur, without introducing additional enforcement mechanisms. Bankruptcy, restructuring, and firm turnover provide natural avenues for shedding obligations if there are no clear liability chains in place. There is also a moral hazard risk in the form of strategic default. On a system level, this might be further amplified by *adverse selection*: firms with high insolvency risk or uncertain business prospects have stronger incentives to take on long-term removal obligations, because they may not be around when the obligations come due.

Taken together, these commitment issues undermine the core requirement that intertemporal claims on future removals remain fully fungible with present-day emission reductions. Hence, even under assumed perfect information, intertemporal instruments require additional mechanisms to strengthen enforcement and commitment. These mechanisms inevitably introduce frictions, making the least-cost benchmark unattainable in practice. The relevant policy question is therefore not whether intertemporal instruments can deliver cost-effectively, but whether they can operate with sufficient credibility and robustness to make a meaningful and feasible contribution to achieving net-negative emission targets.

4.3.2 Intertemporal design proposals

The literature on intertemporal instruments for financing net-negative emissions remains sparse. In this section, we introduce three stylized approaches distilled from the existing literature: a tax-fund approach, an ETS-based removal obligation, and treating CDR like an environmental liability[26]. As noted above, all three approaches are grounded in the premise that each ton of emissions is, in one form or another, priced at the discounted future cost of its removal – thereby simultaneously incentivizing emission reductions and carbon removals. They differ, however, in whether this price emerges from an intertemporal market process or is administratively determined by the regulator. Table 4 compares the pricing or payment components of the three instruments. Notably, each instrument may incorporate an additional charge (the *instrument price* in Table 4) reflecting the cost of temporary atmospheric carbon storage, which may be informed by the social costs of parking CO_2 in the atmosphere. On a more practical level, this charge governs the balance between present emission reductions and future removals.

Before presenting these intertemporal proposals, it is important to recognize that the credible operation of any intertemporal instrument presupposes the existence of a basic CDR ecosystem (see Section 4.3.1). Such an ecosystem must generate sufficiently reliable cost and price information to form credible expectations. Establishing this ecosystem is inherently a multi-sector, multi-decade endeavor, and would likely benefit mission-oriented governance (*72*). CDR approaches are highly heterogeneous and embedded across numerous existing policy domains, including industry, energy, infrastructure, forestry, agriculture, and innovation policy. These policy path dependencies, together with the need to coordinate investments along the entire CDR value chain (e.g., from capture through transport to storage), the large capital requirements, and the long development and deployment timescales, imply a central role for government. Public authorities are therefore essential to coordinate across sectors and time horizons, to make early investments, and to absorb risks that private actors are unlikely to bear on their own.

Moreover, all intertemporal approaches require a definition of *allowed emissions*, that is, emissions that do not need to be compensated by removals (*73*). The cumulative sum of these allowed emissions can be interpreted as a national *remaining cumulative (RC) carbon budget*. This RC carbon budget may be fully depleted before an intertemporal instrument is imposed (Figure 7, panel a). At the global level, the point at which the RC carbon budget compatible with 1.5°C is exhausted – and at which an intertemporal instrument would need to apply to remaining emissions – is likely reached in the 2030s, though with low probability it may already lie in the past.

Alternatively, a national *temporally distributed instantaneous (TDI) carbon budget* can be defined (Figure 7, panels c and e), which in sum equals the RC budget. Under this approach, a fraction of emissions in each period depletes the carbon budget (for example, managed through an ETS with the TDI budget reflected by the cap), while the remaining fraction of emissions (labelled *carbon debt* in Figure 7) is earmarked for later removal through intertemporal instruments. Although the TDI-budget-based approach temporarily involves parallel operation of two instruments (e.g., allowances plus removal obligations under an ETS), it may enable a smoother transition from existing ETS arrangements to intertemporal instruments (e.g., through gradually replacing allowances with removal obligations (*74*)).

[26] For completeness, there is also a proposal based on the social cost of carbon (SCC), reflecting common practice in US climate policy analysis (*70*, *71*). Under this approach, regulated entities are required to post a large upfront collateral, calibrated to a worst-case estimate of the SCC. Realized climate damages are then deducted from this collateral over time, while downward revisions of the worst-case SCC estimate are returned as dividends. This instrument is designed to deliver first-best (welfare-maximizing) incentives for both emission reductions and removals; however, it is not compatible with achieving a fixed climate target.

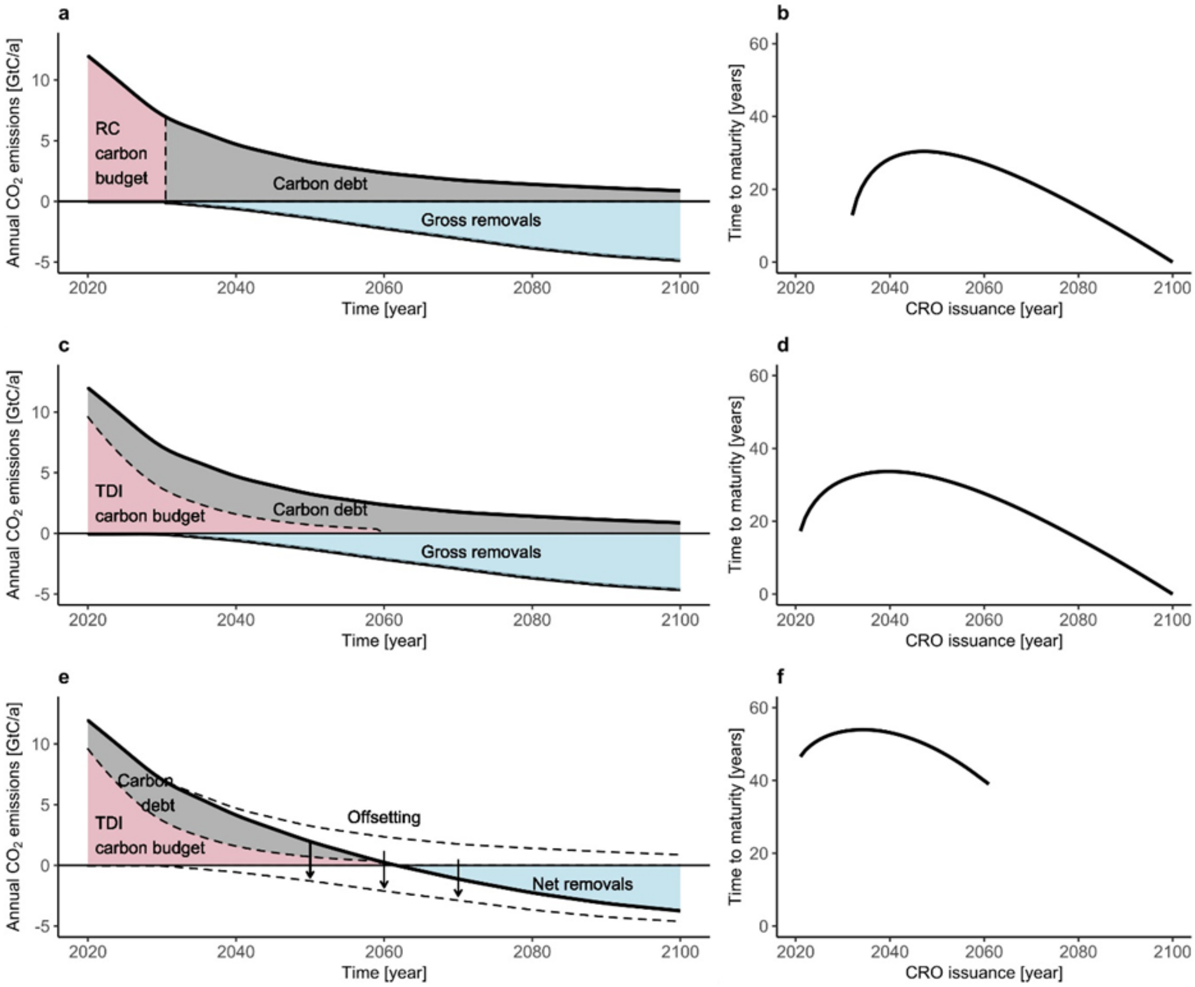

Figure 7. Illustration of various conceptual ways to design intertemporal instruments. Panel a, c, e: Elements characterizing different implementation versions of intertemporal instruments; the figure was obtained from ref *(73)*. Carbon debt (grey) is either defined based on gross emissions and compensated by gross removals (panels a, c), or it is generated by net emissions and compensated by net removals (=net-negative emissions). Panels: b, d, e show the time it takes for a ton of CO_2 emitted in a specific year under the intertemporal instrument until it is removed for the profiles shown in panels a, c, e. This "time to maturity" as a function of the date of emission (= issuance of a carbon removal obligation, CRO) depends on the type of emission accounting (gross vs. net) as well as the distribution of the remaining carbon budget. For an analytical definition see ref *(75)*. Panel a: Carbon debt is generated by gross emissions once the remaining cumulative (RC) carbon budget has been depleted, here around 2030. Carbon debt is compensated intertemporally by gross removals. Panel c: The cumulative sum of the temporally distributed instantaneous carbon budget equals the RC carbon budget. Carbon debt is generated by gross emissions exceeding the TDI carbon budget (pink area). Carbon debt is compensated intertemporally by gross removals. In case a conventional carbon pricing scheme, like an emissions trading scheme (ETS) is operating in parallel to the intertemporal framework, the conventional pricing scheme is bound to the TDI carbon budget (pink). Panel e: Carbon debt is generated by net emissions exceeding the TDI carbon budget (pink area). Carbon debt is intertemporally compensated by net removals. Here it is assumed that the removal obligation is part of an ETS (see Section 1.1.1.1) The emission caps over time of the linked ETS equal the TDI carbon budget. CDR integration into the ETS is required for contemporaneously offsetting gross emissions minus net emissions (blank part of gross emissions) with gross removals minus net removals (blank part of gross removals).

Furthermore, all approaches can be designed to intertemporally finance either *gross* removals (i.e., *all* CDR) or exclusively *net* removals (i.e., net-negative emissions), as illustrated in Figure 7 (compare panels a and c with gross emission accounting, with panel e with net emission accounting). This distinction has important implications:

If the intertemporal instrument finances only net-negative emissions, an additional channel is required to manage the contemporaneous offsetting of residual emissions with CDR (Figure 7, panel e). From a regulatory perspective, this can increase complexity (*73*), as removal units may be retired under two parallel mechanisms (contemporaneous and intertemporal). Moreover, because removals are also used to balance emissions contemporaneously, marginal costs of emission reductions and removals are equalized in each point of time[27].

However, it might be advantageous if marginal cost paths for emission reductions and removals were kept separate[28], for example because removals may require higher price signals in the near term during a learning phase (*76*) and lower prices in the long term to avoid unnecessary rents and associated welfare transfers to the CDR sector (*77*). Moreover, it has been argued that CDR subsidies should exceed the carbon price for emission reductions, because of carbon leakage effects caused by reduced fossil fuel prices resulting from policies focused on emission reductions (*60*) [29].

If intertemporal instruments are instead based on gross accounting (as in Figure 7, panels a and c), marginal costs of emission reductions and removals can, in principle, follow different trajectories, and the regulatory assignment of removals is unambiguous, i.e., there is no distinction between removals that offset residual emissions contemporaneously and removals that deliver net-negative emissions intertemporally (see Footnote 27). In this case, the time lag between emissions and associated removals (which can be seen as idealized maturities of removal obligations) is shorter when measured between gross emissions and gross removals (Figure 7, panels b and d) than when measured between net emissions and net-negative emissions (Figure 7, panel f). As a result, gross accounting intertemporal instruments manage larger volumes but over shorter time horizons, over which removal costs may be easier to forecast. Longer maturities, on the other hand, might imply lower present value marginal removal costs as a consequence of technological learning and discounting[30].

For all existing proposals, explicit management or regulation of maturities is essential. First, it reduces the informational burden on

[27] Conceptually, from a static efficiency perspective, if emissions can be offset by removals within the same period, the marginal cost of emission reductions equals the marginal cost of removals. From a dynamic efficiency perspective, if emissions can be compensated by future removals, the marginal cost of emission reductions equals the discounted marginal cost of future removals. Accordingly, instruments that organize the offsetting of residual emissions with CDR in a contemporaneous way, while financing net-negative emissions intertemporally, imply equal marginal costs of emission reductions and removals at each point in time. By contrast, instruments that finance all CDR purely intertemporally – including CDR required for offsetting residual emissions – allow marginal costs of emission reductions and removals to diverge at a given point in time, even though the intertemporal efficiency / no-arbitrage condition (linking present marginal costs of emission reductions to discounted future marginal removal costs) remains in place.

[28] Even if marginal cost paths of emission reductions and removals differ at each point in time, due to the intertemporal link between current emission reductions and future removals, the two trajectories are interdependent. Higher future marginal removal costs make present emission reductions more attractive, leading to greater abatement and thus higher marginal costs, and vice versa.

[29] The idea is that emission reductions may reduce reliance on and thus demand of fossil fuels, hence, making fossil fuels cheaper in other countries which may increase fossil fuel usage. This form of carbon leakage is not present for CDR.

[30] Formally, if marginal removal costs increase over time at a rate below the discount rate (= market risk-free rate), marginal costs are reduced in present value terms if maturities are increased. See ref (*75*) for stylized scenarios where this is the case.

responsible entities subject to an obligation-based approach, as they do not need to determine the optimal timing of removals, but "only" whether to abate emissions immediately or emit and procure removals at a specified maturity. The intertemporal decision about optimal timing of removals is shifted to the regulator. Second, it provides an important guardrail against excessive postponement of removals that substitute for earlier emission reductions, thereby limiting deterrence risks. Third, if volumes and maturities are publicly disclosed, it generates a predictable stream of demand for removals at each future point in time. Credible information about the timing and scale of future removal demand is crucial for CDR markets to form expectations and to scale investment and deployment in a timely manner. The latter consideration is particularly relevant under a fund-managed approach.

To conclude, intertemporal economic instruments as conceptualized here

- require the existence of at least a basic CDR ecosystem, unless the public sector is willing to absorb the risks associated with fundamentally uncertain CDR costs and scalability;
- need to credibly define a carbon budget beyond whose depletion the instrument becomes operational; and
- can be designed to cover either all CDR (gross removals) or exclusively net-negative emissions;
- need to establish mechanisms to manage maturities (i.e., the time between emission and removal).

The three intertemporal design proposals presented below differ primarily with respect to:

- the timing of compliance payments (i.e., the costs paid by obligated entities – typically emitters and/or fossil fuel producers – for removals),
- the responsibility for delivering removals (e.g., public authorities or regulated intermediaries, emitters or producers of fossil fuels),
- the allocation of risks associated with uncertainty in future removal costs and scale, and
- the political feasibility of implementation, including differences in near-term cost visibility, administrative complexity, and long-term governance requirements.

4.3.2.1 The tax-fund approach

In the tax-fund approach (*78*), pricing one ton of CO_2 emissions is intended to raise (approximately) the discounted marginal cost of removing one ton of CO_2 in the future. The resulting revenues are transferred into a dedicated centralized removals fund. This fund is invested over time and later drawn down to finance removals, either to support removals in general or explicitly to finance net-negative emissions. Recent country-specific reports for the Netherlands (*79*) and Taiwan (*80*) have tended to emphasize such tax-fund approaches.

In principle revenues from an ETS could also be banked for financing removals later on, however, as argued in Section 4.4.1 below, tax-based instruments may be better suited for stable revenue generation.

Compliance payments occur at the time of emission and may comprise three elements (see Table 4). Emitters pay the discounted expected cost of future removal upfront. In addition, regulators may impose an extra charge either to further disincentivize emissions beyond the cost-effective level (*instrument price*)[31] or to address uncertainty in future CDR costs (*risk buffer*).[32]

This design shifts the main exposure to uncertainty regarding future CDR costs and scalability from private actors to the public sector. Conceptually, this can be advantageous because it avoids the commitment and enforcement problems that arise when private firms are required to deliver removals decades after emissions occur (e.g., insolvency, firm turnover, or strategic default, as noted in Section 4.3.1.2), while assigning the management of long-horizon risks and investment tasks to government. The approach might also integrate well with a broader government mission to establish an initial CDR ecosystem, as well as with the potential public utility provision of removals as mentioned in Section 4.4.2.3 below.

The CDR fund can procure removals through a range of instruments (e.g., competitive tenders, auctions, contractual arrangements, or public CDR utilities) and can incorporate mechanisms to limit excessive rents captured by CDR providers (see Section 4.4.2 below). These design choices affect the magnitude of upfront payments, fiscal sustainability under cost uncertainty, incentives for innovation, and distributional outcomes, and therefore require explicit governance.

Challenges and political-economy risks

- Even if reasonably robust estimates of future removal cost distributions are available, policymakers must still decide how much revenue to collect above the central cost estimate (i.e., the *risk buffer* in Table 4) to ensure that the fund remains adequate with a given degree of confidence. Choosing a higher safety margin increases the likelihood that sufficient funds will be available, but it also requires higher upfront payments, which may reduce political acceptability. Conversely, opting for a smaller buffer lowers immediate costs but raises the risk of future funding shortfalls.

- Because the approach can thus imply large near-term compliance payments by emitters to finance future CDR, it may face substantial political opposition and lobbying.

- The approach relies on the fund remaining intact across electoral cycles. Large accumulations of earmarked capital create risks of political capture or repurposing, particularly during periods of fiscal stress.

- Finally, the fund's performance depends critically on how it is governed (e.g., whether it is managed within the treasury or by an independent statutory body) and on its investment mandate. Excessively conservative investment strategies can erode purchasing power, while overly aggressive strategies can expose the fund to drawdown risk (see also the discussion on radioactive waste management funds in Section 4.5). Clear rules are further required to prevent the fund from being used for unrelated political objectives under the guise of "investment."

The central question is thus not only how high the carbon price should be to provide the cost-effective incentives for emission reductions and removals, but also how the fund can be institutionally ringfenced and governed so that earmarked resources remain available for future removals. This shifts the main feasibility

[31] In essence, this drives a "wedge" between the equivalence of discounted future marginal removal costs and the marginal costs of emission reductions at the time of emission (i.e., the no arbitrage condition). This makes future removals more expensive, and increases present-day emission reductions.
[32] The instrument price can simultaneously serve as a risk buffer, both discouraging emissions beyond the cost-effective level and increasing revenues to reduce exposure to uncertainty in future CDR costs.

constraint from private enforcement – a key weakness of obligation-based designs – to long-term public governance and commitment, which constitutes a central vulnerability of the tax-fund approach.

Table 4. Financial components of intertemporal instruments. Intertemporal instruments may include four types of payments: 1. Agent-specific premiums increase the costs for the right to "emit now and remove later" for agents with more limited ability to fulfil future removal obligations. This reduces adverse selection, as discussed in Section 4.3.1.2; 2. Instrument price, collected by regulators or intermediaries to steer the emissions-removals path (set directly, or via auction). The instrument price can also be interpreted as the cost imposed for temporarily storing CO_2 in the atmosphere. 3. Expected removal prices, representing the discounted price of future removals; and 4. Risk buffer, reflecting the difference between the central estimate and a higher-confidence estimate of the future removal-price distribution (e.g., the price corresponding to an 80–90% confidence level), thereby increasing the probability that collected funds will be sufficient. Note that revenues from the "instrument price" could be used in part as risk-buffer. Red shading indicates components requiring upfront payment.

	Agent-specific premium	Instrument price	Expected removal price	Risk buffer
Tax-fund approach (a)	no	Tax		
ETS-based removal obligation (b)	no	ETS auction of tradable permit	Redeemable cash deposit as collateral	
Environmental liability (c)	yes	Stock tax	Balance sheet debt	Re-measuring

(a) Carbon tax is imposed which feeds into a removals fund. Removals fund later pays for CDR.
(b) A permit for the right to "emit now and remove later" is auctioned within an ETS. A cash deposit is required for enforcement of the obligation to remove. Cash deposit can be redeemed upon certified removal.
(c) Discounted expected cost for future removals enters the balance sheet as financial debt (e.g., a provision). A periodic stock charge is imposed for CO_2 temporarily parked in the atmosphere, which includes an emitter-specific premium. Balance sheet debt might require collateral (e.g., lien on assets). Re-measuring adjusts balance sheet debt and collateral requirements as removal price estimates change.

4.3.2.2 ETS-based removal obligations

Under an ETS-based removal obligation (*74*, *78*), the right to emit CO_2 today while committing to remove an equivalent amount at a later date could be established through an auction. Firms are required to surrender either conventional emission allowances or purchase a removal obligation that specifies future delivery of removals.

A central design issue is the role of cash collateral (see Table 4). Collateral is essential to address the commitment and enforcement problems associated with long-dated removal obligations (as discussed in Section 4.3.1.2). Collateral, paid at the time of emission, ultimately becomes the benchmark against which firms will assess whether to reduce emissions immediately or to emit now and remove later.

If collateral requirements are set too low, firms may rationally choose to post collateral with little intention of ever redeeming it through actual removals. In that case, the instrument may effectively revert to a tax-fund-like mechanism, with deposits functioning as a CDR fund rather than as credible commitments to future delivery by obligation holders. Conversely, high collateral requirements strengthen commitment but raise near-term compliance costs, even if deposits are refundable upon delivery of removals, which can significantly undermine political feasibility.

An important extension of the basic design is to allow receipts for collateral deposits to be tradable (*81*). Tradable deposit receipts can enhance liquidity for emitting firms, facilitate risk-sharing among investors with different risk preferences, and support price discovery regarding expected future net redemption values (= face value of the tradable receipt minus realized removal costs). In this sense, they can partially externalize long-term risk from regulated firms to capital market participants potentially better equipped to manage it.

As with the tax-fund approach, governance of the accumulated financial resources is critical. Key design questions include whether collateral funds are held in escrow-like arrangements or actively invested, how they are legally and institutionally ringfenced. A further complication arises from potential ambiguity about the role of the deposit-managing authority: it may be unclear whether this entity is expected to actively invest in CDR and procure removals, or whether it is largely passive, assuming that obligations will be redeemed by private actors.

Path control of emissions and removals under an ETS-based removal obligation differs from the tax-fund approach. While the latter directly governs emissions through a tax or caps and removals through public procurement, path control here operates through capping the number of auctioned removal obligations. This cap determines both the emergence of a positive obligation price (*instrument price* in Table 4) and the maximum volume of future removals (or net-negative emissions, depending on whether accounting is gross or net). In addition, the regulator can specify the maturity of removal obligations, as discussed above.

Comparison with the tax-fund approach

- ETS-based removal obligations align with the view that markets deliver efficient outcomes: emitters decide whether to abate now or emit and remove later, forming expectations about future CDR costs which help price discovery. The tax-fund approach is more consistent with the view that governments are better suited to manage uncertainty, coordinate investment, and absorb risks.

- Familiar ETS-tax trade-offs: The standard distinctions between ETSs and carbon taxes apply, including differences in price volatility, compliance with a given carbon budget, and revenue predictability (see Section 4.4.1), as extensively discussed in the literature.

- The ETS-based approach creates an explicit quantitative and temporal link between emissions and removals through obligations with defined maturities. By contrast, under a tax-fund approach, the volume and timing of removals depend on how funds are accumulated and deployed over time, which may result in a weaker or less direct correspondence between emissions and removals in practice.

- ETS-based removal obligations can be integrated into existing ETS architectures, potentially lowering institutional transition costs relative to establishing new mechanisms (see Section 3.2.3.2 on *the use of established mechanisms*).

- Both approaches may face resistance since potentially large upfront cash payments are required. Under an ETS-based approach, tradable deposit receipts can provide emitters with a financial asset, potentially limiting their net burden to the discounted expected future cost of removals under well-functioning markets for deposit receipts.

- Governance of funds: Both approaches face similar challenges in protecting accumulated financial resources, whether held as collateral funds or as earmarked removals funds, from political interference. However, the role of fund managers is clearer under the tax-fund approach which explicitly manage uncertainty and procurement, making early implementation of a tax-fund system – potentially as part of a broader effort to establish a CDR ecosystem – conceivable even when CDR costs and scalability remain highly uncertain.

- It should be noted that the current Swiss ETS is linked to the EU ETS. As a result, the scope for unilateral modifications or further development of the Swiss system may be constrained, given that linking requires the participating systems to remain compatible in their design and operational features.

4.3.2.3 Carbon waste management as environmental liability

A third approach reflects how environmental liabilities are sometimes addressed in practice – for example, the decommissioning of power plants (notably nuclear facilities), the rehabilitation of contaminated land or depleted mines, and the management of radioactive waste. It frames CDR primarily as a waste management task for which polluters ultimately remain liable.

Acknowledging that jurisdictions differ in how they regulate and enforce environmental liabilities (see also Section 4.5), a generic implementation of this type of carbon removal obligation could draw on established liability frameworks. Specifically, the obligation could be operationalized through an accounting requirement that obliges polluters to recognize a provision on their balance sheets for future carbon removal costs (*73*). This provisioning requirement would formally record the liability and make it visible in firms' financial statements. To ensure that the obligation is credible and enforceable, it would need to be complemented by appropriate financial assurance mechanisms. Responsibility for the delivery of removals and associated risks remain with the emitter (or producer/importer of fossil fuels), but a step-in party ensures performance in case of default.

At the compliance point (e.g., emission or upstream introduction of fossil carbon into the economy), the responsible entity recognizes a provision for a future removal obligation[33]. The obligation is measured as the present value of the regulator-defined best estimate of the cash outflows required to produce or procure compliant removals at the specified maturity. The nominal settlement estimate at maturity (i.e., the expected future removal cost) and the discount rate[34] should be defined by regulators and disclosed as key parameters to inform the "abate-now" versus "emit-now-remove-later decision". Over time, the provision is re-measured as cost estimates evolve and is accreted through unwinding of the discount,

[33] A provisions are accounting instruments used when the following conditions apply (*82*):
- Present obligation: There is a legal or constructive obligation arising from a past event (i.e., remove CO_2 emitted earlier).
- Probable outflow: It is more likely than not that resources (usually cash) will be required to settle the obligation (outflow is certain, cash amount is uncertain).
- Reliable estimate: The amount can be estimated with sufficient reliability (this requires at least a basic CDR market, or reliably engineering-based estimates; otherwise this amount can be defined by the regulator initially).

[34] The discount rate should reflect (a) current market assessments of the time value of money, and (b) the risks specific to the liability, including uncertainty in the amount or timing of the expenditure required to settle it. Such risks typically increase the measured value of the liability and should therefore be reflected by *reducing* the discount rate when determining the present value of the expected expenditure (*83*).

such that the carrying amount of the provision equals the required settlement amount at maturity.

To recap, under idealized conditions, the tax-fund-based approach charges (at least) discounted removal costs as an emissions tax; the ETS-based obligation approach charges (at least) discounted removal costs in the form of cash collateral; and the approach discussed here records discounted removal costs as a liability on firms' balance sheets (see Table 4). In present-value terms, the intended economic burden should thus be similar[35]; the difference is whether it shows up mainly as an upfront cash payment that binds on liquidity, or as a booked liability with later cash settlement that binds more on leverage (see Figure 8).

Under the proposed tax-fund regime and an ETS design with collateral requirements, cash outflows occur upfront (implying large near-term payments that decline as emissions or fossil fuel production fall) whereas under provisioning, cash outflows occur at the time of removal and therefore scale with the ramp-up of removals. The removal trajectory implied by the instrument's maturity structure is thus decisive for the timing and magnitude of these later cash outflows. For firms for which liquidity, rather than long-term profitability, is the binding constraint, provisioning may therefore be more tolerable.

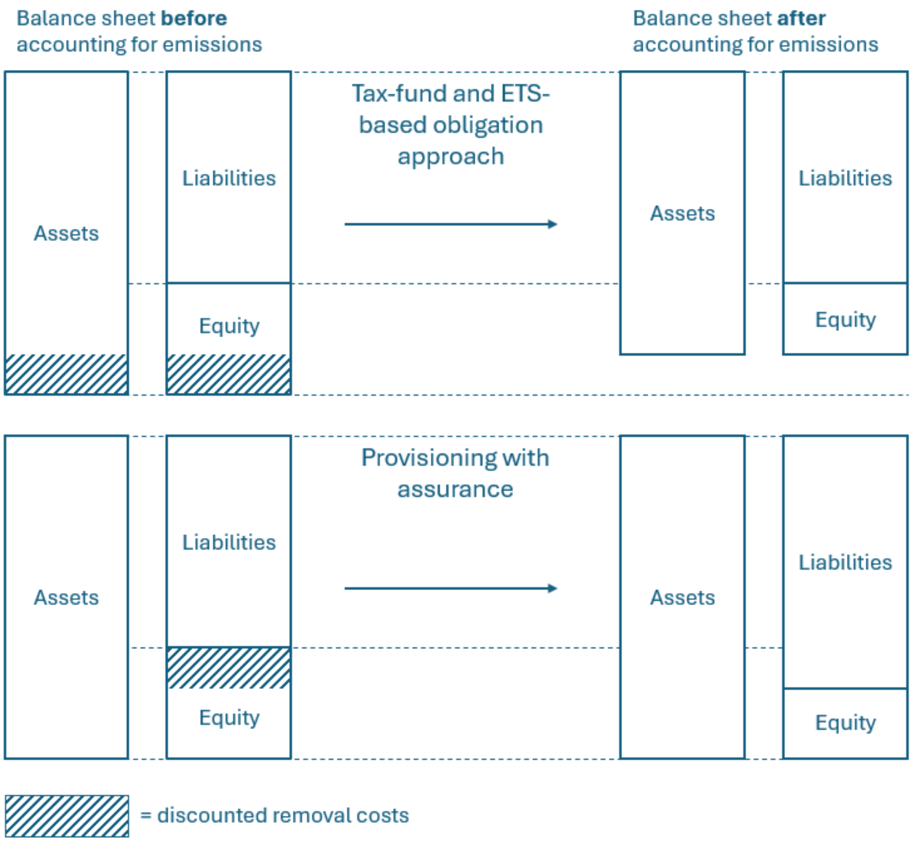

Figure 8. Changes in a stylized balance sheet at the time of emission for entities subject to either a carbon tax paid into a removals fund or a collateral requirement (top panel), or a provision-based approach (bottom panel). In this stylized example, discounted removal costs are identical across instruments but affect balance sheets differently. Under a tax- or ETS-based approach, compliance payments would reduce cash (assets) and equity, thereby affecting liquidity; under a provision-based approach, total assets remain unchanged, while equity is reclassified as liabilities, primarily affecting leverage.

[35] Unlike some environmental provisions that are capitalized into a related asset (e.g., decommissioning), the removal obligation proposed here could be treated as a period expense at inception to reflect that it is triggered by the emission/compliance event rather than by the construction of a specific asset.

Financial assurance of the obligation

In order to address the commitment and enforcement challenges noted in Section 4.3.1.2, the proposed approach needs to be backed by stringent financial assurance mechanisms (*73*). Specifically, a financial intermediary, such as a commercial bank or insurance company, acts as a step-in party in the event that the responsible entity defaults. For environmental integrity, ideally intermediaries are required to guarantee the successful settlement of the obligation – i.e., that compliant removals are delivered, either directly via contracted supply or via funding that ensures replacement procurement. In return for assuming these risks, the financial intermediary charges a premium that reflects the risk profile and creditworthiness of the responsible entity.

Several points are relevant in relation to this enforcement mechanism:

- Intermediaries would need to internalize both counterparty default risk and delivery risk, giving them strong incentives to monitor liable entities as well as the CDR supply chain. As a result, technology and execution risks are partly intermediated through the financial system. Since intermediaries are thereby exposed to real-economy transition risks, they are likely to invest directly in CDR capacity and contribute to removals market development in order to manage their exposures. Compared to the tax- and ETS-based approaches, this creates a strong channel through which financing is directed toward CDR.

- Because financial intermediaries charge premiums that reflect the financial position of responsible entities, riskier firms face stronger incentives to decarbonize rather than to emit now and remove later. In this way, adverse selection concerns are counterbalanced through risk-based pricing of the assurance.

- Intermediaries may require collateral, but they are likely to be more flexible than ETS-based collateral requirements. Collateral may take various forms, such as liens on assets or parent-company guarantees, and may be re-margined if the nominal settlement estimate of the provision changes over time. If collateral requirements involve cash, however, the resulting liquidity impact may become similar to that under tax- or ETS-based approaches.

- Financial intermediaries such as commercial banks are already subject to extensive regulation and supervision. From their perspective, the assurance contract creates a guarantee exposure (and potentially a recognized obligation) whose valuation and regulatory capital treatment depend on the instrument design and supervisory regime. To manage and potentially reduce these capital impacts, intermediaries may hedge their exposure through investments in CDR.

- Similarly, strategic CDR reserves could be required by regulation, sized in proportion to intermediaries' aggregate exposure. These reserves could be designed to operate counter-cyclically, being replenished during periods of economic expansion and drawn down during periods of financial stress.

Because large-scale carbon-liability management would become system-relevant – and unmitigated climate change is itself a financial-stability risk – central banks could interpret their mandates as encompassing carbon management (*73*). In this role, they would set a transparent base rate embedded in assurance premia (the *instrument price* in Table 4) to manage the supply of removal obligations and dampen procyclicality, with the base rate and a (potentially adjustable) maturity structure jointly shaping the emissions-removals path.

Comparison with the tax-fund and ETS-based obligation approaches

In conclusion, the main differences between the ETS and tax-based approaches and provisioning are as follows:

- Cash-constrained entities, and entities familiar with provisioning, may prefer this approach over a tax-fund or ETS-based obligation regime. For such firms, upfront cash payments compete with other investment needs. Provisions, by contrast, may allow for the smoothing of cash flows over the business cycle.

- Parts of the financial sector, including banks, insurers, and project financiers, may support the policy due to new intermediation and hedging opportunities. Integration of carbon management into the financial mainstream might lead to increased CDR financing.

- The provision-based approach introduces additional intermediation costs relative to the other proposals (the *agent-specific charge* in Table 4). These costs are likely to be smaller per unit of emissions for larger firms. Accordingly, the provision-based approach is generally better suited for large firms, e.g., large point sources or producers/importers of fossil fuels.

- The proposed architecture introduces systemic risk channels (notably concentration, procyclicality, and wrong-way risk between emitter credit quality and CDR cost/availability), which is why the approach must be paired with appropriate prudential and macroprudential safeguards to contain amplification channels. This consideration underpins the suggested role for central banks.

- In many jurisdictions, payments associated with the obligation (removal procurement costs and assurance premia) would likely be treated as deductible business expenses, reducing the base for other taxes, subject to applicable tax rules.

4.4 Additional considerations for the affordability of large-scale CDR

This section introduces additional demand- and supply-side design considerations, building on the discussion of contemporaneous and intertemporal instruments in the preceding sections. The feasibility of large-scale CDR provision, and, in particular, of achieving net-negative emissions, hinges on both sufficient capacity to pay on the demand side and the availability of low-cost removals on the supply side. Low-cost removals depend not only on cost reductions through technological progress (a key focus of current CDR governance) but also on the design of policy instruments that manage rents in the CDR sector so as to limit compliance costs (i.e., the costs paid by obligated entities – typically emitters and/or fossil fuel producers – for removals), as well as international sourcing of CDR. While early-stage CDR deployment support is out of scope, any large-scale approach will nonetheless need to account for path dependencies arising from governance and institutional structures established during earlier phases of CDR support.

4.4.1 Demand-side

Demand for CDR will primarily need to be generated through compliance-based instruments (*56*). Beyond the distinction between contemporaneous and intertemporal instruments, a further distinction can be drawn between instruments that directly link emissions and removals, and instruments that generate revenues through emissions pricing and procure removals via an intermediary.

Linking emissions or fossil products directly to removals can be implemented through an ETS or through explicit mandates or obligations. Under such integration, a ton-by-ton linkage between emissions and removals would represent the natural benchmark (i.e., the strict PPP); achieving net-negative outcomes with contemporaneous instruments, however, may require a one-to-many linkage, as discussed in Section 4.2.1.

Alternatively, demand for removals could come from an intermediary (e.g., a public fund or purchasing agency, such as the proposed European Carbon Central Bank (*84*)) funded by revenues from pricing emissions or fossil products.

4.4.1.1 Potential sources of revenue for CDR financing

From a revenue perspective, a carbon tax tends to be preferable when marginal cost curves of emission reductions are relatively inelastic, as changes in the tax rate then lead to only modest changes in emissions, resulting in more predictable revenues. By contrast, an ETS is generally preferable when marginal cost curves of emission reductions are relatively elastic, since adjustments in the cap would then lead to only small changes in prices, thus allowing for more predictable revenues. Along ambitious mitigation pathways, however, marginal costs of emission reductions are typically rather inelastic (i.e., approaching the Inada condition), suggesting that tax-based instruments may be better suited for stable revenue generation to finance large-scale CDR through an intermediary.

Moreover, financing net-negative emissions might require moving beyond a purely economic approach where every ton of emission is priced at the (discounted future) marginal cost of one ton of removal to increase the base of contributors to CDR provision. Where the primary objective is to generate sufficient revenues financing net-negative emissions, i.e., to ensure *funding adequacy* (see Section 4.5.2 for a discussion in the context of radioactive waste management) for future CDR rather than primarily providing incentives for emission reductions, financing of CDR could be placed on a *broader base* (in line with the principle established in Section 3.2.3.3). A range of additional sources could provide partial contributions (though, all of them address polluters in one way or another, and layering them might cause proportionality issues):

- Pricing can be applied upstream through a levy or tariff on fossil fuel imports. If implemented by a sufficiently large coalition of importing countries, such a measure could reduce global demand enough to lower international fossil fuel prices, generating a *terms-of-trade effect* (*60*). In this case, part of the revenues would effectively reflect rents shifted from fossil fuel producers to importing jurisdictions. Revenues could either be fully earmarked for financing CDR procurement, or only the resource-rent component could be allocated to CDR, in which case it would constitute only a small contribution to overall CDR financing, with the remaining revenues used to address distributional and welfare impacts of the tariff.

- Moreover, international aviation and shipping represent sizable emissions bases which are promising candidates for revenue-raising through levies or carbon charges, which could also contribute to finance CDR. An attraction for aviation levies is that cost pass-through tends to fall disproportionately on higher-income households, given the strong concentration of air travel (and especially premium travel) among affluent consumers. As with fossil-fuel import charges, however, their effectiveness hinges on sufficiently broad international cooperation. Recent attempts to advance such pricing at the global level have faced significant political resistance, with the United States actively opposing emissions-based economic measures in IMO shipping talks (*85*), and also pushing back against proposals for new taxes/levies discussed in the ICAO context (*86*).

- An additional partial contribution to CDR financing could come from levies on actors that benefit from the fossil-based economy while exhibiting comparatively low direct (Scope 1) emissions (e.g., parts of the digital/tech and service sectors), or from progressive carbon pricing that targets very high-emission consumption (e.g., luxury travel). However, Swiss voters rejected the climate-earmarked federal inheritance and gift tax proposal ("Initiative for a Future") in the 30 November 2025 referendum (*87*), underscoring the political challenges of financing CDR through measures that primarily target high-wealth households.

4.4.2 Supply-side

Alternative procurement structures for CDR supply can reduce compliance costs on the demand side. A reduction of compliance costs can be achieved by limiting the rents earned by CDR providers – i.e., reducing the gap between what they are paid and their underlying costs. Across suppliers, this means moving away from remunerating CDR provision based on marginal costs (which can generate substantial infra-marginal rents for lower-cost providers) toward payments that are more closely aligned with average production costs across CDR projects.

However, such rent-reducing designs may also weaken investment incentives, particularly for higher-cost or riskier projects, unless they are combined with long-term contracts or credible volume commitments that provide revenue certainty and reduce investment risk.

4.4.2.1 Technology-neutral procurement on a single market

Removals of comparable quality – most importantly with respect to durability (incl. reversal risk/liability) and side-effects – could be procured in a single pool without differentiation by underlying CDR technology and associated costs. Remuneration would be uniform across eligible suppliers, either through (i) a market-clearing price determined in reverse auctions, or (ii) a uniform support rate. Key characteristics of this approach include:

- Potentially stronger investment incentives and entry signals.
- The technology mix is determined largely by market forces.
- Because costs for CDR currently range from 20 USD/tCO2 to above 1000 USD/tCO2 (*56*), uniform remuneration linked to the marginal (i.e., most expensive) supplier is likely to generate substantial inframarginal rents for lower-cost providers and thereby increase compliance costs on the demand side (e.g., under emissions pricing).

Options to shift remuneration towards system level average removal costs

The options outlined below should be embedded in the market design from the outset as clear, rule-based mechanisms. They should not be introduced retrospectively as discretionary interventions to claw back windfall profits – such as the emergency measures adopted in several EU countries following the recent surges in energy prices:

- Inframarginal revenue caps / claw-backs: Net revenues/margins could be capped above a benchmark and the surplus recycled (e.g., to reduce compliance costs at the demand side or fund additional procurement).

- Targeting the price-setting segment: Analogous to the Iberian power-market mechanism (*88*), in markets where the clearing price is determined by the most expensive unit needed to meet demand (the marginal supplier), regulators could intervene specifically at that margin. For example, they could partially subsidize or in other ways directly address the costs of the marginal supplier, thus reducing the clearing price. However, this approach is mainly effective when the marginal removal segment is narrow and identifiable – such as when a small number of high-cost technologies (e.g., DACCS) determine the market price.

- Pay-as-bid: Replacing uniform pricing with pay-as-bid pricing can reduce observed windfalls, but suppliers tend to bid toward expected clearing prices, such that strategic bidding might reintroduce quasi-marginal pricing; compliance cost savings are therefore uncertain.

4.4.2.2 Technology-specific markets or rates

Instead of pooling removals with potentially fundamentally different cost profiles, removals could be procured separately by CDR technology (or technology families) – such as the recent reverse auction for BECCS in Sweden – with either:

- Technology-specific reverse auctions, where prices reflect within-technology marginal costs; or

- Technology-specific administered rates (subsidies/tax credits), based on audited project costs or standardized cost benchmarks plus a regulated markup.

Splitting a single, technology-neutral removals market into separate, technology-specific markets changes how prices are formed. In a unified market, the most expensive technology needed to meet demand (the marginal supplier) determines the price for all providers, allowing lower-cost technologies to earn cross-technology infra-marginal rents. By contrast, in technology-specific markets, each technology is remunerated largely based on its own cost structure. High-cost technologies no longer set the price for low-cost ones. As a result, remuneration across technologies tends to be more closely aligned with system level average removal costs rather than the marginal cost across all technologies, while maintaining competition among supplier of similar CDR projects. Key characteristics of this approach include:

- It can support a diversified portfolio and hedge technology/scale-up risk, where technology neutrality might over-concentrate procurement in the cheapest near-term options.

- The technology mix becomes partly administrative (requires a portfolio target / social planner logic to decide volumes per technology and to update them over time).

- It entails a greater design burden, e.g., for defining eligible technology classes and cost benchmarks, and how they evolve over time.

Technology specific procurement can be paired with the following complementary instruments to balance any potential loss in investment incentives:

- Two-way CfDs: CDR supplier remuneration could be settled against a strike price (which is either determined competitively or an administered rate): when the reference price exceeds the strike price, suppliers pay back the difference; when the reference price falls below the strike price, suppliers receive a top-up. This preserves competition for the strike price while limiting windfall gains when market values rise. At the same time, it increases revenue certainty and thereby strengthens investment incentives. CfD-style programs are being tested in Denmark (CCUS Fund), the UK (Industrial Carbon Capture contracts), and the Netherlands (SDE++) (*56*).

- Offtake contracts for removals: Private or public offtake at fixed or indexed prices shifts revenue formation from volatile spot/auction outcomes toward contract prices that better reflect project economics.

4.4.2.3 Public-utility provision of CDR

A state-owned CDR utility can invest in and operate removal infrastructure and sell removals either into competitive procurement or under regulated tariffs.

- In competitive settings, a public utility can bid at cost-reflective prices and recapture inframarginal rents for the public (reducing distributional concerns while maintaining competitive allocation).
- Under monopoly-style regulation, tariffs can be set close to average cost, but this raises classic concerns about cost discipline, information asymmetry, and potential monopoly rents.

Public provision can reduce private windfalls, but the degree of competition vs. regulation determines whether the system behaves more like marginal pricing (with public rent capture) or explicit average-cost pricing (with stronger governance requirements).

4.4.2.4 International sourcing of CDR

Under Article 6 of the Paris Agreement, Switzerland can source CDR abroad. Indeed, the long-term climate strategy already foresees a substantial role for international removals, on the order of 4-5 MtCO_2 per year from 2050 onwards (see also Section 2.3.2). Current policy signals suggest a preference or requirement for bilateral cooperation under Article 6.2 (*89*, *90*). This implies that international CDR sourcing would likely proceed through government-to-government agreements rather than through a multilateral market infrastructure (Article 6.4). Switzerland will have limited leverage over foreign market design as such. Instead, it can shape outcomes primarily through its own eligibility criteria and procurement or contracting choices. In practice, supply-side instrument design under Article 6 becomes largely a matter of contract and partnership design, negotiated with host countries that retain authority over project authorization and domestic value capture.

The feasibility of achieving net-negative emissions at scale is likely to depend on access to comparatively abundant and lower-cost removal potential outside Switzerland, in particular in the Global South. At the same time, there remains considerable uncertainty regarding the scale and composition of CDR supply that will materialize in the Global South. While nature-based removals, particularly in the land-use sector, may play a role[36], the availability of large volumes of engineered CDR beyond forestry remains uncertain, given constraints related to infrastructure, finance, governance capacity, and competing development priorities (*91*).

[36] Such international nature-based removals are not eligible for compliance with the Swiss climate target under the current Swiss regulatory framework. Article 6 credits are presently used primarily within the compensation obligation for transport fuel importers, who may surrender "international attestations" as defined in the CO_2 Ordinance. Annex 2a of the Ordinance explicitly excludes nature-based solutions from abroad. See: https://www.fedlex.admin.ch/eli/cc/2012/856/de#annex_2_a/lvl_u1

4.5 Lessons learned from nuclear waste management

This section examines nuclear decommissioning and radioactive waste management (RWM) drawing primarily on the 2021 joint report by the Nuclear Energy Agency (NEA) and the OECD (*92*). The report evaluates recent developments in funding and governance frameworks based on twelve detailed country case studies: Belgium, Canada, Finland, France, Germany, Japan, Korea, Spain, Sweden, Switzerland, the United Kingdom, and the United States. The present assessment does not claim to provide a comprehensive or legally exhaustive account of national arrangements. Rather, it offers a structured overview of governance and funding features that are particularly relevant for drawing analogies and lessons for CDR. Readers are invited to draw parallels between the governance approaches discussed for radioactive waste and those considered for CO_2, even where these similarities are not explicitly highlighted throughout the text.

Governance and funding arrangements for decommissioning and RWM are considerably more mature than those currently emerging for CDR. Hence, the nuclear sector offers a uniquely rich empirical base which should be further researched to draw conclusions for the provision of CDR. Like CDR, it needs to confront long time horizons and intergenerational obligations, deep cost uncertainty, legal and regulatory uncertainty, uncertainty about future social preferences, including evolving standards of safety and environmental protection. Moreover, the operator structures most responsible for generating the respective waste streams – large energy utilities, fossil fuel producers, and other major industrial actors – are broadly comparable across the two cases.

As many nuclear facilities reach the end of their operational lifetimes, the policy debate in the nuclear energy sector is shifting from a context in which decommissioning and RWM were perceived as distant and somewhat abstract contingencies (like net-negative emissions might be perceived today) to one in which financial provisions and governance structures must become concretely operational. The nuclear sector demonstrates how such a transition can be institutionalized through liability allocation, fund design, and regulatory oversight.

In NEA/OECD countries RWM and nuclear decommissioning are broadly structured around the PPP, coupled with an understanding that current generations should not leave unfunded liabilities to future generations. However, the operationalization of this principle depends critically on whether the polluter is technically and financially capable of managing the relevant risks. This distinction becomes central when differentiating decommissioning from RWM.

Decommissioning is not yet a fully standardized industrial activity, but it is rapidly becoming one. Several characteristics support allocating operational and financial responsibility primarily to operators:

- The required skill sets, risk profiles, and timeframes broadly match the competencies and risk-management capacities of operators and their shareholders.
- The legal obligation – typically a return to greenfield status – is well defined and relatively stable from a regulatory / legal perspective.
- Cost estimation methodologies are increasingly codified, benchmarks exist, and practical experience is accumulating.
- In the United States, a secondary market for decommissioning liabilities has emerged, indicating increasing industrialization and transferability of obligations.

Where technical solutions are well specified and timeframes align with project lifecycles, liabilities and their adequate funding can credibly remain with industrial enterprises.

Because of the nature of high-level waste, such as spent nuclear fuels, RWM presents a qualitatively different challenge:

- Time horizons extend over centuries or longer.
- Technological options are more varied and site-specific.
- Costs depend on country context, geology, and political choices.
- Legal and regulatory frameworks may evolve discontinuously.
- Social preferences regarding disposal pathways may change.

These features create a condition of uncertainty that cannot be fully diversified or hedged by private actors. RWM is therefore not akin to traditional project finance but rather a dynamic societal process requiring iterative adjustments. Residual, non-diversifiable risks necessitate some form of public participation.

If uncertainties are not explicitly managed, they risk becoming implicitly mutualized through bankruptcy or funding shortfalls – typically at higher cost to society. Economic theory would therefore suggest integrating the definition of final objectives, technical solutions, funding, and possibly implementation under a single responsible actor. In practice, national governments are often the only entities with sufficient credibility and longevity to oversee such open-ended processes.

In many countries, funds for RWM and the operational responsibility to deliver RWM are held by public or quasi-public institutions capable of managing substantial residual risks. Where social preferences, technical solutions, and cost profiles become sufficiently specified, more decentralized and/or market-oriented incentive structures could be envisioned.

4.5.1 Design elements of national approaches to RWM and decommissioning

Governance structures for RWM and nuclear decommissioning differ significantly across countries and are often institutionally complex. Divergence begins with the recognition and classification of different waste types and treatment pathways (e.g., reprocessing, on-site storage, interim storage facilities, geological disposal), and extends to the allocation of responsibilities along the waste management chain. National approaches vary along several core dimensions:

- Operational responsibility for RWM and decommissioning
- Location and management of funds
- Mechanisms to ensure funding adequacy
- Timing and conditions under which liabilities transfer from operators to public entities
- Number and robustness of *lines of defense* to enforce residual liabilities

4.5.1.1 Decommissioning fund management and operational execution

Operational responsibility for decommissioning is typically decentralized, residing at the operator level. This is the case in 11 out of the 12 national case studies, see Table 5. However, fund adequacy is usually subject to close regulatory monitoring, and only in 6 of the national case studies are funds also held at the operator level.

The role of the public authorities is to ensure that adequate financial provisions are in place and remain available, including in scenarios involving operator insolvency or default. Mechanisms include (see Table 5):

- Internal but segregated funds outside administrative control of the operator
- Internal balance sheet provisions
- Centralized funds outside operator control

These arrangements differ in their robustness against insolvency risk.

4.5.1.2 RWM fund management and operational execution

Managing RWM funds in accordance with an investment mandate is institutionally distinct from carrying out RWM activities. However, RWM is mostly centralized, involving significant public-sector participation. In most cases, funds are transferred to some form of public entity, although in certain jurisdictions the fund and/or disposal entity may be partly or entirely owned by operators (e.g., in Belgium, Canada, Finland, Sweden and Switzerland).

Funds are often located at – or institutionally close to – the entity responsible for operational implementation. Aligning fund management with operational responsibility may be advantageous, as cost estimates generated through operations directly inform funding adequacy assessments. However, this alignment is not universal.

Crucially, having RWM centralized and publicly supervised does not mean that all liabilities are transitioned to the public sector (which is important with respect to the tax-fund-approach sketched out in Section 4.3.2.1). Moreover, if funds are indeed held by public entities, such funds are in most jurisdictions segregated from state budgets, to avoid diversion for other purposes. In fact, in many jurisdictions (1) operators make contributions to a public fund (or to an operator-owned fund under state supervision); (2) contributions are regularly adjusted in line with updated cost estimates and risk assessments; (3) an entity closely linked to the fund, and possessing technical expertise regarding required financing levels, is tasked to carry out disposal activities; (4) operators remain liable for residual risks, meaning that funding gaps can be recovered from them if necessary.

In Germany, Spain, and the United States, RWM responsibility is largely or entirely transferred to the state, including residual risks. Legacy waste from Sellafield operations in the UK is also publicly funded. Some of these arrangements illustrate potential governance weaknesses:

- In Germany all liabilities were transferred to the state in exchange for a one-time payment including a risk premium. This model implicitly assumes that all costs and risks can be priced ex ante – an assumption that is debatable. The reform was likely a response to weaknesses in the previous RWM system.
- In the United States, since 1998 the Department of Energy (DOE) has been legally obligated to begin accepting nuclear waste for disposal. The absence of a deep geological repository has prevented DOE from fulfilling this obligation. Utilities successfully sued the DOE and have received compensation. The nuclear waste fee was subsequently set to zero.
- In the UK the century-scale cleanup program for the Sellafield operations, financed through public expenditure, has experienced persistent delays, cost escalation, and slower-than-anticipated risk reduction. Oversight bodies have repeatedly questioned value-for-money and delivery performance.

4.5.1.3 Ownership structures

Ownership of waste has significant implications for how residual liabilities are allocated and managed. If ownership remains with operators, both their ownership structures and the legal arrangements governing shareholder liability become critical – particularly with respect to the enforceability of residual risk claims. State ownership of operators may be especially consequential in this regard.

In several jurisdictions, ownership of waste is explicitly transferred to and assumed by the state, at least following approved disposal. This applies, for example, in Finland, United States, United Kingdom, Spain, and Germany. By contrast, other countries maintain operator ownership of the waste or residual financial liability even after disposal, such as France or Belgium. In some jurisdictions, the state holds significant equity stakes in nuclear operators (e.g., South Korea, France, and parts of Canada). In others, foreign states are major shareholders – for example in Belgium and the United Kingdom, where the French state holds substantial ownership interests in operating companies.

4.5.2 Managing fund adequacy

Fund adequacy for RWM depends on several dimensions:

4.5.2.1 Investment mandate

Historically, RWM funds were managed conservatively – often held in escrow accounts at finance ministries or invested in national government bonds. Low-interest rate environments some years ago prompted many countries to broaden permissible asset classes to include equities, real estate, and in some cases private equity. This increases return potential but also risk exposure, raising governance and oversight challenges.

4.5.2.2 Credibility of cost estimates

Key factors include:

- Frequency of cost estimate revisions
- Regulatory treatment of discount rates
- Treatment of uncertainty and risk margins
- Credibility of cost estimation methodologies
- Credibility of underlying RWM programs

Earlier funding models often relied on discounting highly uncertain future liabilities using social discount rates with weak conceptual foundations. Contemporary systems increasingly employ risk-adjusted cost estimates and more realistic assumptions. However, more realistic cost assessments may render operations unprofitable. In Sweden, stricter funding requirements contributed to plant shutdowns, illustrating a potential negative feedback loop (particularly relevant for CDR): higher funding requirements reduce profitability, which in turn reduces funding streams.

4.5.2.3 Competence to collect funds and lines of defense

Funding adequacy further depends on the mechanisms for RWM fee collection, the authority to adjust contributions, and the safeguards in place should operators cease to exist.

For example, in Spain, the organization responsible for RWM and decommissioning, Enresa, does not have the authority to adjust RWM fees. The NEA review identified a funding gap and warned that, absent corrective measures, the shortfall could ultimately fall on taxpayers.

By contrast, in Belgium, where payments from the operator-owned RWM fund are transferred to the public RWM entity upon transfer of the waste, the disposal organization explicitly retains the competence to recover additional funding from nuclear operators even after waste transfer. This preserves a legal claim against operators in the event of cost increases. More broadly, jurisdictions implement different lines of defense to reduce the probability that residual liabilities are socialized. For instance, Sweden requires financial guarantees covering both cost escalation and default risks. Germany has parent or shareholder liability for decommissioning under default. Switzerland applies a collective responsibility principle, under which all contributors to the fund are required to provide proportional supplementary payments if one contributor cannot meet its obligations. Such institutional safeguards can materially strengthen the resilience of funding frameworks against insolvency and cost uncertainty.

4.5.3 Implications for CDR

Two fundamental differences distinguish CDR from nuclear back-end liabilities:

- Postponement option: In the nuclear sector, interim storage can defer final disposal, reducing present-value costs through discounting and, potentially, technological progress. For CDR, postponement increases cumulative climate impacts; delay thus substantially increases social costs.
- Scale: The scale of CO_2 removal required across the global economy far exceeds that of nuclear waste management. This disparity holds both at the operator level – when comparing waste management costs per unit of final energy produced from fossil fuels versus nuclear energy – and at the system level, given the dominant role of fossil energy in the global energy mix relative to nuclear power. Consequently, funding inadequacies in large-scale carbon management systems would arise at a magnitude that cannot easily be absorbed or backstopped through public budgets alone.

4.5.3.1 Who is best suited to handle CDR?

According to the *subsidiarity principle*, and as argued in the NEA report, a task should be assigned to the lowest – or most decentralized – level of governance capable of addressing it effectively; higher levels should intervene only where lower levels lack the necessary capacity. In the case of CDR, however, it is not self-evident which actors are best equipped to assume operational and financial responsibility. The answer depends on scale, duration, country-specific policy preferences, technological maturity, and the risk profile of the respective approach.

Substantial expertise already exists in conventional CDR activities, such as afforestation and reforestation. Nonetheless, material challenges remain in MRV, as well as in ensuring and incentivizing permanence. This segment of the AFOLU sector could plausibly be tasked with managing emissions from land-use change, consistent with a *like-for-like* principle (*93*).

Pilot projects involving permanent geological CO_2 storage demonstrate technical feasibility and provide preliminary cost benchmarks. Fossil fuel firms possess relevant expertise in CO_2 injection operations and subsurface reservoir management, suggesting they could credibly assume responsibility for the back-end of carbon waste management (*67*). However, many countries – including Switzerland – are importers of fossil fuels and therefore have limited jurisdiction over upstream producers. In addition, scaling uncertainties remain profound. Novel CDR currently accounts for only a small fraction of the volumes required, and aggregate deployment remains far below pathways consistent with the Paris Agreement (*56*).

If CDR were fully internalized within firms' abatement portfolios, liabilities could be allocated on a ton-by-ton basis. Emitters or fossil fuel producers would then optimize between emission reductions and removals within a market framework. Much of the literature – including in part the stylized proposals discussed in Section 4.3.2 – assumes or explores fungibility between standardized removal units and emissions, anticipating markets in which firms internalize the trade-off between "abate now" and "emit now and remove later."

By contrast, if CDR is conceptualized in analogy to radioactive waste management (RWM), the central objective shifts to *cumulative funding adequacy* – that is, ensuring that sufficient resources are available to remove the entire stock of anthropogenic GHGs accumulated in the atmosphere from a defined point onward and attributable to a specific country or firm, without necessarily pricing each ton of CO_2 at its discounted future removal cost.

Such a framework would likely rest on centralized operational responsibility combined with robust public oversight. Importantly, such a "public waste management" model need not imply taxpayer financing. Rather, it denotes centralized coordination under strong public oversight, ideally combined with enforceable mechanisms to recover residual liabilities from emitters or fossil fuel firms wherever such contributions remain feasible. At the same time, the circle of entities contributing to funding adequacy could extend beyond emitters or fossil fuel firms, thereby placing the financing of net-negative emissions on a broader base.

Given the current state of the CDR ecosystem (see Section 4.3.1.1), the field more closely resembles the RWM paradigm – characterized by deep uncertainty, long time horizons, and significant coordination requirements. Moreover, sourcing CDR through government-to-government agreements under Article 6.2, as discussed in Section 4.4.2.4, shifts responsibility away from individual operators toward states, thereby reallocating accountability and risk-bearing capacity to the sovereign level. Over time, as technologies mature, standards stabilize, and cost trajectories become more predictable, CDR may evolve toward a decommissioning-like industrial activity with decentralized liability structures and more routinized financial governance.

Table 5: Operational responsibility and the location of funds for radioactive waste management (RWM) and decommissioning in selected jurisdictions. The table identifies three broad governance constellations: (1) centralized arrangements with operator ownership or joint structures (green); (2) centralized arrangements with stronger public ownership or control (blue); and (3) decentralized, operator-managed systems (red). The categorization is necessarily stylized. In practice, distinctions are not always clear-cut, and the assessment is based solely on the descriptions provided in the 2021 NEA/OECD report, without undertaking an in-depth review of national governance frameworks beyond the case studies as presented in the report. Where multiple arrangements exist for different types of waste or waste-treatment, RWM classifications generally refer to final disposal of spent nuclear fuel. While financial responsibility rests with operators across all jurisdictions, in some cases – notably Germany – liability for residual risks are transferred to the state. The allocation of residual liability is not assessed in this table.

Centralized, (partially) operator controlled	Centralized, public control	Decentralized, operator control

Country	Radioactive Waste Management (RWM)		Decommissioning	
	Operational responsibility	Location of funds	Operational responsibility	Location of funds
Belgium	National agency	Legal entity owned by the operators with the Belgian government having a "golden share"	Operators	Same as RWM
Canada	Nuclear waste management organization created by operators	Independently managed third-party fund maintained by the waste management organization	Operators	Operator-internal segregated funds

Table 5: continued.

Centralized, (partially) operator controlled	Centralized, public control	Decentralized, operator control

Country	Radioactive Waste Management (RWM)		Decommissioning	
	Operational responsibility	Location of funds	Operational responsibility	Location of funds
Finland	Joint venture of operators	Special-purpose fund under ministerial administration, but separate from the state budget	Operators	Same as RWM
France	National agency for RWM	Operator-internal segregated funds	Operators	Same as RWM
Germany	Federal company for radioactive waste disposal	Public external fund	Operators	Internal provisions on company balance sheets
Japan	Nuclear waste management organization	Government-authorized statutory body managing the fund	Operators	Internal provisions on company balance sheets
Korea	Public not-for-profit corporation	Segregated public fund managed by organization with operational responsibility	Operators	Internal provisions on company balance sheets
Spain	State-owned company	Public fund managed by organization with operational responsibility	Same as RWM	Same as RWM
Sweden	Entity jointly founded and owned by operators	Segregated public fund overseen by government	Operators	Same as RWM
Switzerland	Joint initiative by operators and Swiss confederation	Segregated public fund supervised by Confederation	Operators	Same as RWM
UK	Different arrangements for different operators (legacy, EDF, new build)	Different arrangements for different operators (legacy, EDF, new build))	Different arrangements for different operators (legacy, EDF, new build)	Different arrangements for different operators (legacy, EDF, new build)
US	Federal government	Public fund	Operators	Operator trusts held outside of their administrative control

5 Synthesis

5.1 Key conclusions

This report was prepared to support Switzerland's legally anchored but operationally under-specified transition to net-negative GHG emissions in the second half of the century. Four overarching conclusions emerge.

1. Setting a net-negative greenhouse gas emission target

- For Switzerland, almost any carbon budget allocation that reflects common global equity principles (especially considering financial capacity) and that is consistent with a temperature limit of well below 2°C, let alone 1.5°C, implies that net-zero emissions should be reached sooner than 2050. For some weightings of capacity and responsibility principles, the net-zero date would even be set in the past.

- These conclusions are strengthened if Swiss emissions are counted on a consumption-basis rather than only territorial emissions, given that consumption-based emissions for Switzerland significantly exceed territorial emissions.

- This implies that if equity principles are used as guide, Switzerland will have more than exhausted its "fair share" allocation by 2050 and, if it wishes to support a return of global warming to 1.5°C, would need to reverse some of the warming its past emissions have caused already and additional warming caused by emissions up to 2050. Other considerations about path-dependency, leakage etc. may modify these conclusions but are unlikely to change them fundamentally.

- Equity principles allow a wide range of different interpretations and make it challenging to derive specific post-2050 targets for net-negative emissions based purely on global carbon budgets and equity principles. A more pragmatic way of setting a quantified target beyond 2050 would be for Switzerland to set unconditional contributions that would be expected to be scaled reciprocally by the size of economy within OECD countries or wider groups of countries. These targets should be based on feasibility, i.e., sustained for decades or longer, and coordinated with similar countries.

- Two complementary benchmarks illustrate the range of plausible ambition.

  - First, a conservative extrapolation of the Swiss EP-2050+ scenario – combining continued reductions in residual emissions with a gradual scale-up of CCS and CDR (see Section 2.3.2) – yields a net-negative GHG target of around **10 Mt CO_2-eq by 2060**. Even under a large coalition of countries replicating Swiss ambition within the framework introduced in Section 2.3.3, this level would represent an insufficient contribution to the global removal burden.

  - Second, a more ambitious net-negative target of roughly **20 Mt CO_2-eq by 2060** can be interpreted as a credible replication of Denmark's net-negative ambition under the proposed framework. Under a sufficiently large coalition of countries adopting comparable reciprocal targets, such an ambition would exceed removals in about 50% of global mitigation scenarios assessed. Requiring this fraction to increase to 83% would lead to a target of roughly **35 Mt CO_2-eq by 2060.**

- For these targets, it is assumed that net-negative emissions would be sustained and, where necessary, further scaled up through at least the end of the 21st century (and likely beyond), contingent on the evolution of global efforts and international agreements.

2. Minimizing residual emissions is a key element for reaching net-negative emissions

The ability to achieve net-negative GHG emissions depends not only on the availability of CDR at scale, but also on policies to minimize residual emissions. Current projections imply residual territorial emissions in 2050, after including CCS for energy and process emissions in the cement and chemical industries, of more than 8 Mt CO_2-eq per year. These residual emissions will need to be compensated by CDR even just to reach and maintain net-zero GHG emissions. Further reductions in residual emissions directly reduce the required scale of CDR for any given net-negative target, lowering CDR costs and risks and easing governance and financing challenges.

Reducing residual emissions, potentially far beyond the level they are currently envisaged to reach in 2050, is therefore a critical component of the ability to sustain CDR volumes needed for net-negative emissions at scale for many decades. This may require targeted policies to address residual emissions, which could encompass improved material efficiency, new technologies and demand-side and structural changes, mainly in the agriculture and parts of the energy and industry sectors. The detailed design of such policies is beyond the scope of this work.

3. Purely contemporaneous incentives or obligations for CDR are unlikely to support sustained net-negative emissions

Policy designs that rely on post-2050 public budgets or on regulatory incentives (such as emissions trading systems or explicit mandates imposed on the private sector) to finance and deliver net-negative emissions are unlikely to be consistent with general public policy principles. Approaches that depend primarily on future public spending raise concerns about long-term fiscal sustainability. By contrast, polluter-financed instruments to drive net-negative emissions at national scale become structurally fragile as net emissions reach zero, because they would rely on a shrinking pool of residual emitters. Such a shrinking pool may not be able or willing to carry the financial burden of delivering net-negative emissions. Some policy designs could even incentivize higher residual emissions in order to preserve a revenue base, directly conflicting with the objective of minimizing residual emissions.

These constraints imply that net-negative emissions are more likely to be achieved through intertemporal policy instruments, i.e. where both public and private financial resources and clearly documented private sector obligations accrue over time, starting well before 2050, to reach a point where CDR exceeds residual emissions beyond 2050.

Intertemporal approaches have the key advantage that they can draw on today's broader base of emitters or fossil fuel importers. This base will shrink as net-zero approaches and, consistent with the principle of avoiding retroactive liability, past emissions cannot easily serve as the legal anchor for future obligations. Timely development of more detailed policy approaches, including clearly set out principles and resulting current and future expectations and obligations, are likely to be critical for enabling a robust path into net-negative emissions.

4. Nuclear waste disposal frameworks offer a valuable reference for "carbon waste governance"

Nuclear waste policy is instructive because it is designed to operate under deep uncertainty in costs and over very long time horizons. Its central objective is funding adequacy, and several core design features could translate to the governance of net-negative emissions:

- Responsibility remains with operators, backed by multiple lines of defense. Among the national case studies reviewed in this report, liability for waste management typically remains with operators, minimizing the risk that costs and delivery failures are shifted to the state. This experience is particularly relevant when assessing the "tax-fund" proposal, discussed in Section 4.3.2.1, that implies full liability transfer to the public sector.

- Cost estimates and contributions are regularly updated. Nuclear waste regimes rely on iterative re-estimation of costs and corresponding adjustments in required contributions. This logic is closely aligned with the proposal discussed in Section 4.3.2.3 which implies that even funding for the removal of past emissions (covered by the policy) can be recalibrated over time without triggering issues of retroactive liability.

- Residual risks are addressed through assurance mechanisms. Because funding adequacy cannot be guaranteed ex ante, collateral and other assurance mechanisms are used to manage default risk. Importantly, these mechanisms need not rely solely on cash deposits and can be structured to limit disruption to operators' ongoing activities.

- Credibility depends on fund location and protection. Funds may either remain with the operator (subject to assurance requirements or separation from operators' balance sheets) or be pooled centrally to enable coordinated deployment. In the latter case, credibility hinges on:
    - robust ring-fencing from general public budgets and protection against diversion over political cycles,
    - a narrow and clearly defined purpose and investment mandate, and
    - a delivery-oriented mission (experience in the UK and the US, discussed in Section 4.5 shows that the mere creation of a public fund does not guarantee effective implementation).

At the same time, carbon waste management differs from nuclear waste management in three important respects:

- Scale and macroeconomic risk. Carbon waste management is likely to be far more costly and involves a much larger set of obligated entities, requiring careful management of system-level risks and macroeconomic oversight. Unlike in RWM, final disposal of CO_2 can not easily be delayed as a cost-saving measure, as this would increase climate related risks.

- Parallel incentives to reduce residual emissions. Residual emissions should be reduced as much as possible. Obligations to finance or deliver removals increase the cost of emitting and therefore further discourage emissions. This linkage does not exist in the nuclear case (or at least it is not intended), where waste management is not meant to disincentivize production or transition production towards an alternative.

- Producer responsibility, as in the case of nuclear power operators, is not the only plausible policy principle by which to allocate the burden for net-negative emissions; capacity to finance CDR, regardless of the past or present amount of "carbon waste" produced by an operator, is also a valid and potentially necessary approach to ensure a sufficiently broad base for net-negative policies.

5.2 A possible way forward

5.2.1 Tensions between objectives and the current policy context

Designing a path forward will need to reconcile two realities. On the one hand, our analysis suggests that intertemporal instruments are needed, with clear obligations and expectations set out as soon as possible. On the other hand, CDR costs and scalability remain highly uncertain, making it unrealistic to expect obligated private sector entities to form reliable expectations about future removal costs, and linking these expectations to decisions about the timing and form of mitigation (emission reduction and removal). Internalizing "carbon waste management" into firms' operational decisions in a manner that grants extensive discretion – i.e., requiring firms to form expectations about future removal costs, to choose between near-term emission reductions and later removals, and to determine the timing of removals – can deliver the "correct" incentives for emission reductions and investment in CDR capacity only under highly idealized assumptions. In practice, while such conditions may evolve over time, they are unlikely to hold now given the current state of the CDR ecosystem.

This leaves two broad policy options, at least initially. The first is support internalization of CDR into firms' abatement portfolios by constraining their discretion and explicitly specifying, through regulation, the removal cost assumptions – and, where relevant, delivery timelines – that must be used for compliance decisions, for example under a tax-fund approach or standardized collateral requirements under an ETS-based removal obligation (as discussed in Section 4.3.2). Under such approaches, part of the cost and delivery uncertainty associated with future removals would necessarily be absorbed by the public sector if realized costs exceed the regulated benchmark. The second option, in line with governance approaches of radioactive waste management (as discussed in Section 4.5), is to prioritize *cumulative funding adequacy* to achieve national removal targets, rather than implementing a *ton-by-ton* linkage. This would initially maintain existing instruments for driving decarbonization (such as the ETS) as the primary mechanism for emission reductions, while addressing CDR separately through mechanisms that allocate the associated costs and liabilities across polluters and other actors in the economy.

5.2.2 Accounting for policy path-dependency

The stylized approaches discussed in Section 4.3.2 outline policy design directions for achieving net-negative emissions, conditional on the emergence of a sufficiently mature CDR ecosystem. However, policy design is inherently path-dependent. In the near-term, instruments for net-negative emissions will therefore need to build on existing governance structures, including the Swiss ETS, the CO_2 levy on fossil thermal fuels, and the mineral oil tax.

In principle, integrating intertemporal elements into the Swiss ETS – along the lines of an ETS-based removal obligation (Section 4.3.2.2) – could provide information about market expectations and confidence in CDR. In practice, however, such signals are unlikely to be reliable at the moment. Most ETS-regulated entities currently have limited expertise in CDR, and the system would be vulnerable to strategic behavior, coordination problems, or collective misjudgment. Moreover, an ETS without intertemporal obligations is almost by definition unable to deliver sustained net-negative emissions.

At the same time, approximately three quarters of Swiss GHG emissions are already covered by the ETS, the CO_2 levy, or the mineral oil tax. In other words, a large fraction of emissions is already priced, and polluters already pay to a significant extent under the current policy architecture. A pragmatic starting point that builds on these existing instruments would therefore be to hypothecate a share of government revenues into a dedicated CDR fund, analogous to nuclear waste management funds and taking into account the lessons learned from the field (see Section 4.5).

To illustrate the intertemporal potential of such an approach, consider the average ETS price of approximately CHF 60/tCO_2 in 2024. Assuming annual real returns of 1%, 3%, or 5%, the purchasing power per priced ton would increase to approximately[37]:

- After 20 years: ~CHF 75, 110, or 160
- After 30 years: ~CHF 80, 145, or 260
- After 40 years: ~CHF 90, 195, or 420
- After 50 years: ~CHF 100, 260, or 690

For comparison, the purchasing power associated with the CO_2 levy – currently CHF 120/tCO_2 – would be roughly twice as high. On a per-ton basis, such amounts could be sufficient to finance CDR in the future. Whether they are in fact adequate depends on several factors, including (i) the coverage of emission pricing, (ii) future carbon price levels, (iii) the costs of CDR technologies, and (iv) competing claims on earmarked revenues.

Importantly, future ETS prices will themselves depend on whether and how CDR is integrated into the system, and on which types of removals are deemed eligible – an issue on which the literature offers a wide range of perspectives[38].

At present, ETS auction revenues are already earmarked for emission-reduction measures benefiting ETS-covered entities. While the majority of CO_2 levy revenues are redistributed, a significant share is already used to reduce emissions in buildings, support renewable energy, and promote innovation. By analogy, a dedicated share of these revenues could be earmarked for financing net-negative emissions.

Consistent with nuclear waste governance in countries such as Sweden and Finland, a robust architecture could combine a central CDR fund – initially capitalized through revenues from carbon pricing but potentially supplemented by other funding sources not directly linked to emissions – with residual liability remaining with emitters or importers of fossil fuels, for example following the approach in Section 4.3.2.3[39]. This residual liability would primarily serve as a legal anchor, preserving the ability to mobilize additional contributions from polluters in the future when justified – both in proportion to their contribution to pollution and their capacity to pay – rather than functioning as the main mechanism for CDR financing. In other words, it ensures that, should additional funding needs arise in the future, further contributions can be levied on a sound legal basis, without running into issues of retroactive liability. As additional external funding enters the system and as upfront carbon price-based contributions increase, the residual risk borne by firms correspondingly declines.

The fund could emphasize public-utility provision of CDR, e.g., potentially similar to how vertically integrated energy utilities were structured in Europe and elsewhere over

[37] These time horizons correspond to typical maturities discussed for intertemporal approaches (see Figure 7).
[38] Recent policy developments in the EU and the UK point toward concrete steps in this direction, and it is assumed that Switzerland will adopt a similar approach, as an ETS with caps declining to zero but without provisions for residual emissions would risk becoming non-functional.
[39] For the ETS, this additional layer of assurance would imply a shift in the legal interpretation of emission allowances. While allowances would continue to function as regulatory instruments to steer the emissions trajectory and generate revenues, they would no longer constitute a full legal discharge of responsibility for the associated carbon once surrendered.

decades. Alternatively, or additionally, it could focus on strategic procurement and market-building, including standardization, competitive tenders, and exchange-based trading and thus contribute to the development of a system where the CDR option can be fully internalized by emitters or other responsible entities. The appropriate balance depends, among other things, on the future CDR portfolio, the scope of international sourcing under Article 6 of the Paris Agreement, and the extent to which certain technologies require coordinated investments along the value chain (from capture to transport and injection and storage), parts of which might exhibit natural-monopoly characteristics.

5.2.3 Improving adequacy of the fund

The fund's adequacy for financing removals at the required scale can be improved by reducing effective removal costs and by adding other funding sources.

Reducing effective removal costs, i.e., the costs paid by obligated entities for removals, involves not only technological progress but also managing rents potentially captured by the CDR sector. Options to reduce these costs include:

- Innovation support for cost reduction, potentially sitting within the fund's mandate.
- International agreements for CDR supply under Paris Agreement Article 6 (see Section 4.4.2.4).
- Rent management options, including claw backs, technology-specific tenders, and public-utility provision (as discussed in Section 4.4.2).

If rent limits reduce investment incentives, this can be partially offset by raising certainty: long-term offtake contracts, CfDs, and credible years-in-advance announcements of volumes, timing, and procurement channels.

Supplementary funding sources could reinforce the revenue base while serving broader objectives:

- CBAM-type mechanisms. These mechanisms would address competitiveness concerns and carbon leakage, while also creating incentives for other jurisdictions to introduce or strengthen carbon pricing.
- Fossil fuel import tariffs. Such tariffs would likely require a coalition of major importing jurisdictions (for example, the EU in combination with China). Beyond their revenue potential, they could reduce strategic dependence on fossil fuel imports and shift economic rents away from geopolitically adverse suppliers.
- Consumption-based contributions, with larger participation from top income households or as part of company tax. This would provide flexibility regarding the extent to which such contributions are intended to reflect actual or imputed emissions based on income or revenue, or simply draw on the financial capacity of high-income earners and companies to support a public good outcome.

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7 Annexes

Annex 1 – Estimation of Switzerland's contribution to global warming

This analysis estimates the contribution of Switzerland's territorial GHG emissions to global mean temperature change over the period 1850–2100, under a stylized scenario in which Switzerland follows the balanced net-zero pathway to 2050 and maintains net-zero GHG emissions thereafter.

Historical greenhouse gas emissions excluding land use, land-use change and forestry (LULUCF) until 1990 are taken from the PRIMAP emissions database (*1, 2*), while emissions from 1990 onward are consistent with Switzerland's national greenhouse gas inventory. Historical national LULUCF emissions are taken from the Global Carbon Project dataset (*3*), using the mean estimate across available bookkeeping models.

Emissions for the period 2025–2050 follow the emissions trajectories associated with Switzerland's long term climate strategy. Based on the interpretation that Switzerland does not intend to rely on LULUCF removals to achieve its net-zero target, future LULUCF emissions are set to zero.

For the period after 2050, emissions are assumed to remain at net-zero. This is implemented by holding non-CO_2 emissions constant at their 2050 levels and adjusting CO_2 removals such that total net GHG emissions remain equal to zero. The resulting trajectory therefore represents a stylized counterfactual in which Switzerland reaches net-zero emissions by 2050 and maintains the same balance of net-zero GHG emissions from 2050–2100, rather than transitioning to net-negative emissions (see Figure A1).

Temperature impacts are calculated using the FaIR simple climate model (*4*), calibrated to reproduce the climate response to emissions assessed in IPCC AR6 (*5*). Global background emissions follow the SSP1-2.6 pathway.

Under these assumptions, Switzerland's contribution to global mean temperature change peaks at just under approximately 2.1 mK and declines slightly to just above 2.0 mK by 2100 (see Figure A1). To express this result in per-capita equivalent terms, the modelled warming contribution is scaled by a fixed factor of 910, reflecting Switzerland's share of the global population in 2020. Switzerland currently accounts for approximately 0.11% of the global population and is expected to represent somewhat less than 0.1% by mid-century.

Scaling the modelled warming contribution by a population share of 0.11% implies that if global warming were proportional to population-weighted national contributions and all countries caused warming at the same per-capita level as Switzerland, global warming would already be approximately 1.8°C today and would remain close to 2°C by 2100.

The estimated warming contribution would be somewhat lower if historical LULUCF emissions were excluded from the calculation.

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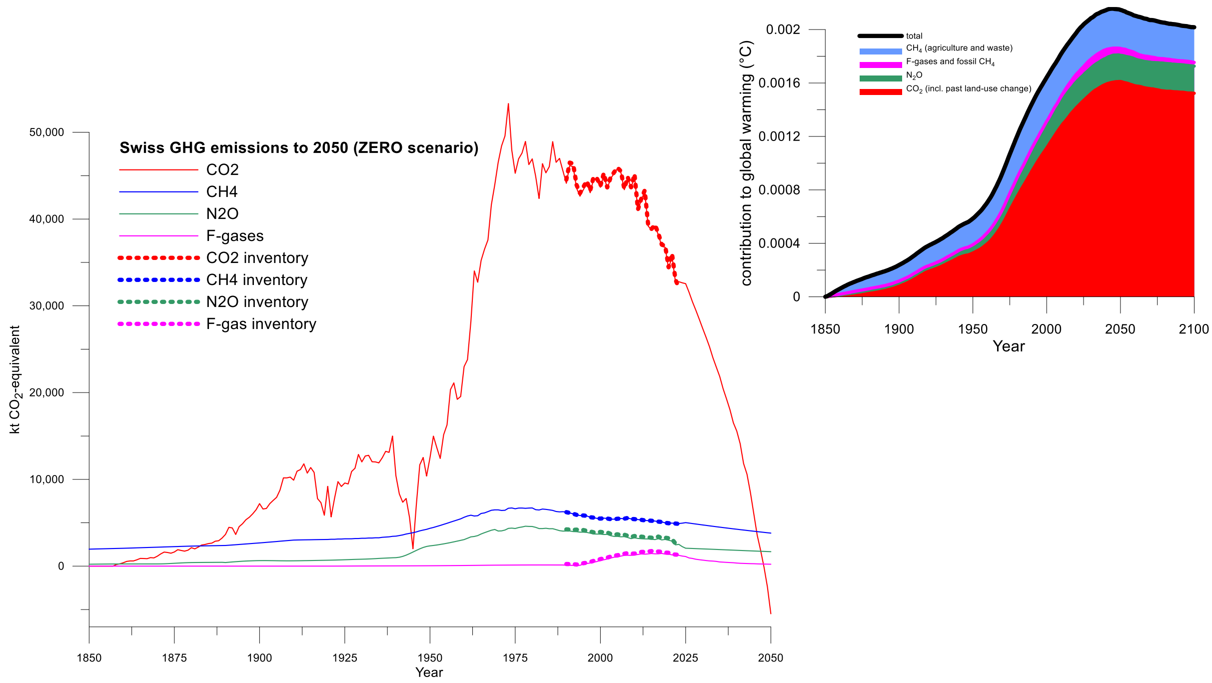

Figure A1. Swiss historical and projected future emissions to net-zero in 2050, and resulting contribution to global warming.

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Annex 2 – Gross removals benchmarking framework

The benchmarking framework for gross removals uses 1.5°C-compatible scenarios (C1 and C2) from the ENGAGE scenario database, which provides a set of relatively harmonized mitigation scenarios under an SSP2 narrative. Global CDR in ENGAGE includes removals from BECCS, DACCS, and the agriculture, forestry, and other land-use (AFOLU) sector. These components are aggregated to obtain a global gross CDR estimate for 2060 in each scenario.

Because AFOLU emissions are not reported separately as gross emissions and gross removals, negative net AFOLU emissions are used as a proxy for CDR. This introduces a downward bias, as gross removals from AFOLU are generally larger than the net values used here. In principle, net AFOLU emissions should not be aggregated with gross emissions or removals, but this approximation is necessary given the available reporting in the scenario database.

Consider a coalition of countries I that deploy carbon removals in a specified year. Countries outside the coalition are assumed to deploy no removals. Let y_i denote GDP of country $i \in I$ in a fixed reference year and x_i denote gross removals deployed by country i. Let X denote total removals deployed by the coalition.

Define GDP-based allocation weights

$$w_i = \frac{y_i}{\sum_{j \in I} y_j}, \qquad i \in I$$

so that $\sum_{i \in I} w_i = 1$.

Country-level removals are allocated proportionally to GDP:

$$x_i = w_i X, \qquad i \in I$$

which implies $\sum_{i \in I} x_i = X$.

Given global removals X, country-level removals are $x_i = w_i X = \frac{y_i}{\sum_{j \in I} y_j} X$. This is the equation used to derive the values in Table 2, where country i is Switzerland, and X is a selected quantile of the underlying distribution of global removals derived from the mitigation scenarios.

Likewise, global removals can be inferred from one country's removal target, being reciprocated by other countries within the coalition. Hence, given removals in country i, global removals are $X = \frac{x_i}{w_i} = x_i \frac{\sum_{j \in I} y_j}{y_i}$.

Finally, a removal target in one country i can be translated into a removals target in any other country j using ratio of respective national GDPs, i.e., $x_j = \frac{w_j}{w_i} x_i = \frac{y_j}{y_i} x_i$. This is the equation used to infer a possible Swiss removals target from the announced Danish ambition.

Denmark's 2050 target, a 110% cut in GHG emissions compared to 1990 levels, means net-negative emissions of ~7.8 Mt CO_2-eq. Accounting for projected residual emissions, total removals could reach ~16 Mt CO_2-eq annually by 2050 *(1)*. There is one complication: the Danish target is specified for 2050, whereas the Swiss target is considered for 2060. Rather than projecting what Danish removals might be in 2060 based on potentially rising deployment rates, we use Denmark's removals intensity with respect to GDP, defined as the ratio of gross removals to GDP, x_i^t / y_i^t, from 2050 to scale the Swiss target in 2060.

Formally, the assumption of constant removals intensity with respect to GDP is written as $\frac{x_d^{2050}}{y_d^{2050}} = \frac{x_d^{2060}}{y_d^{2060}}$, where indices d and s denote Denmark and Switzerland, respectively, while superscripts indicate the year. The implied

Swiss removals target in 2060 follows from the GDP-based allocation rule is therefore given by

$$x_s^{2060} = x_d^{2050} \frac{y_s^{2060}}{y_d^{2050}}.$$

Denmark's projected GDP in purchasing power parity (PPP) terms in 2050 amounts to USD 648 billion (2021 prices), while the corresponding projection for Switzerland equals USD 1,052 billion. Using these values yields implied Swiss gross removals of 26 Mt CO_2e in 2060, corresponding to the median of the distribution reported in Table 2.

GDP projections are from the OECD Economic Outlook long-term scenarios *(2)*. While the use of GDP-PPP in burden-sharing contexts remains debated *(3, 4)*, it is widely used as the default allocation basis *(5)*.

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