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DemoUpCARMA

WP4 – Upscaling potential of CCUS and CCTS chains and CO_2 network

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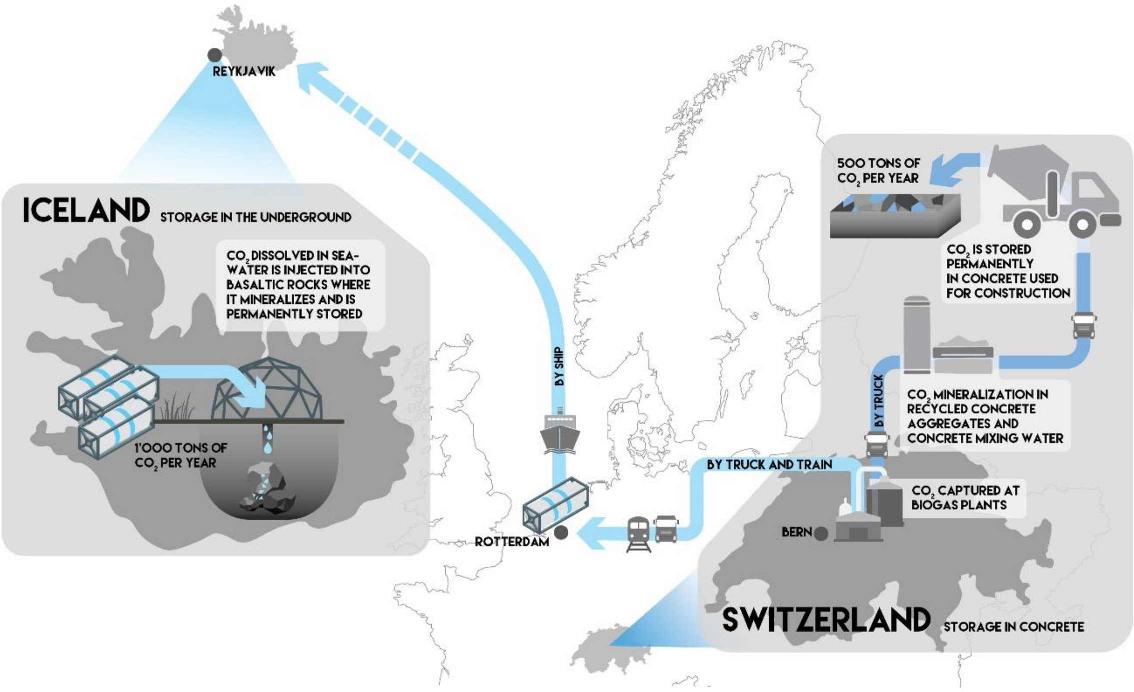

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Zusammenfassung

Das Ziel dieses Arbeitspakets ist es, zum einen das kurzfristige Skalierungspotenzial von CO_2 Capture-, Utilization- und Storage-Ketten (CCUS) und von CO_2 Capture-, Transport- und Storage-Ketten (CCTS) zu bewerten, und zum anderen das langfristige Potenzial eines CO_2-Netzwerks zu untersuchen, um Schweizer CO_2-Punktquellen mit nationalen und internationalen Speicherstandorten zu verbinden. Im Folgenden werden CO_2-Versorgungsketten, die CO_2-Capture und den Transport ins Ausland zur geologischen Speicherung beinhalten, als CCTS bezeichnet. CO_2-Versorgungsketten, die CO_2-Capture und -Utilization sowie die dauerhafte Speicherung in Beton durch Mineralisierung verfolgen, werden als CCUS bezeichnet.

Zunächst konzentrierten wir uns auf die Analyse einiger Schweizer Punktquellen-Emittenten, darunter die KVA-Hagenholz – eine Kehrichtverbrennungsanlage (KVA) in Zürich, Jura Zement – eine Zementproduktionsanlage in Wildegg, und die ARA Region Bern – eine Biogasaufbereitungsanlage, welche CCUS und CCTS in naher Zukunft, d.h. ab ca. 2030, zur Emissionsvermeidung einsetzen könnten. In dieser Arbeit wurde die gesamte CO_2-Versorgungskette betrachtet, von CO_2 Capture und Verflüssigung am Standort des Emittenten, über Transport bis hin zu Speicherung in Beton (inländische Lösung) oder in einem geologischen Reservoir in der Northern Lights Speicherstätte in Norwegen oder in isländischem Basalt durch die Carbfix-Technologie. Aufgrund des kurzfristigen Zeithorizonts wurde davon ausgegangen, dass diese Transportketten das CO_2 hauptsächlich auf dem Landweg per Lastkraftwagen und Zug transportieren werden. Als Folge davon machen die Transportkosten den größten Anteil von bis zu 60% für die Early-mover-Ketten aus, da solche multimodalen Transportlösungen für weite Entfernungen nicht von Skaleneffekten profitieren. Es wird jedoch erwartet, dass diese Kosten langfristig erheblich sinken werden, dank effizienterer Lösungen wie einem Pipeline-Netzwerk, was die Kosten der gesamten CCTS-Kette per vermiedenem CO_2 halbieren dürfte. Die Kosten sind unabhängig von der CO_2-Quelle und berücksichtigen CO_2-Reduktion und -Entfernung. Eine Ökobilanz (LCA) wurde ebenfalls durchgeführt und zeigt, dass alle Ketten das Treibhauspotenzial (GWI) des entsprechenden Emitters um mindestens 70% bis zu 85% reduzieren, da die Treibhausgasemissionen entlang der CCTS-Kette deutlich niedriger sind als die Menge an gespeichertem CO_2. Verglichen mit dem Betrieb ohne CO_2-Vermeidung, werden 70% bis 85% der Treibhausgase vermieden. Bei Emittenten mit biogenem Treibstoff entsteht ein Potential für netto CO_2-Entfernung falls die CO_2-Reduktion grösser ist als die biogenen Emissionen des Emittenten. Die größten Beiträge zum GWI stammen vom CO_2 Capture und Transport, deren Treibhausgasemissionen in Zukunft voraussichtlich abnehmen werden, insbesondere durch die Dekarbonisierung technischer Systeme im Transportbereich.

Im nächsten Schritt wurde ein Netzwerkmodell verwendet, um eine optimale CO_2-Netzwerkstruktur und Ausroll-Szenarien für den Übergang von Early-Mover-Ketten zu einem integrierten schweizerischen CCTS- und CCUS-Versorgungsnetzwerkes zu untersuchen, das mit einer europaweit gemeinsam genutzten Infrastruktur verbunden ist. Die Auswertung hat die hohe Unsicherheit hinsichtlich der Entwicklung und Zugänglichkeit einer solchen Infrastruktur hervorgehoben, sowie den Vorteil für schweizerische Akteure, frühzeitig mit der Entwicklung nationaler Infrastruktur zu beginnen, d.h., CO_2-Capture, Transport (unter Verwendung von Pipelines) und möglicherweise Speicherung. Die Analyse wurde auf andere Sektoren ausgeweitet, z.B. auf die Chemie-, Pharma- und Life-Sciences-Industrie. Ein solches Netzwerk wird Schweizer CO_2-Punktquellen bedienen und Direct Air Capture (DAC)-Einheiten umfassen, deren optimale Lage in Bezug auf verfügbare CO_2-Speicherzentren im Ausland untersucht wird.

Im Hinblick auf CCTS- und CCUS-Geschäftsmodelle wurde festgestellt, dass ihre Realisierbarkeit von folgenden Faktoren abhängt: (i) das regulatorische Umfeld, d. h. welche Industrien und welches CO_2 im schweizerischen Emissionshandelssystem (ETS) einbezogen sind, wann und wie das überarbeitete CO_2-Gesetz verabschiedet wird, welche Dynamik im freiwilligen Kohlenstoffmarkt (VCM) auftritt; (ii) die Gestaltung des Dekarbonisierungspfads, den Emittenten wählen, was unterschiedliche Risikoprofile und Kostenschätzungen beinhaltet; (iii) die Organisation und Verwaltung der Versorgungsketten, wobei entweder eine integrierte Capture-Anlage, die vom einzelnen Emittenten verwaltet wird, oder ein Capture-Cluster, das von einer Gruppe von Emittenten verwaltet wird, an einen oder mehrere Dritte gekoppelt werden, die mit dem Transport und der Speicherung beauftragt werden; (iv) die Unsicherheit hinsichtlich der Stabilität und Langlebigkeit von Einnahmen und Finanzierungsinstrumenten. Bei der Untersuchung der Widerstandsfähigkeit, d. h. der Möglichkeiten, den reduzierten Service oder dessen Fehlen zu minimieren, unterscheidet man zwischen kostengünstigen Lösungen (billiger) und umweltfreundlichen Lösungen (kostspieliger). Solche Lösungen existieren, obwohl die Widerstandsfähigkeit möglicherweise in einem so frühen Stadium der Entwicklung von CCTS-Ketten eine geringere Priorität hat als die Indikatoren, die sich aus TEA und LCA ergeben.

Schliesslich wurde die Integration von Punktquellen-CO_2-Capture in Kehrichtverbrennungsanlagen und Zementanlagen am Beispiel der KVA von ERZ in Hagenholz (Zürich) und des Zementwerks Jura in Wildegg (Aargau) evaluiert. Dies beinhaltet die Konzeption und Dimensionierung der CO_2-Capture-Anlagen, die für beide Standorte erforderlich sind, sowie die Durchführung einer techno-ökonomischen Analyse der Prozessintegration. Hierbei wurden diverse Restriktionen wie die Betriebsbedingungen der Anlagen, die Verfügbarkeit von Wärme, saisonale Energiebedarfe und räumliche Limitationen berücksichtigt. Für das Jura Zementwerk wurde der CO_2 Capsol EoP™ Prozess mit heißem Kaliumcarbonat als Lösungsmittel gewählt, der darauf ausgelegt ist, ausschließlich Elektrizität als Energiequelle zu verwenden. Im Gegensatz dazu, verfügt die KVA-Hagenholz über ausreichend Prozessdampf, um einen Amin-basierten CO_2-Capture-Prozess zu betreiben, nämlich den von der BASF lizenzierten OASE® Blue-Prozess. Der CO_2-Capture-Prozess kann dort installiert werden, während die abgegebene Fernwärmemenge durch den fortschrittlichen Wärmeintegrationsansatz beibehalten werden kann. Auf Basis dieser Ergebnisse werden Leitlinien zur Verallgemeinerung entwickelt, welche auf andere schweizerische Emittenten aus diesen Branchen angewendet werden können.

Résumé

L'objectif général de ce bloc d’activité (WP) est d'évaluer le potentiel d'extension des chaînes de captage, d'utilisation et de stockage du carbone (CCUS) et de captage, de transport et de stockage du carbone (CCTS) à court terme, ainsi que celui d'un réseau de CO_2 reliant les sites d'émission suisses aux sites de stockage nationaux et internationaux à long terme. Dans ce qui suit, les chaînes logistiques de CO_2 qui impliquent le captage et le transport du CO_2 à l'étranger en vue d'un stockage géologique sont désignées comme CCTS, tandis que les chaînes logistiques de CO_2 qui impliquent le captage et l'utilisation du CO_2 et son stockage permanent dans le béton par minéralisation sont désignées comme CCUS.

Tout d’abord, l'analyse s’est focalisée sur quelques sources d’émissions localisées en Suisse provenant des secteurs de la valorisation énergétique des déchets, du ciment et du biogaz (par exemple, l’usine d’incinération ERZ à Hagenholz, la cimenterie Jura à Wildegg) qui pourraient déployer le CCUS et le CCTS comme solutions de réduction des émissions à court terme, c'est-à-dire à partir de 2030. Ce travail a pris en compte la chaîne logistique globale en CO_2 avec le captage et la liquéfaction du CO_2 sur le site de l'émetteur, le transport et le stockage dans du béton (solution domestique) ou dans un réservoir géologique à l'étranger, soit dans le site de stockage Northern Lights en Norvège, ou dans les basaltes islandais par le biais de la technologie Carbfix. En raison de l'horizon proche, on s’attend à ce que ces chaînes logistiques reposent principalement sur le transport terrestre du CO_2 par camion et par train. Par conséquent, les coûts de transport constituent la part la plus importante (jusqu'à 60 %) pour les pionniers, car ces solutions de transport multimodal sur de longues distances ne bénéficient pas d'économies d'échelle. Ces coûts devraient toutefois diminuer considérablement à long terme grâce à des solutions plus efficaces, par exemple un réseau de carboducs, ce qui réduirait de moitié le coût par unité d’émissions de carbone évitée pour l'ensemble de la chaîne CCTS, ce coût étant indépendant de l’origine du CO_2 et qui inclut la réduction ainsi que l’extraction et élimination du CO_2. L'analyse du cycle de vie (LCA) a également été réalisée et démontre que toutes les chaînes réduisent le potentiel de réchauffement planétaire (GWI) de l'émetteur correspondant d'au moins 70 % et jusqu’à 85 %, étant donné que les émissions de gaz à effet de serre le long de la chaîne CCTS sont nettement inférieures au CO_2 stocké. Par rapport à un fonctionnement inchangé, les émissions de gaz à effet de serre sont donc réduites de 70 à 85%. Pour les émetteurs de CO_2 d’origine biogénique, il existe un potentiel d’élimination nette du carbone si la quantité nette d’émissions évitées par la chaîne logistique CCTS est plus importante que les émissions d’origine biogénique de l’émetteur. Les contributions les plus importantes au GWI sont le captage et le transport, dont les émissions de gaz à effet de serre devraient diminuer à l'avenir, en particulier dans le domaine du transport, à mesure que la décarbonisation des systèmes techniques progresse.

Dans un second temps, un modèle de réseau a été utilisé pour étudier les structures optimales d’un réseau de CO_2 ainsi que les scénarios de déploiement des technologies CCTS et CCUS en Suisse, faisant la transition des précurseurs dans ce domaine aux chaînes logistiques intégrées et interconnectées à une infrastructure paneuropéenne commune. Cette évaluation a mis en évidence le niveau élevé d'incertitude quant au développement et à l'accessibilité de ces infrastructures, et l'avantage pour les parties prenantes suisses de commencer tôt à développer des infrastructures nationales, c'est-à-dire le captage, le transport (au moyen de carboducs) et éventuellement le stockage. L'analyse a été étendue à d'autres secteurs, à savoir les secteurs chimique, pharmaceutique et des sciences de la vie. Un tel réseau desservira les émetteurs ponctuels suisses et inclura des unités de

captage direct dans l'air (DAC), dont l'emplacement optimal par rapport aux sites de stockage de CO_2 opérationnels à l'étranger sera étudié.

En ce qui concerne les modèles commerciaux du CCTS et du CCUS, il a été constaté que leur viabilité dépendait des éléments suivants (i) le contexte réglementaire, c'est-à-dire quelles industries et quel CO_2 sont inclus dans le système d'échange de quotas d'émission (SEQE) suisse, quand et comment la loi révisée sur le CO_2 sera adoptée, quelle dynamique se produira sur le marché volontaire du carbone (VCM) ; (ii) la conception de la trajectoire de décarbonisation choisie par les émetteurs, qui détermine différents profils de risque et projections de coûts ; (iii) l'organisation et la gestion des chaînes logistiques, pour lesquelles soit une installation de capture intégrée gérée par un seul émetteur, soit un regroupement d'installations de capture gérées par un groupe d'émetteurs, seront couplées à une ou plusieurs tierces parties, auprès desquelles le transport et le stockage seront entièrement externalisés ; (iv) l'incertitude concernant la stabilité et la durabilité des revenus et des outils de financement. Lorsque l'on étudie la résilience, c'est-à-dire les moyens de minimiser la réduction ou l'absence de service, on distingue entre les solutions optimales en termes de coûts (moins chères) et les solutions optimales en termes d'environnement (plus coûteuses). De telles solutions existent, bien que la résilience soit peut-être moins prioritaire que les indicateurs résultant de l'analyse techno-économique et de l'analyse du cycle de vie à un stade aussi précoce du développement des chaînes de CCTS.

Enfin, l'intégration optimale du captage post-combustion du CO_2 aux usines de d'incinération des déchets et aux cimenteries a été évaluée en se référant à la cimenterie Jura à Wildegg (Argovie) et à l'usine de valorisation des déchets (KVA) de ERZ à Hagenholz (Zurich). Pour ce faire, on a conçu et dimensionné les unités de captage du CO_2 nécessaires pour les deux sites et effectué une analyse techno-économique des intégrations de captage en tenant compte de diverses contraintes telles que les conditions d'exploitation, la disponibilité de chaleur, les besoins énergétiques saisonniers et les contraintes spatiales. À la cimenterie Jura, la technique CO_2 Capsol EoP™ utilisant du carbonate de potassium chaud (HPC) comme solvant a été choisie, car elle est conçue pour utiliser uniquement de l'électricité comme source d'énergie. En revanche, KVA Hagenholz dispose de suffisamment de vapeur sur site pour permettre l'utilisation d'un procédé de captage à base d'amines, à savoir la technologie OASE® blue sous licence de BASF. Le captage du CO_2 peut être installé efficacement sans compromettre le chauffage urbain en utilisant des solutions avancées d'intégration de la chaleur. A partir de ces résultats, des directives seront fournies pour généraliser les résultats de cette analyse à d'autres émetteurs suisses de ces secteurs.

Summary

The overall purpose of this work package was to assess the upscaling potential of carbon capture, utilization, and storage (CCUS) and carbon capture, transport, and storage (CCTS) chains in the near term, as well as that of a CO_2 network connecting Swiss emission sites to national and international storage sites in the long term. In the following, CO_2 supply chains that involve CO_2 capture and transport abroad for geological storage are referred to as CCTS, while CO_2 supply chains that involve CO_2 capture and usage and permanent storage in concrete via mineralization are referred to as CCUS.

First, we focused on the analysis of a few Swiss point-source emitters, KVA Hagenholz – a waste treatment plant in Zurich, Jura Cement – a cement production plant in Wildegg, and ARA Region Bern – a biogas upgrading plant, who may deploy CCUS and CCTS as an emission mitigation solution in the near-term, e.g., from 2030 on. This work considered the overall CO_2 supply chain with CO_2 capture and liquefaction at the emitter's site, transport, and storage in concrete (domestic solution) or in geological storage in the Northern Lights storage hub in Norway, or in Icelandic basalts through the Carbfix technology. Because of the near-time horizon, it is expected that these supply chains will mostly rely on CO_2 transport on land by truck and train. As a result, transport costs constitute the largest share of up to 60% for early movers, as such multimodal transport solutions for long distances do not profit from economies of scale. Their costs are however expected to decrease significantly in the long term with more efficient solutions, e.g., a pipeline network, thus halving the levelized cost of avoided carbon of the entire CCTS chain, which are independent of the origin of the CO_2, accounting for reduction and removal. Life cycle assessment (LCA) was also conducted and demonstrates that all chains reduce the global warming potential (GWI) of the corresponding emitter by at least 70% to 85%, since the greenhouse gas (GHG) emissions along the CCTS chain are significantly lower than the CO_2 stored. Compared to unabated operation, greenhouse gas emissions are, therefore, reduced by 70% to 85%. At emitters with biogenic feedstock, a potential for net carbon removal exists if the net emission reduction by the CCTS chain is larger than the biogenic emissions from the plant. The largest contributions to GWI are capture and transport, whose GHG footprints are expected to decrease in the future, particularly transport as decarbonization of technical systems proceeds.

In a next step, a network model was used to study optimal network structures and rollout scenarios of the transition from early-movers to integrated Swiss CCTS and CCUS supply chains interconnected to a pan-European shared infrastructure. The assessment highlighted the high level of uncertainty about the development and the accessibility of such infrastructure, and the advantage for Swiss stakeholders of an early start in developing national infrastructure, i.e., capture, transport (using pipelines) and possibly storage. The analysis was extended to other sectors, i.e., chemical, pharma, and life sciences sectors. Such a network will serve the Swiss point-source emitters and will include Direct Air Capture (DAC) units, for which the optimal location will be investigated with respect to operational CO_2 storage hubs abroad.

As far as CCTS and CCUS business models are concerned, it was found that their viability depends on: (i) the regulatory landscape, i.e., which industries and which CO_2 are included in the Swiss ETS, when and how the revised CO_2 Act is adopted, which voluntary carbon market (VCM) dynamics occurs; (ii) the design of the decarbonization pathway chosen by emitters, which determine different risk profiles and cost projections; (iii) the organization and management of the supply chains, whereby either an integrated capture setup managed by the single emitter or a capture cluster managed by a pool of emitters will be coupled to one or more third parties, to whom transport and storage are completely outsourced; (iv) the uncertainty regarding the stability and longevity of revenues and financing instruments. When investigating resilience, i.e., ways to minimize reduced service or lack thereof, one distinguishes between cost-optimal solutions (cheaper) and environment-optimal solutions (more

costly). Such solutions exist, though resilience possibly has a lower priority than the indicators resulting from TEA and LCA at such an early stage of the development of CCTS chains.

Finally, the integration of post-combustion CO_2 capture with WtE and cement plants was evaluated with reference to the Jura Cement plant and KVA Hagenholz. This was tackled by designing and sizing the CO_2 capture units needed for both sites and conducting a techno-economic analysis of the capture integrations, taking into account various constraints such as plant operating conditions, heat availability, seasonal energy demands, and spatial constraints. At Jura Cement, CO_2 Capsol EoP™ using hot potassium carbonate (HPC) as solvent was chosen, which is designed to use only electricity as energy source. On the other hand, KVA Hagenholz has enough steam available onsite to allow for the use of an amine-based capture process, namely the OASE® blue process technology licensed by BASF. CO_2 capture can effectively be installed without compromising district heating using advanced heat integration solutions. From these results, guidelines will be provided to generalize the outcomes of this analysis to other Swiss emitters from these sectors.

Main findings

- For each of the three Swiss early-moving emitters that were considered in this study, it was possible to use reliable data from different sources to carry out a techno-economic assessment (TEA), a life cycle analysis (LCA), and a resilience study to assess the feasibility of a near-term deployment of the corresponding CCTS chain.
- The LCA demonstrates that all early-mover chains reduce the global warming potential (GWI) of the corresponding emitter by up to 85%.
- Transport constitutes the largest share of costs for early movers, as multimodal (truck, train, barge, ship) transport solutions for long transport distances do not profit from economies of scale. Such transport costs are expected to decrease significantly in the long term with more efficient solutions.
- At large scale and in the long term, pipelines are the most cost-effective transport solution. The assessment of scenarios of a potential European transnational CO_2 infrastructure highlighted the high level of uncertainty about its development and the benefit for Swiss stakeholders to initiate the development of such national infrastructure at an early stage.
- Different CO_2 capture technologies were evaluated and selected for the emitters depending on the heat availability. At Jura Cement, CO_2 Capsol EoP™ that requires only electricity was chosen, while KVA Hagenholz has enough steam available onsite for the BASF OASE® blue amine technology, with which effective heat integration can be carried out to ensure district heating is not compromised.
- The viability of CCTS and CCUS business models depends on the regulatory landscape, the decarbonization pathway chosen by emitters, the organization and management of the supply chains, and the uncertainty regarding the stability and longevity of revenues and financing instruments.
- The work carried out in this work package has led to the identification of a set of action items that are essential to drive forward CCTS and CCUS, and consequently, are integral in advancing the Swiss climate strategy. These action items are reported in Section 5.

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Abbreviations

ARA: Abwasserreinigungsanlage (DE for wastewater treatment plant)

BECCS: Bio-energy with carbon, capture and storage

CCTS: Carbon capture, transport and storage

CCUS: Carbon capture, utilization and storage

DH: District heating

GHG: Greenhouse gases

GWI: Global warming potential

JC: Jura Cement

T&S: transport and storage

KVA: Kehrichtsverwertungsanlage (DE for waste incineration plant)

WtE: Waste-to-energy

WP: Work package

1 Introduction

1.1 Background information and current situation

Based on the pledges made in the frame of the Paris Agreement and the recent Climate and Innovation law, Swiss emissions of greenhouse gases (GHG), particularly of carbon dioxide (CO_2), will have to be substantially curbed in the next three decades. Beside technology and infrastructural changes to eliminate distributed GHG emissions in sectors such as mobility and buildings, as of 2050 there will be the need to capture, transport and store millions of tonnes of CO_2 per year from large Swiss point sources (CO_2 capture, transport and storage, CCTS). These large emitters are waste-to-energy plants (currently 29 plants with total emissions of ca. 4.0 million tonnes CO_2/y; note that 50% of these consist of biogenic CO_2), cement manufacturing facilities (6 plants with current total emissions of ca. 2.3 million tonnes CO_2/y), chemical plants (with current total emissions of ca. 0.7 million tonnes CO_2/y). Moreover, negative CO_2 emissions, also in the order of millions of tonnes of CO_2 per year, will have to be generated to compensate for unavoidable residual emissions (e.g., from agriculture and aviation), through the deployment of e.g., Direct Air Capture with CCS (DACCS) and Bio-energy with CCS (BECCS).

Reducing or removing CO_2 emissions, by capturing fossil or biogenic CO_2, respectively, from point sources, and storing it permanently away from the atmosphere is one in a portfolio of solutions aimed at fulfilling Swiss climate goals. Within this framework, it is fundamental to evaluate the technical, economic, environmental, political and societal feasibility as well as the quantitative potential of the upscaling of such technologies, i.e., of BECCS and CCTS.

CCTS and BECCS cannot rely on CO_2 underground storage sites in Switzerland today, and possibly not for the next 20+ years. In fact, the recently completed Elegancy project has reached such conclusion, while describing an updated roadmap to identify and make available for CO_2 storage suitable geological structures. Currently, CO_2 hubs are being developed mostly in North Sea (e.g., Northern Lights storage site or Carbfix Coda Terminal) and already now offer the possibility of storing CO_2 from European emitters. The geographical distribution of the ca. 40 large scale Swiss CO_2 emitters (see Figure 1) and the need to collect the captured CO_2 and to convey it to locations where it is permanently stored make a CO_2 transport network necessary in Switzerland and in Europe. The Saipem study (Saipem, 2021) provides a static design of a pipeline network serving the thirty largest point source emitters in Switzerland. Such a network will most likely be based on pipelines and may require years or even decades to be built. In the short- to medium-term, available CO_2 transport solutions can already be deployed to connect single point sources or small clusters to storage sites. A multi-objective optimization model has been developed at ETH for the characterization of multi-modal CO_2 networks and provides a cost-optimal infrastructure rollout to decarbonize Swiss waste-to-energy sector (Becattini, et al., 2022). The feasibility study for a CCTS supply chain for KVA Linth (Sustainability in Business Lab, 2021) has assessed the integration of a capture unit at and the deployment of a supply chain from KVA Linth. This Work Package aims at providing generalized results for other Swiss emitters both in terms of capture integration and possible transport pathways. Worldwide, there are around 40 commercial capture facilities in operation (International Energy Agency (IEA), 2023). Currently, capture with chemical absorption via amine scrubbing is the most mature technology. The main challenges associated with absorption technologies is the high heat demand (Friday O. Ochedi, 2021), which makes efficient heat integration crucial in terms of energy intensification and cost reduction. In this landscape, this Work Package (WP) aims at carrying out a thorough techno-economic analysis, and an environmental and risk assessment of CCTS technologies (including a rigorous Life Cycle Assessment), as well as an evaluation of their deployment potential for a time horizon until 2050. Furthermore, the WP focuses on paving the way for the deployment of CCTS routes for early movers among the waste treatment, cement manufacturing, chemical and biogas sectors, as well for the planning of the deployment of CCTS solutions for the entire sectors.

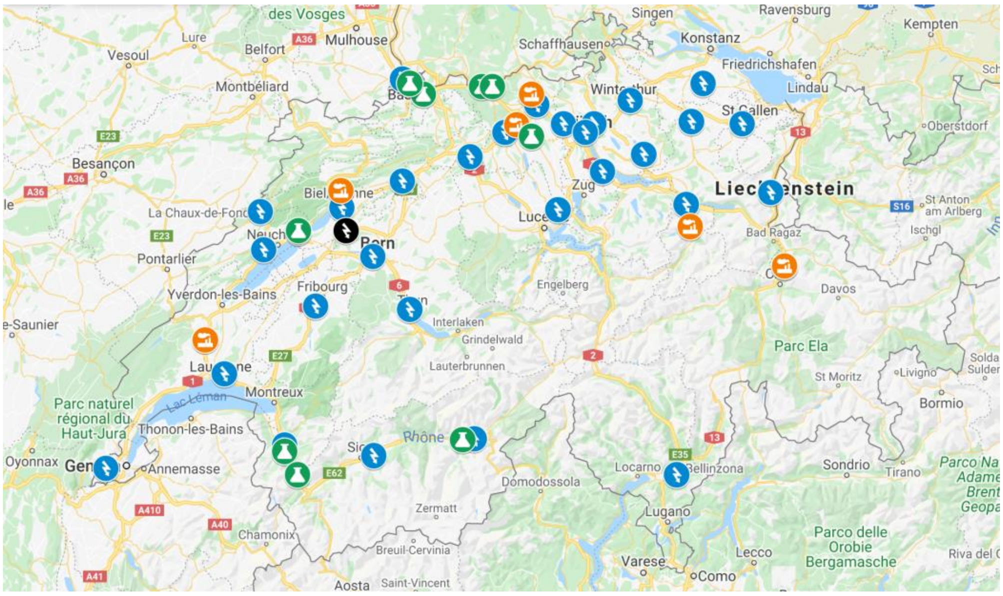


Figure 1 - Geographical distribution of large-scale Swiss CO_2 emitters: Waste-to-Energy plants emitting ca. 4.0 $MtCO_2/y$ (in blue), cement manufacturing plants emitting ca. 2.3 $MtCO_2/y$ (in orange), and chemical plants emitting ca. 0.7 $MtCO_2/y$ (in green). Note: Emissions data refer to year 2021.

1.2 Purpose of the work package

The overall purpose of this WP is to assess the upscaling potential of carbon capture, utilization, and storage (CCUS) and carbon capture, transport, and storage (CCTS) chains in the near term, as well as that of a CO_2 network connecting Swiss emission sites to national and international storage sites in the long term. In the following, CO_2 supply chains that involve CO_2 capture and transport abroad for geological storage are referred to as CCTS, while CO_2 supply chains that involve CO_2 capture and usage and permanent storage in concrete via mineralization are referred to as CCUS.

First, we will focus on the analysis of few Swiss point-source emitters from the waste-to-energy (WtE), cement and biogas sectors (e.g., ERZ plant in Hagenholz, Jura cement plant in Wildegg) that may deploy CCUS and CCTS as an emission mitigation solution in the near-term, e.g., from 2030 on. This work will consider the overall CO_2 supply chain with CO_2 capture and liquefaction at the emitter's site, transport, and storage in concrete (domestic solution) or in a geological reservoir abroad. Because of the near-time horizon, it is expected that these supply chains will mostly rely on CO_2 transport on land by truck and train.

In a next step, the development and optimal integrated design of a CO_2 network interconnected to a pan-European shared infrastructure will be investigated as a long-term emissions mitigation solution. The analysis will be extended to other sectors, i.e., chemical, pharma, and life sciences sectors. Such a network will serve the Swiss point-source emitters and will include Direct Air Capture (DAC) units, for which the optimal location will be investigated with respect to operational CO_2 storage hubs abroad. The findings from analyzing the Swiss CCTS network will help to evaluate the effect of large-scale decisions, such as a shared pipeline network or establishing a domestic geological storage site. The optimization shows pathways how federal CO_2 sequestration targets may be reached and which steps are required to avoid large cost increases or missing sequestration targets.

Finally, the integration of post-combustion CO_2 capture with WtE and cement plants will be evaluated with reference to the Jura Cement plant in Wildegg (Aargau) and the ERZ WtE plant in Hagenholz, Zurich. This will be tackled by designing and sizing the CO_2 capture units needed for both sites and conducting a techno-economic analysis of the capture integrations, taking into account various constraints such as plant operating conditions, heat availability, seasonal energy demands, and spatial constraints. The insights obtained from the integration analysis of post-combustion CO2 capture with the Jura Cement plant and the ERZ WtE plant hold significant value for stakeholders beyond the immediate projects. Specifically, other plants within the same sectors stand to benefit by extrapolating and adapting the learnings to their specific contexts. The comparison of different capture systems, considerations for heat recovery, trade-offs between heat and electricity, and the impact on district heating networks provide a valuable blueprint for similar cement plants and WtE facilities. By understanding the challenges, advantages, and energy requirements of integrating CO2 capture, these insights empower other plants to make informed decisions, potentially accelerating the adoption of these technologies in the cement and WtE sectors.

1.3 Objectives

- Investigate the techno-economic, environmental, and reliability performance of early mover chains with foreseen implementation in the near-term. This will encompass Swiss point-source emitters from the WtE, cement and biogas sectors that may deploy CCUS and CCTS as an emission mitigation solution in the near-term, e.g., around 2030.
- Investigate the development and optimal integrated design of a CO_2 network interconnected to a pan-European shared infrastructure as a long-term emissions mitigation solution. The analysis will be extended to other sectors, i.e., chemical, pharma, and life sciences sectors.
- Explore how to build viable business models that support the implementation of CCTS and CCUS technologies for the WtE, cement, and chemical and pharma sectors.
- Develop scenario-based roadmaps of Swiss CCUS and CCTS infrastructure rollout over time compatible with Swiss climate and energy goals and industry roadmaps.
- Assess optimal integration options for post-combustion CO_2 capture technology in Waste-to-Energy (WtE) and cement plants. This is to be done in a first step with reference to specific Swiss emitters: WtE plant in Hagenholz, and Jura Cement in Wildegg, and then further generalized to other plants in these sectors.

1.4 Work package structure

The WP is structured in three tasks, summarized in the following:

Task 1: Techno-economic, environmental and reliability performance of early mover CCUS and CCTS chains with foreseen implementation in the near-term (e.g., before 2030).

- Subtask 1.1 – Data collection and identification of Swiss CO_2 emitters and concrete production sites with the potential to implement CCUS and CCTS chains in the near-term (e.g., before 2030).
- Subtask 1.2 – Development, design, and techno-economic analysis of early mover CCUS and CCTS chains.

- Subtask 1.3 – Assessment of the lifecycle environmental impact of CCTS and CCUS chains.
- Subtask 1.4 - Reliability analysis of CCTS and CCUS chains.

Task 2: Investigating techno-economic, environmental and reliability performance of a Swiss CO_2 network interconnected to an EU-wide shared CO_2 infrastructure as long-term solution.

- Subtask 2.1 - Further collection of data and information, and model development on the spatial and temporal dimensions.
- Subtask 2.2 - Clustering potential and strategies.
- Subtask 2.3 - Definition of scenarios for an EU-wide shared CO_2 infrastructure.
- Subtask 2.4 - Development of real-world constraints for infrastructure rollout, financial implications of rollout scenarios and feedback into industry roadmaps.
- Subtask 2.5 - Scenario-based optimal integrated designs of a Swiss CO_2 network and rollout scenarios.
- Subtask 2.6 – Business models for WtE, cement, and chemical and pharma industries.

Task 3: Integration of post-combustion CO_2 capture with Waste to Energy (WtE) and cement plants.

- Subtask 3.1 – Post-combustion CO_2 capture integration with reference to the Jura cement plant in Wildegg (emitting ca. 500’000 tCO_2/y) and definition of general guidelines for other cement plants.
- Subtask 3.2 – Post-combustion CO_2 capture integration with the ERZ WtE plant in Hagenholz (emitting ca. 250’000 tCO_2/y today, projected to emit almost 400’000 tCO_2/y from 2026) and definition of general guidelines for other WtE plants.

2 Procedures and methodology

2.1 Task 1

The data collection has been performed, whenever possible, in direct exchange with industrial partners, as can be seen in Figure 2. It has been carried out in 2021 and early 2022. More details about the data collection are given in Section 3.1.1.

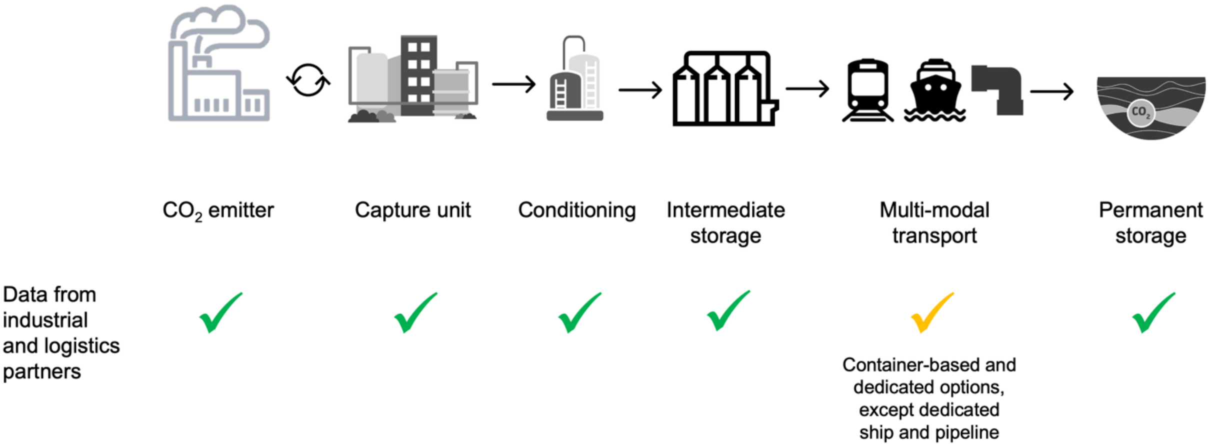


Figure 2 – Data collection scheme for the subsequent stages of CCTS chain: capture, conditioning, intermediate storage, multi-modal transport, and permanent storage.

The techno-economic analysis of the CCTS chains comprises the capture, the conditioning, the intermediate storage, the transport, and the permanent storage of CO_2. Further details about the methodology applied can be found in the published work by (Oeuvray, Burger, Roussanaly, Mazzotti, & Becattini, 2024). The data collected has been used to identify feasible connections and potential transport exchange nodes, hence, to create a network of feasible connections for each pair of industrial emitters and identified storage site. Each network can be represented as a directed graph for which the weight of each edge is characterized by a transport cost corresponding to the transport mode j available for this connection, as shown in Figure 3. Applying a shortest-path algorithm to this graph yields the most economical path from the CO_2 source to the sink.

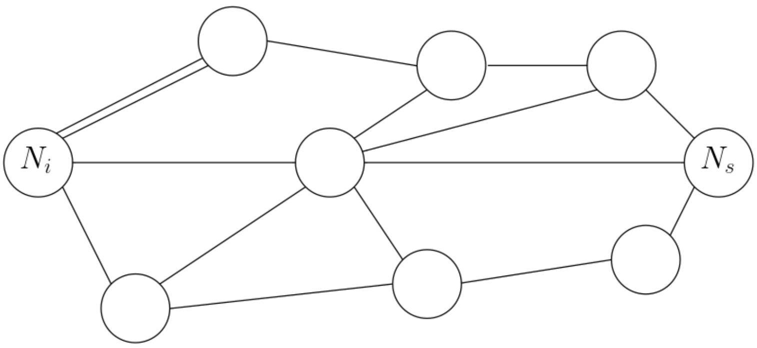


Figure 3 - Network between source node N_i that corresponds to emitter i and sink node N_s that corresponds to a storage site s.

The energy and natural resources required to deploy CCTS supply chains have been evaluated based on the same dataset to provide general guidelines about the direct energy consumption along the chain, as well as the land footprint of the installation of capture and conditioning units at the emitter's site.

The life cycle assessment (LCA) determines the global warming impact of early-mover CCTS chains over their whole life cycle and hence quantifies their avoidance potential, which is described below. For instance, it is examined whether Swiss CCTS chains connected to geological storage sites abroad can avoid GHG emissions already today. Furthermore, potential areas of burden shifting are identified, where impacts in one impact category are reduced at the cost of another impact category. The LCA of the early mover CCTS chains considers the same boundaries and processes as the techno-economic assessment and includes the capture, conditioning, transport, and geological storage steps. Both amine-based and hot potassium carbonate post-combustion capture processes are investigated, and various energy sources are assessed. The CO_2 avoidance efficiency η_{av} of the supply chain accounts for the emissions arising from the energy and material consumption associated with the deployment of the chain, $m_{\text{CO}_2\text{.eq}}^{\text{emitted}}$, and is defined as

$$\eta_{\text{av}} = 1 - \frac{m_{\text{CO}_2\text{.eq}}^{\text{emitted}} \left[\frac{\text{t}}{\text{y}}\right]}{m_{\text{CO}_2}^{\text{stored}} \left[\frac{\text{t}}{\text{y}}\right]}$$

where $m_{\text{CO}_2}^{\text{stored}}$ is the amount of CO_2 annually captured, conditioned, transported and stored within a supply chain.

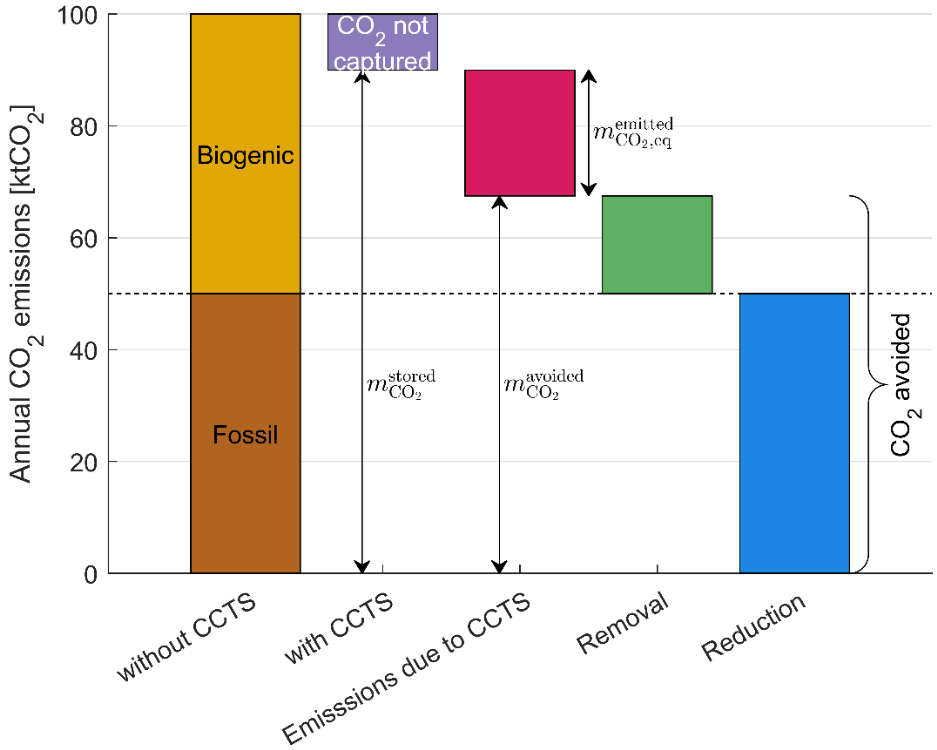


Figure 4 – Scheme of the emissions of an imaginary waste-to-energy plant accounting for the origin of the CO_2, the amount of CO_2 annually captured, conditioned, transported and stored by the supply chain, the emissions associated with the deployment of the chain, and the potential for removal and reduction, respectively.

In this report, the origin of the CO_2 differs between the emitters considered. In the case of a cement plant, the CO_2 emitted is non-biogenic, while in the case of a waste-to-energy plant such as KVA Hagenholz, approximately 50% of the CO_2 is of biogenic origin. Figure 4 shows the emissions breakdown and avoidance values for an imaginary waste-to-energy plant. Without CCTS, the plant emits 100 $ktCO_2$/y, which are divided into fossil (brown bar) and biogenic (yellow bar) emissions. The amount of CO_2 annually captured, conditioned, transported and stored $m_{\mathrm{CO_2}}^{\mathrm{stored}}$ is generally limited by the capture rate. In Figure 4, we assume a capture rate of 90%. This means that the remaining 10% are still emitted with the implementation of CCTS (violet bar). The emissions associated with the deployment of the CCTS chain $m_{\mathrm{CO_2.eq}}^{\mathrm{emitted}}$ (red bar) reduce the potential for CO_2 avoidance (reduction and/or removal). The amount of CO_2 avoided $m_{\mathrm{CO_2}}^{\mathrm{avoided}}$ is the difference between the total CO_2 emitted to the atmosphere without CCTS and the CO_2 emitted implementing a CCTS scheme comprising the CO_2 not captured and the direct and indirect emissions associated with the deployment of the CCTS chain, assuming a CCTS chain efficiency η_{av} of 25% in Figure 4. The CO_2 avoided comprises the reduction (blue bar) and the removal (green bar). The avoidance of fossil emissions to the atmosphere is expressed as a reduction, while the removal indicates a net removal of CO_2 emissions from the atmosphere, because the uptake of CO_2 by biomass is larger than the CO_2 emissions to the atmosphere. In the example of Figure 4, we can observe that all fossil emissions (50 $ktCO_2$/y) are reduced, and that there is a potential for removal (17.5 $ktCO_2$/y). It is important to note that there is potential for carbon dioxide removal (CDR) only if the CCTS chain can avoid more CO_2 than the amount of non-biogenic CO_2 emitted in the process (Becattini, et al., 2024). In this report, we refer to avoidance when we consider both removal and reduction, thus using the term 'avoidance' interchangeably with the term 'mitigation' as defined by the IPCC (IPCC, 2022) and in the Paris Agreement (United Nations Environment Programme, 2015).

The total annual costs of a supply chain are computed by combining the transport costs with the capture, conditioning, intermediate and permanent storage expenses. Thereupon, the levelized costs of CO_2 stored ($\mathrm{LC_{st}}$) and the levelized costs of CO_2 avoided ($\mathrm{LC_{av}}$) are chosen as key performance indicators to evaluate the economic performance of supply chains. The levelized costs of CO_2 avoided considers both the techno-economic and climate impact of a supply chain. The metrics are calculated as follows:

$$\mathrm{LC_{st}}\left[\frac{\mathrm{EUR}}{\mathrm{t}}\right] = \frac{\mathrm{TAC}\left[\frac{\mathrm{EUR}}{\mathrm{y}}\right]}{m_{\mathrm{CO_2}}^{\mathrm{stored}}\left[\frac{\mathrm{t}}{\mathrm{y}}\right]}$$

$$\mathrm{LC_{av}}\left[\frac{\mathrm{EUR}}{\mathrm{t}}\right] = \frac{\mathrm{LC_{st}}\left[\frac{\mathrm{EUR}}{\mathrm{t}}\right]}{\eta_{\mathrm{av}}\,[-]}$$

where TAC are the total annual costs. In this analysis, the origin of the CO_2 is disregarded, thus not accounting for the biogenic share of the CO_2 emissions; in other words, no negative emissions generated by the possible biogenic nature of the CO_2 stored are accounted for. In this way, the costs obtained are independent of the origin of the CO_2 and can be transferred and applied to emitters from different sectors.

The importance of a resilient CCTS supply chain can be acknowledged from different perspectives, depending on the harm that may occur in case the infrastructure fails to operate properly. From a climate perspective, the interrupted functionality of the supply chain, which results in the release of CO_2 into the atmosphere, would prevent achieving net-zero-CO_2-emissions goals. From an economic perspective, a failure in delivering the CO_2 to the permanent storage site would result either in a tax being paid for the emissions caused or in a credit being missed in case the stored CO_2 would contribute to generate negative CO_2 emissions. Additionally, it is likely that in such a case the CO_2 emitter would incur in extra costs to be paid to, for example, the CO_2 transport or storage providers depending on legal and liability agreements in place. Moreover, simply venting CO_2 to the atmosphere in case of failure might result in low public acceptance, whereas resilient CCTS supply chains would contribute to gain credibility and public confidence.

Based on the above considerations, we define and investigate CCTS supply chain resilience by adopting two perspectives:

- From the infrastructure resilience perspective, an infrastructure-resilient CCTS supply chain is able to store CO_2 upon the occurrence of failures or unexpected scenarios, while minimizing the total system costs;
- From the environment resilience perspective, an environment-resilient CCTS supply chain is able to store CO_2 upon the occurrence of failures or unexpected scenarios, while minimizing the total system emissions.

Such resilient supply chains should be compared against cost-optimal supply chains, which release CO_2 into the atmosphere in case of failures or unexpected scenarios, i.e., which are not resilient. Within the framework of CCTS supply chains, disruptions to the nominal operation could stem from a failure in capturing the CO_2 at the emissions sites (e.g., an industrial plant), from an interrupted connection between the capture site and the storage site, from delays in transporting the CO_2, or from an interruption in the operation of the storage facilities. When looking at CO_2 transport, and especially at CO_2 pipelines, the relevant failure mechanisms are similar to those of natural gas pipelines. More specifically, both CO_2 and natural gas pipelines are fabricated from carbon steel, both are installed using similar equipment and practices, and both are subject to potential internal corrosion damage, as well as potential failures due to excavation issues (Gabrielli, Campos, Becattini, Mazzotti, & Sansavini, 2022).

Whereas we do not perform a risk assessment, and we base our study on previous analyses that quantify the failure rates of the different components of a CCTS supply chain, we propose strategies to increase the resilience of the entire CCTS supply chains. More specifically, we consider three strategies to improve resilience of CCTS supply chains, namely (1) installing parallel transport connections to introduce redundancy in case of connection failures, (2) installing temporary storages to buffer CO_2 until a failed component is repaired, and (3) installing direct air capture facilities to compensate for CO_2 that is lost to the atmosphere during a failure state.

We performed various resilience analyses. We first performed a qualitative resilience assessment of early-mover supply chains, as such supply chains correspond to single subsequent connections. Next, we perform the multi-objective optimization of Swiss CCTS supply chains to decarbonize an entire industrial sector (the Swiss waste-to-energy, WtE, sector in the following). In this case, we determine optimal designs of the supply chains that minimize costs while maximizing resilience, and we quantify the cost of resilience; we perform this analysis for resilience strategy (1), which is illustrated in Figure 5. The results of these analyses are presented in section 3.1.4.

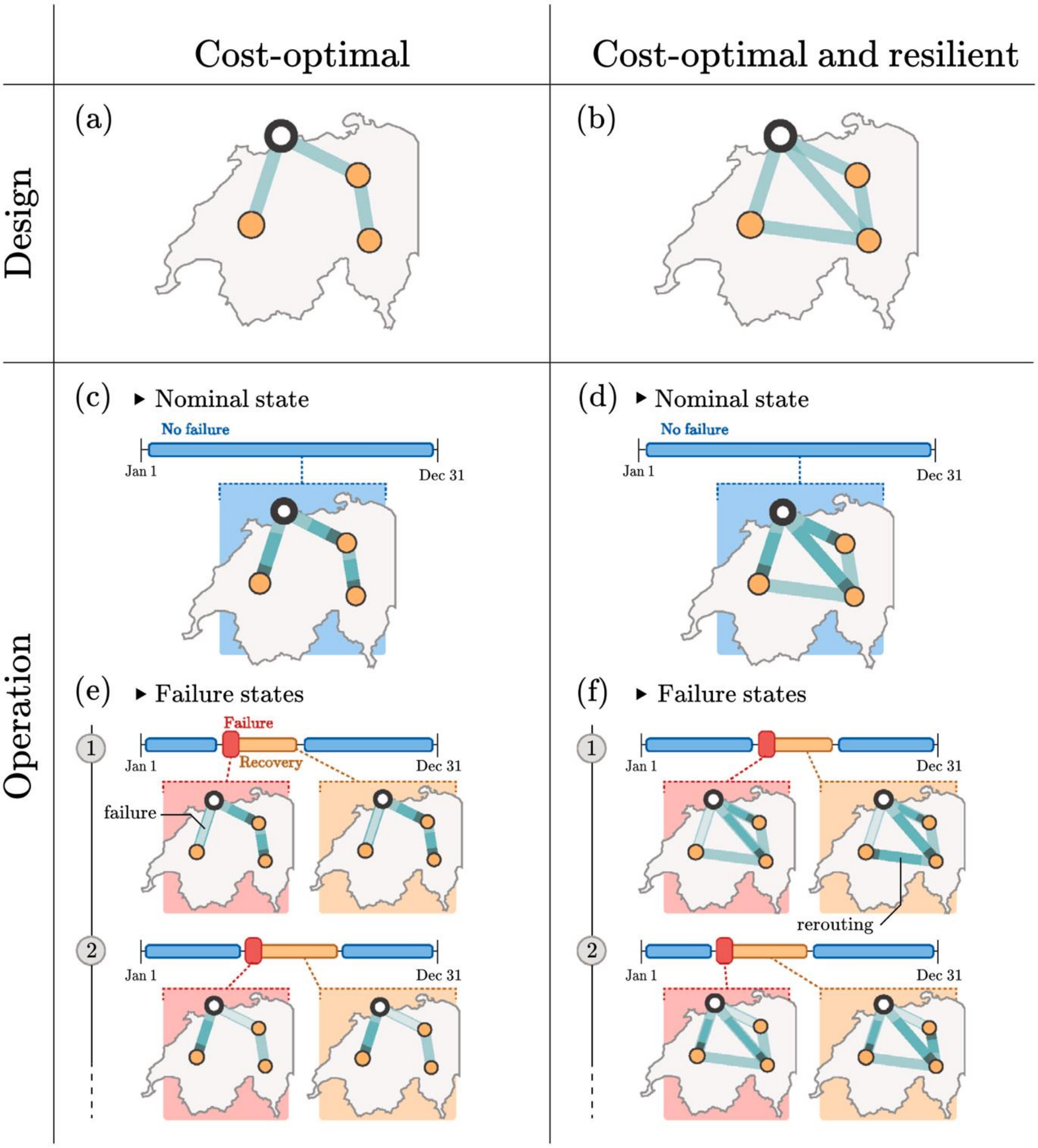


Figure 5 – Illustration of the definitions used to determine and compare the minimum-cost and the maximum-resilience designs of CCTS supply chains.

2.2 Task 2

The project also investigates the transition from the single supply chains of the early movers to an integrated Swiss CCTS supply chain. The optimal design and rollout of a Swiss CCTS supply chain is determined via a mathematical optimization model. The optimization model is based on mixed-integer linear programming (MILP) and on the data collected in Tasks 1.1, 2.1, and 2.4; it determines the time-dependent installation, sizing and operation of the CO_2 capture and transport technologies that minimizes the total costs of the system while complying with fixed CO_2 emissions targets and resilience constraints. All aspects of the optimization problem, namely input data, decision variables, constraints, and objective function are described in the following.

Input data. The input data to the optimization problem consists of: (i) location and current CO_2 emissions of Swiss emitters, (ii) location and capacity of CO_2 storage sites, (iii) performance, carbon footprint, and costs of capture, storage, and transport technologies, (iv) availability of transport technologies (i.e., connectivity between nodes), (v) price and region-specific carbon intensity of electricity, and (vi) targets of CO_2 emissions (reflecting different climate policy strategies). Detailed information on the input data (e.g., costs and emissions functions and parameters, sources, etc.) can be found in (Becattini, et al., 2022).

Decision variables. Based on the input data above, the optimization problem determines the (i) selection, location and size of CO_2 capture and transport technologies, (ii) input and output electricity and CO_2 streams of production technologies, and (iii) CO_2 flow for installed transport technologies.

Constraints. The constraints of the optimization problem include (i) energy and mass balances, (ii) performance behavior and operating limits of the capture and transport technologies, (iii) CO_2 emissions, and (iv) reliability constraints.

Objective. The optimization problem minimizes the total costs of the system while complying with predetermined CO_2 emissions targets and reliability constraints for the whole system. The total costs consist of annualized investment costs, operation costs, and maintenance costs.

The optimization is carried out for the time horizon from 2025 to 2050 and uses a yearly time resolution. For assessing the different aspects of CCTS networks, two separate versions of the optimization model have been used. One is based on MILP, the other on linear programming (LP). The advantage of LP optimization is the fast building and solving time as well as the proven optimality of the solution obtained. The short solution time compared to MILP optimization enables an increase in the problem size, i.e., more technologies, emitter locations, transport routes, and time steps, as well as running multiple scenarios within a reasonable duration.

Definition of scenarios for an EU-wide shared CO_2 infrastructure

The development of a continent-wide CO_2 transport and storage (T&S) infrastructure is in its early stages, and most of it presently remains non-operational. For defining the real-world scenarios in subtask 2.4, a broad overview of the overall development landscape is first provided, with particular attention to targets and policies at the EU level. A set of criteria has been established to comprehensively identify cross-border CO_2 transport and storage plans relevant to Switzerland's network. Analyzed project plans must (i) involve storage and/or transport components, (ii) be publicly disclosed, (iii) be located within Europe, (iv) intend to have durable storage as an endpoint, and (v) have an announced capacity of at least 2 million tonnes per annum (Mtpa). After identifying the relevant projects, detailed descriptions of the T&S project plans that align with the criteria are provided. These projects are analyzed with regard to their potential to establish pathways connecting the Swiss CO_2 pipeline network to storage sites. A directional approach is applied based on the two delivery points proposed in the Swiss CO_2 network plans. Projects are divided by their Northern or Southern location in relation to Switzerland to cluster potentially interacting infrastructure. Future scenarios for the T&S route from Switzerland to storage sites are provided, followed by a brief discussion of the critical uncertainties that will remain during the development of the European network.

The study draws upon open databases maintained by the (International Energy Agency, 2023) (IEA) and (Clean Air Task Force, 2023) (CATF), both of which list openly communicated CCTS projects across Europe. To ensure a comprehensive overview, both databases are merged and compared, considering their slight differences in scope and detail. Projects not listed in these databases are not considered. However, essential project details missing from these databases had to be collected from other relevant sources (Oeuvray, Burger, Roussanaly, Mazzotti, & Becattini, 2024).

Certain limitations constrain this analysis. Since it mostly relies on project plans, there is a possibility of changes. Challenges on the technical, legal, financial, and social front are still to be effectively managed for many projects. Furthermore, new projects are likely to emerge and be developed in the near future. Additional projects will be critical to the success of the European T&S network, given that the current capacities of confirmed projects still fall short of meeting the rapidly growing demand for CCTS across Europe.

Business models for waste-to-energy, cement, and chemical and pharma industries

For the analysis of viable business models, this report focuses on hard-to-decarbonize industries in Switzerland. These mainly include waste-to-energy, cement, as well as chemical and pharma, which are expected to have residual emissions of around 7 million tons of CO_2 per year as of 2050 that would need to be addressed through CCTS and CCUS (see Figure 1).

Table 1: Overview of the largest hard-to-decarbonize industries in Switzerland.

	Waste-to-energy	Cement	Chemical and pharma
Emitters with annual emissions of >100’000 tons of CO_2 as of 2021	20	6	4
Expected residual emissions in 2050 (whole industry)	3.6 Mt CO_2	2.4 Mt CO_2	1.5 Mt CO_2
Origin of emissions	~ 50% fossil ~ 50% biogenic	~ 90% fossil ~ 10% biogenic	~ 90% fossil ~ 10% biogenic
Ownership	Public	Private	Private

In general, business models can be defined as the structures for how an organization creates, delivers, and captures value. The main components include the definition of a value proposition, the structure and management of the value chain, and a financial model aggregating the costs and revenues and distributing them across the involved actors. In addition, the existing regulatory landscape shapes the options for designing a business model. And ultimately, certain policy measures can support the development of a sustainable business model.

In the context of CCTS and CCUS, the value proposition can be described as the positive climate impact through emissions reductions or removals. These are achieved through the durable storage of captured CO_2, which determines the last activity of the value chain. The durable storage, in turn, is accompanied by the supposedly most important revenue stream – the sale of CO_2 credits. However, there are different options for the management and organization of the value chain and the distribution of responsibilities for the capture, transport, and storage activities. This, in turn, impacts the costs, risk, and complexity from the emitter's point of view.

In this report, the viability of business models for CCTS and CCUS is assessed along the following four key building blocks:

First, the regulatory landscape determines in which markets, or with which instruments an emitter can generate revenue by implementing CCTS or CCUS. The different markets and instruments as well as their inclusion/exclusion of certain industries or pathways are assessed. Second, the design and choice of the specific CCTS or CCUS pathway, as these are characterized by different costs and risks. In this regard, the structures of the CCTS and CCUS value chains (i.e., the respective capture, transport, and storage activities for both pathways) are described. Third, the organization and management of the respective capture, transport, and storage activities (i.e., the integration vs. outsourcing of such activities from an emitter's perspective). Conclusively, different setups for the organization and management of the CCTS and CCUS value chains are discussed. Fourth, supporting revenue streams and financing that could further support the implementation of CCTS and CCUS and the viability of their business models are identified.

Lastly, the findings and the key open challenges that require future research are summarized. Due to the novelty of this topic and the scarcity of existing business models for the two decarbonization pathways specific to the Swiss context, this report does not provide concrete recommendations but rather an extensive overview of building blocks to consider when developing first-of-a-kind business models for CCTS and CCUS projects.

2.3 Task 3

The design of the optimal CO_2 capture integration with early movers, the waste-to-energy plant KVA Hagenholz, Zurich and the Jura Cement plant in Aargau, was realized following the same methodology. With ERZ, a regular bi-weekly meeting was set up for project updates and discussions.

As a first step, the design basis that provides the input data for the assessment of the CO_2 capture units and relevant integration in the existing plant was fixed. It includes the definition of the battery limits of the respective plant, the flue gas conditions at the battery limits, the final CO_2 specifications, the utilities and amount of energy (both heat and electricity) available on site, as well as the site climatic conditions. Several solvent licensors were contacted to screen different commercial technical solutions in order to identify the most optimal supplier of capture technology for each case. This decision was based on the process performance of each technology, experience with similar flue gas to be treated, ease of integration, and space requirements.

The capture technologies for both sites, were designed taking into account seasonal variation of energy demand, plant operating conditions, spatial and technical constraints, and available energy sources, and the final scheme of heat integration with the existing facilities were determined. Finally, the following project deliverables were prepared (found in Appendix III and V).

Deliverables

1. Project design basis
2. Process description for integration with existing plant
3. Process description for carbon dioxide removal technology
4. Process flow diagrams
5. Heat and mass balances
6. Item list
7. Plant production & performance
8. Utilities consumption
9. Preliminary plot plan
10. Cost estimate (with accuracy of +/- 30%)

In addition to the design studies, complementary analyses of the CO_2 capture integration with waste-to-energy plants have been carried out. The effect of the flue gas temperature on the CO_2 capture performance was investigated by running simulations on a chemical engineering process software, Aspen Plus; sensitivity analysis of the flue gas temperature was conducted while keeping all other variables constant and the CO_2 capture efficiency as well as the specific reboiler duty, which is defined as the heat required per kg of CO_2 captured, was assessed.

Integrating CO_2 capture into a waste-to-energy plant can be considered as a compromise between supplying heat, producing electricity, and improving CO_2 capture efficiency, while WtE plants have to meet certain constraints, such as contractual heat demands. This dynamic is mathematically addressed by modeling the steam cycle of the waste-to-energy plant. Further details about the methodology can be found in (Otgonbayar & Mazzotti, Modeling and assessing the integration of CO_2 capture in waste-to-energy plants delivering district heating, 2024).

3 Results and discussion

3.1 Task 1 – Techno-economic, environmental and reliability performance of early mover CCUS and CCTS chains with foreseen implementation in the near-term

3.1.1 Subtask 1.1 – Data collection and identification of Swiss CO_2 emitters and concrete production sites with the potential to implement CCUS and CCTS chains in the near-term

The data collection performed in subtasks 1.1 and 2.1 is based, whenever possible, on exchange with industrial stakeholders. Literature values have been used in case data was lacking for the assessment. The economic, energetic, and location characteristics of the post-combustion capture plant are based on the design studies from Task 3 for KVA Hagenholz and Jura Cement Wildegg, while it is outside of the system boundaries for ARA Bern, because the separation of the biogas is already performed nowadays. The costs include capital and operational expenditures for steam, electricity, water, solvent, labor and maintenance, as well as for the heat pumps in the case of KVA Hagenholz. The characteristics of the conditioning plant are also obtained from Task 3 for KVA Hagenholz and Jura Cement Wildegg, while they are based on current operation for ARA Bern. In the case of ARA Bern, the costs of electricity are assumed to be the Swiss average, and the scale-up of the plant from the current size to 6 kt/y is modelled with a power scaling law. The intermediate storage is assumed to have a buffer capacity of 5 days of production of CO_2, and the costs are linearly interpolated as a function of the size based on data received from logistics stakeholders. The techno-economic assessment of the transport options includes aspects such as the transport distance and duration, maintenance, fuel, insurance and taxes, infrastructure, administrative fees and supplements. The transport costs are calculated according to the methodology proposed by (Oeuvray, Burger, Roussanaly, Mazzotti, & Becattini, 2024). They are based on data delivered by Meerberg and Neustark for the ISO tank containers, by ASTAG and Linde for container-based and dedicated truck transport, by ChemOil for container-based and dedicated train transport, by Contargo for container-based barge transport, by Victrol for dedicated barge transport, by Samskip, North Sea Container Line and Sea Cargo for container-based ship transport. For the options mentioned thus far, the data is specific to chosen connections. The energetic requirements for transport are obtained from Ecoinvent for all container-based transport options and dedicated road, railway and inland waterway transport (Wernet, et al., 2016). For dedicated ship transport (Roussanaly, Deng, Skaugen, & Gundersen, 2021) and pipeline transport (Knoope, Guijt, Ramírez, & Faaij, 2014), the cost and energetic assessment are based on literature. The land footprint of the logistics on-site is considered, while the impact of transport and storage is outside the scope of this study. The costs of storage have been obtained from exchanges with Northern Lights and Carbfix, two providers of geological storage in Norway and Iceland. The potential for domestic storage through mineralization in concrete has been obtained from the investigations performed in WP2 and from previous literature (Rosa, Becattini, Gabrielli, Andreotti, & Mazzotti, 2022), including technical, economic, energetic and environmental assessments. The design of a pipeline network from Switzerland to a geological site in Norway is based on the studies or projects of (Saipem, 2021), (TES, 2023) and (Wintershall Dea, 2022).

The overall energy consumption for a Swiss network has been evaluated based on the 32 largest point-source emitters in Switzerland. For capture, we assume amine scrubbing with 90% capture rate (Pérez-Calvo & Mazzotti, 2022) and compute the required energy depending on the typical flue gas concentration for the industry segment of each point-source emitter (Wang & Song, 2020; Durán, Rubiera, & Pevida, 2017; Gabrielli, Gazzani, & Mazzotti, The role of carbon capture and utilization, carbon capture and storage, and biomass to enable a net-zero-CO2 emissions chemical industry, 2020; Hansson, Hackl, Taljegard, Brynolf, & Grahn, 2017; IPCC, 2005). The energy required to operate the pipeline network is obtained from the Saipem report (Saipem, 2021). Table 2 reports summarized technical specifications for the three early mover emitters considered in this study, while the flue gas properties are reported in Table 14 and Table 15 in Section 3.3.

Table 2: Technical specifications of the emitters considered for the early mover supply chains.

Plant	**KVA Hagenholz**	**Jura Cement Wildegg**	**ARA Bern**
Location	Zürich (ZH)	Wildegg (AG)	Bern (BE)
Sector	Waste-to-energy	Cement	Wastewater treatment
Emissions amount	405 ktCO_2/y (from 2027)	645 ktCO_2/y	5-7 ktCO_2/y
Capture type	Post-combustion capture	Post-combustion capture	Biogas upgrading
CO_2 concentration in the flue gas	12.4 vol%	15.7 vol%	99.3 vol%
Access options	Pipeline	Road and railway	Road
Space available on-site for:			
- conditioning	No	Only for compression	Yes (WP3)
- loading	No	No	Yes (WP3)

As shown in Table 2, the three emitters considered in this study belong to the waste-to-energy, the cement industry, and the biogas sector. They emit amounts of CO_2 varying from a few thousand to more than half a million tonnes per year. The CO_2 concentration in the flue gas of the waste incineration plant at KVA Hagenholz is lower than at the cement plant, and both emitters are considered to be retrofitted with a post-combustion capture plant. In the case of ARA Bern, the biogas upgrading unit separates already today the biomethane from the carbon dioxide, hence no additional capture unit is needed. When considering capture, it is important to distinguish between separation of CO_2 from nitrogen (typically post-combustion capture) or from methane.

The dimensions of the capture and conditioning plants are obtained from the layout proposed by Casale in Task 3, the intermediate storage site is modelled based on literature (Fraga, et al., 2021), and the area for logistics and CO_2 handling is based on a report about KVA Hagenholz (Rapp AG, 2022). It is worth mentioning that due to space scarcity both at the KVA Hagenholz and at the Jura Cement sites, liquefaction, intermediate storage and logistics handling might need to be performed outside of the site. In the case of KVA Hagenholz, a concept has been developed and allows to compute the costs associated with this concept. In the case of Jura Cement in Wildegg, a concept has not been developed yet and the costs associated to this modification are not included. It is worth noting that in the case of KVA Hagenholz, these costs represent less than 1% of the total supply chain costs (see Figure 11), and they are expected to be at a similar level for Jura Cement.

Figure 6 - Location map of KVA Hagenholz (source: openstreetmap.org)

Concerning the options for access to the plants, KVA Hagenholz is located in a densely populated area as can be seen in Figure 6. The Glatt river is not navigable, and the plant is not connected to the rail track passing next to it. Moreover, KVA Hagenholz has very limited space availability on-site, hence they are envisioning building a pipeline to a location nearby where enough space is available for a conditioning unit and the handling of logistics, according to a study conducted by Casale. In this study, ARA Werdhölzli has been selected (see subtask 3.2).

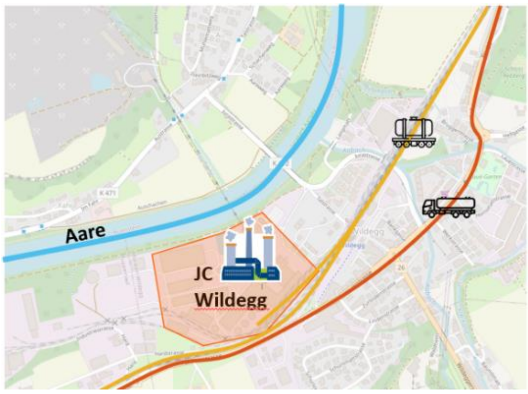


Figure 7 - Location map of Jura Cement Wildegg (source: openstreetmap.org)

Figure 7 shows the location of Jura Cement in Wildegg. It is the only one of the three plants considered that has a private railway station. It is also located nearby the river Aare, which is however not suitable for goods transport. Road transport is also feasible from the cement plant. However, the layout plan developed by Casale in Task 3 indicates that there is limited space available on-site. While capture and conditioning units can be installed at the plant site, space is lacking to install a liquefaction unit (see Appendix IV)

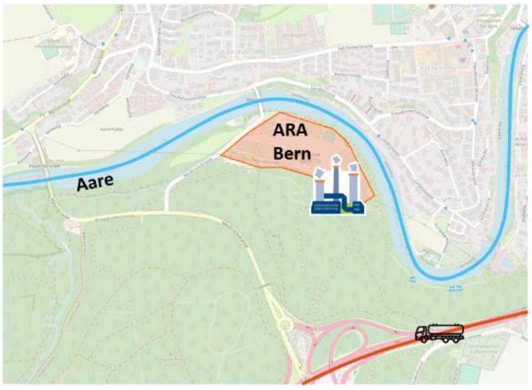


Figure 8 - Location map of ARA Bern (source: openstreetmap.org)

ARA Bern is located next to the river Aare, which is not navigable, see Figure 8. It does not have a private railway station but is located nearby the motorway. The pioneering chain operated in WP3 exploits liquefaction and loading of the isotainers on-site.

In this task, the selected transport options for CO_2 pioneering supply chains are already existing and established. They all involve transporting CO_2 in liquid form at medium pressure (16 bar and -27°C at loading). On the one hand, they consist of ISO tank containers (isotainers) that contain approximately 20 tCO_2 each and can be loaded onto trucks, trains, barges, and ships, which are referred to as container-based transport modes. On the other hand, fixed tanks can be installed on trucks and trains, which are referred to as dedicated trucks and dedicated trains, transporting 26 tCO_2 and 50 tCO_2, respectively. Dedicated vessels for waterway transport are not yet included in the pioneering pathways of task 1, as such vessels are still under development. However, they might become available at the same time as when capture plants will be constructed, hence they are included for comparison. Typically, dedicated barges on the Rhine River have a volume between 3,000 and 5,000 tCO_2, whereas dedicated ships can range from 2,500 to 50,000 tCO_2. Furthermore, options requiring significant greenfield infrastructure, such as large intermediate storage and filling stations at exchange sites or a railway station, are not considered for pioneering chains. Additionally, gas and dense phase pipelines, with the exception of the short segment connecting KVA Hagenholz and ARA Werdhölzli, are not within the scope of transport options for the near term.

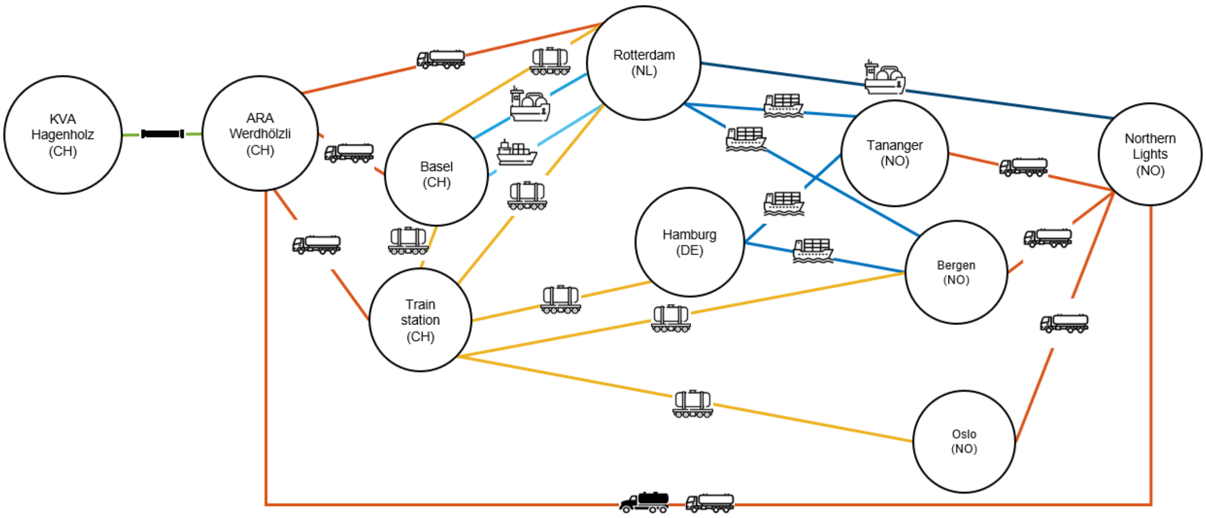


Figure 9 – Network of feasible connections from KVA Hagenholz to Northern Lights.

The data collection on the transport options aims at identifying meaningful connections and transport exchange hubs, and to create a network of feasible connections as shown in Figure 9. The transport distances and durations are calculated based on geospatial mapping platforms[2] and historical data. The cost factors are based on the indications from the service providers. The numerous exchanges with service providers also helped to identify limitations and challenges for all transport modes, including the typical congestion and delays, the holding time of the CO_2, and the frequency of transport on each connection.

The storage options considered in this study are Northern Lights in Norway and Carbfix in Iceland for geological storage abroad, as well as domestic storage in concrete. Data has been shared by both stakeholders and by Neustark. Geological storage in Switzerland is considered outside the scope of this study. The different parameters for the techno-economic analysis of the chains will also be used as parameters for the multi-objective optimization model.

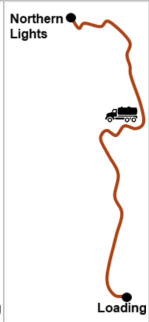
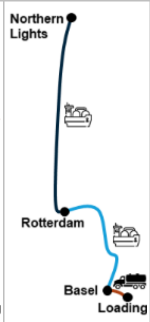
[2] GoogleMaps, RailNetEurope, sea-distances.org

3.1.2 Subtask 1.2 – Development, design, and techno-economic analysis of early mover CCUS and CCTS chains

This subtask aims to develop and design full CCUS and CCTS chains for early movers. As described in task 1.1, the emitters screened are KVA Hagenholz, Jura Cement in Wildegg and ARA Bern. The results presented here provide an overview of the levelized costs of avoided carbon for the cost-effective supply chains reaching the geological storage sites of Northern Lights in Norway and of Carbfix in Iceland in the near term. A similar study has been conducted about KVA Linth and published in the proceedings of the 16th International Conference on Greenhouse Gas Control Technologies (Oeuvray, Becattini, & Mazzotti, Carbon Capture, Transport and Storage (CCTS) supply chain assessment for early movers, 2022). For ARA Bern, the pioneering supply chain is compared with two distinct reference cases. One reference case assumes domestic storage in concrete based on the characteristics described in the LCA of WP2, and the second reference case assumes a full pipeline network derived from the Saipem study (Saipem, 2021). Furthermore, the resources requirements for the deployment of CCTS supply chains and the impact of the transport of CO_2 onto Swiss infrastructure are analyzed and discussed at the end of the section.

For each emitter, the Yen’s algorithm (Yen, 1971) is applied to the simple directed graph derived from Figure 3 and allows to obtain the most economical transport pathways for single source – single sink supply chains, meaning that no shared infrastructure is considered to be available for pioneering supply chains. Based on the findings for all emitters, selected solutions described in Table 3 are presented to document the alternative pathways and their implications. Considering that all emitters are located in Switzerland, the structure of the transport chains – i.e., combinations of transport options from the emitter site to a selected storage site –, is similar and they share certain transport exchange sites. Note that potential costs for reconditioning of the CO_2 when transferring it between dedicated transport options is out of the scope of this study; these would mainly concern the solutions 5 and 6. The global warming impact and avoidance efficiency are reported based on the results in subtask 1.3 and allow the computation of the levelized costs of avoided carbon. They are based on conventional transport options and current energy mixes, which impacts for instance train transport and pipeline transport through Germany.

Table 3: Selected solutions for transport chains from an emitter site to a storage site.

	Early movers solutions					**Dedicated vessels**	
Solution	1	2a	2b	3	4	5	6
							
Description	Cost-effective pioneering chain	DemoUpCARMA WP3 demonstration chain		Truck to harbor	Dedicated truck	Cost-effective dedicated solution	Dedicated train and ship
Lead time	None					3-5 years	
Private railway station required			✓				✓
Transport to Basel	Cont.-b. truck	Cont.-b. truck				Dedicated truck	
Transport to Rotterdam	Cont.-b. barge	Cont.-b. train	Cont.-b. train	Cont.-b. truck		Dedicated barge	Dedicated train
Transport to harbor near storage site	Cont.-b. ship	Cont.-b. ship	Cont.-b. ship	Cont.-b. ship			
Transport to storage site onshore facilities or ship terminal	Cont.-b. truck	Cont.-b. truck	Cont.-b. truck	Cont.-b. truck	Dedicated truck	Dedicated ship	Dedicated ship

For KVA Hagenholz, the transport pathways described in Table 3 only start at ARA Werdhölzli. Indeed, the CO_2 is transported in gaseous phase by pipeline from KVA Hagenholz to ARA Werdhölzli, where it is liquefied and loaded into ISO tank containers. Table 4 outlines the characteristics of supply chains from KVA Hagenholz to the Northern Lights storage site based on the abovementioned transport solutions.

Table 4: Selected transport chains from KVA Hagenholz to the Northern Lights onshore location with characteristics corresponding to each chain (rounded values).

Transport pathway KVA Hagenholz – Northern Lights (± ca. 10%)	Solution 1	Solution 2a	Solution 3	Solution 4	Solution 5
Levelized costs of avoided CO_2 (LC_{av}) [EUR/t]	480	495	510	870	355
Levelized costs of stored CO_2 (LC_{st}) [EUR/t]	360	380	380	520	280
LC transport [EUR/t]	160	170	170	310	80
Gas pipeline	2	2	2	2	2
Truck	20	20	100	310	20
Train/barge	70	80			40
Ship	60	60	60		20
Truck – NO	10	10	10		
Distance [km]	2000	1950	1850	2500	1950
Gas pipeline	15	15	15	15	15
Truck	100	100	800	2500	100
Train/barge	850	800			850
Ship	1000	1000	1000		1000
Truck – NO	50	50	50		
Duration roundtrip [d]	16	10	6.5	5.5	n.a.
Truck	0.5	0.5	1	5.5	0.5
Train/barge	10	4			6
Ship	5	5	5		4.5
Truck – NO	0.5	0.5	0.5		
Containment					
isotainers/day[3]	60	60	60	0	0
trucks/day[3]	60	60	60	50	50
wagons/day[3]	0	60	0	0	0
trains/day[3]	0	2.5	0	0	0
barges/week	2	0	0	0	3.5
ships/week	1	1	1	0	1
Energy for transport [GJ/t]	0.58	0.43	1.05	2.16	0.29
Gas pipeline	0.01	0.01	0.01	0.01	0.01
Truck	0.09	0.09	0.89	2.15	0.07
Train/barge	0.33	0.18			0.13
Ship	0.10	0.10	0.10		0.08
Truck – NO	0.06	0.06	0.06		

[3] Accounting for 6 working days per week

Transport pathway KVA Hagenholz – Northern Lights (± ca. 10%)	Solution 1	Solution 2a	Solution 3	Solution 4	Solution 5
Global warming impact of transportation [kg CO_2-eq / t CO_2-transported]	135	127	152	293	94
Gas pipeline	0.2	0.2	0.2	0.2	0.2
Truck	15	15	120	290	12
Train/barge	80	77			54
Ship	19	19	19		28
Truck	7	7	7		
Container	14	9	6		
Global warming impact of CCTS chain [kg CO_2-eq / t CO_2-stored]	250	240	260	400	210
CO_2 avoidance efficiency of CCTS chain (η_{av})	75%	76%	74%	60%	79%

The levelized costs of transport of the first three chains are similar, while they almost double when truck transport only is considered. One also observes that the levelized costs of transport would almost be halved with the use of dedicated transport options, however reconditioning costs, which are not considered, might be significant. In Table 4, one can observe that the costs of transport reflect mainly the distance, because economies of scale are very limited with the available existing transport modes. The duration of the roundtrip depends mainly on the choice of transport option and influences the number of isotainers needed to sustain the whole chain.

Table 5: Selected transport chains from KVA Hagenholz to Carbfix with characteristics corresponding to each chain (rounded values).

Transport pathway KVA Hagenholz – Carbfix (± ca. 10%)	Solution 1	Solution 2a	Solution 5
Levelized costs of avoided CO_2 ($\mathrm{LC_{av}}$) [EUR/t]	590	600	365
Levelized costs of stored CO_2 ($\mathrm{LC_{st}}$) [EUR/t]	430	440	280
Levelized costs of transport [EUR/t]	240	250	90
Gas pipeline	2	2	2
Truck	20	20	20
Train/barge	70	80	40
Ship	140	140	30
Truck – IS	10	10	

Transport pathway KVA Hagenholz – Carbfix (± ca. 10%)	Solution 1	Solution 2a	Solution 5
Distance [km]	3200	3150	3150
Gas pipeline	15	15	15
Truck	100	100	100
Train/barge	850	800	850
Ship	2200	2200	2200
Truck – IS	50	50	
Duration roundtrip [d]	21	15	n.a.
Truck	0.5	0.5	0.5
Train/barge	10	4	6
Ship	10	10	8
Truck – IS	0.5	0.5	
Containment			
isotainers/day[3]	60	60	0
trucks/day[3]	60	60	50
wagons/day[3]	0	60	0
trains/day[3]	0	2.5	0
barges/week	2	0	3.5
ships/week	1	1	1
Energy for transport [GJ/t]	0.70	0.55	0.39
Gas pipeline	0.01	0.01	0.01
Truck	0.09	0.09	0.07
Train/barge	0.33	0.18	0.13
Ship	0.23	0.23	0.18
Truck – IS	0.05	0.05	
Global warming impact of transportation [kg CO_2-eq / t CO_2-transported]	163	154	127
Pipeline	0.2	0.2	0.2
Truck	15	15	12
Train/barge	80	77	54
Ship	42	42	61
Truck	7.5	7.5	
Container	19	13	
Global warming impact of CCTS chain [kg CO_2-eq / t CO_2-stored]	270	270	240
CO_2 avoidance efficiency of CCTS chain (η_{av})	73%	73%	76%

Comparing Table 4 and Table 5, one observes again that the costs scale with the distance for existing transport options with limited volume, while the distance has less influence in the case of dedicated transport. This is mainly because for longer distances, the designed vessels are larger but run less often, and their cost does not scale linearly with their size. Smaller vessels are used for shorter distances because less temporary storage is required, thus decreasing the overall costs of transport.

Since the chains follow the same pathway until Rotterdam before bifurcating either towards Northern Lights or towards Carbfix, the following tables are merged, the figures for the two destinations being reported in the same column but with different colors. As shown in Table 6 below, the direct access to the railway network thank to the private railway station of Jura Cement Wildegg makes different alternative solutions possible, e.g., solution 2b and solution 6. The difference in transport costs between the barge and the train solution is small, and the latter allows for shorter transport paths, both in distance and time.

Table 6: Selected transport chains from JC Wildegg to the Northern Lights and Carbfix onshore locations with characteristics corresponding to each chain (rounded values).

Transport pathway JC Wildegg – Northern Lights / Carbfix (± ca. 10%)	**Solution 1**	**Solution 2b**	**Solution 5**	**Solution 6**
Levelized costs of avoided CO_2 $(\mathrm{LC_{av}})$ [EUR/t]	390 / 490	385 / 485	270	275 / 280
Levelized costs of stored CO_2 $(\mathrm{LC_{st}})$ [EUR/t]	300 / 365	305 / 370	220 / 210	225 / 220
Levelized costs of transport [EUR/t]	155 / 235	160 / 240	75 / 80	80 / 85
Truck	20	0	15	0
Train/barge	65	90	40	60
Ship	60 / 140	60 / 140	20 / 25	20 / 25
Truck – NO / IS	10	10		
Distance [km]	1950 / 3150	1900 / 3100	1900 / 3100	1850 / 3050
Truck	50	0	50	0
Train/barge	850	850	850	850
Ship	1000 / 2200	1000 / 2200	1000 / 2200	1000 / 2200
Truck – NO / IS	50	50		
Duration roundtrip [d]	16 / 21	9.5 / 14.5	n.a.	n.a.
Truck	0.5		0.5	
Train/barge	10	4	6	4.5
Ship	5 / 10	5 / 10	4.5 / 8	4.5 / 8
Truck – NO / IS	0.5	0.5		
Containment				
isotainers/day	90	90	0	0
trucks/day	90	0	70	0
wagons/day	0	90	0	40
trains/day	0	4	0	2
barges/week	2	0	6	0
ships/week	1	1	1	1

Transport pathway JC Wildegg – Northern Lights / Carbfix (± ca. 10%)	Solution 1	Solution 2b	Solution 5	Solution 6
Energy for transport [GJ/t]	0.55 / 0.67	0.35 / 0.47	0.26 / 0.36	0.26 / 0.36
Truck	0.06		0.05	
Train/barge	0.33	0.19	0.13	0.18
Ship	0.10 / 0.23	0.10 / 0.23	0.08 / 0.18	0.08 / 0.18
Truck – NO / IS	0.06 / 0.05	0.06 / 0.05		
GWI of transportation [kg CO_2-eq / t CO_2-transported]	128 / 155	113 / 140	88 / 121	97 / 130
Truck	7		6	
Train/barge	80	78	54	69
Ship	19 / 42	19 / 42	28 / 61	28 / 61
Truck	7	7		
Container	14 / 19	8 / 13		
Global warming impact of CCTS chain [kg CO_2-eq / t CO_2-stored]	230 / 250	210 / 240	190 / 220	200 / 230
CO_2 avoidance efficiency of CCTS chain (η_{av})	77% / 75%	79% / 76%	81% / 78%	80% / 77%

The transport costs for CO_2 from ARA Bern shown in Table 7 show that for small amounts to be transported, container-based transport options are more economical than dedicated transport options, which come with very large investments. Nonetheless, this outcome is to be taken carefully, as multiple small emitters would probably merge into a common supply chain or would possibly share the same infrastructure, and thus achieve costs of transport similar to those of larger emitters.

Table 7: Selected transport chains from ARA Bern to the Northern Lights and Carbfix onshore locations with characteristics corresponding to each chain (rounded values).

Transport pathway ARA Bern – Northern Lights / Carbfix (± ca. 10%)	Solution 1	Solution 2a	Solution 5
Levelized costs of avoided CO_2 (LC_{av}) [EUR/t]	410 / 510	425 / 525	1'350 / 1400
Levelized costs of stored CO_2 (LC_{st}) [EUR/t]	330 / 400	350 / 420	1150
Levelized costs of transport [EUR/t]	200 / 280	220 / 300	1030
Truck	40	40	60
Train/barge	70	90	520
Ship	60 / 140	60 / 140	450
Truck – NO / IS	30	30	
Distance [km]	2000 / 3200	1950 / 3150	1950 / 3150
Truck	100	100	100
Train/barge	850	800	850
Ship	1000 / 2200	1000 / 2200	1000 / 2200
Truck – NO / IS	50	50	

Transport pathway ARA Bern – Northern Lights / Carbfix (± ca. 10%)	Solution 1	Solution 2a	Solution 5
Duration roundtrip [d]	16 / 21	9.5 / 14.5	n.a.
Truck	0.5		0.5
Train/barge	10	4	6
Ship	5 / 10	5 / 10	4.5 / 8
Truck – NO / IS	0.5	0.5	
Containment			
isotainers/day	1	1	0
trucks/day	1	0	1
wagons/day	0	1	0
trains/month	0	1-2	0
barges/year	2	0	3
ships/year	1	1	3
Energy for transport [GJ/t]	0.60 / 0.71	0.45 / 0.56	0.30 / 0.39
Truck	0.11	0.11	0.09
Train/barge	0.33	0.18	0.13
Ship	0.10 / 0.23	0.10 / 0.23	0.08 / 0.18
Truck – NO / IS	0.06 / 0.05	0.06 / 0.05	
Global warming impact of transportation [kg CO_2-eq / t CO_2-transported]	135 / 162	126 / 154	93 / 126
Truck	15	15	12
Train/barge	80	77	54
Ship	19 / 42	19 / 42	28 / 61
Truck	7	7	
Container	14 / 19	8 / 13	
Global warming impact of CCTS chain [kg CO_2-eq / t CO_2-stored]	190 / 220	180 / 210	150 / 180
CO_2 avoidance efficiency of CCTS chain (η_{av})	81% / 78%	82% / 79%	85% / 82%

The structure of the cost-effective supply chains for early mover solutions is very similar for both foreign permanent storage sites and for all emitters. Due to the lack of space on-site, the CO_2 captured at KVA Hagenholz is first transported via a gas pipeline to ARA Werdhölzli, where the conditioning takes place. In the cases of Jura Cement Wildegg and ARA Bern, one assumes that the conditioning is performed on-site. For all chains, the isotainers are filled and loaded onto trucks at the conditioning site. The isotainers are transported to Basel by truck, transferred to a barge and transported to Rotterdam where they are loaded on cargo ships. Those are going either to Bergen in Norway or to Reykjavik in Iceland, where the last transport exchange occurs. The last part of the chain to the storage sites of either Northern Lights or Carbfix is covered by truck.

The selected transport chains illustrated in Figure 10 and Figure 11 are the cost-effective pioneering supply chains (i.e., solution 1 in Table 3), although other might be preferred for logistics, environmental, societal or resilience reasons. Indeed, the transport pathways have been designed with respect to costs only and considering existing options. Figure 10 schematically illustrates the geographic features of the transport solutions. Figure 11 reports the levelized costs of stored CO_2 ($\mathrm{LC_{st}}$) as well as the levelized costs of avoided CO_2 ($\mathrm{LC_{av}}$). The levelized costs of stored CO_2 are the direct expenses for the deployment of the chain without accounting for the project emissions, while the levelized costs of avoided CO_2 account for the emissions associated with each supply chain, as described in Section 3.1.3.

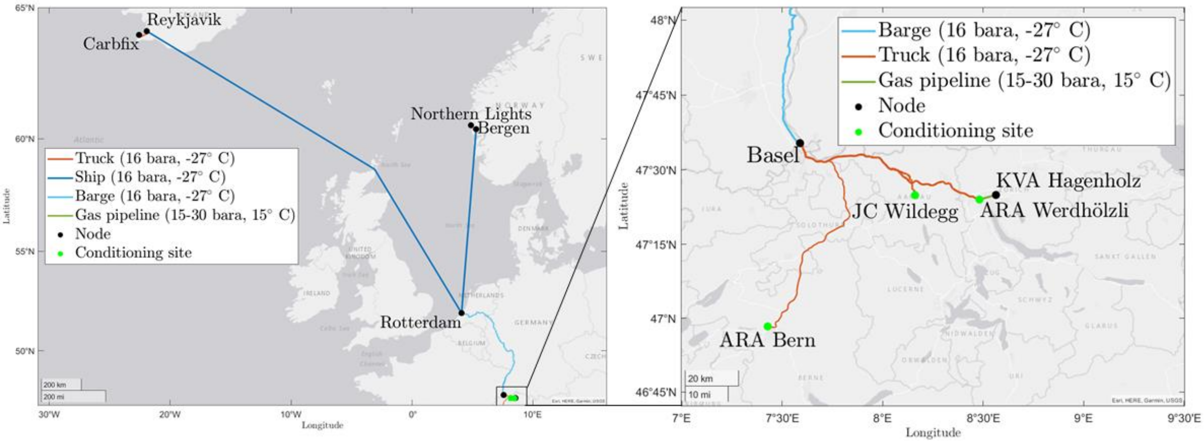


Figure 10 – *Left:* Cost effective supply chains for early movers in Switzerland to the permanent storage sites of either Northern Lights or Carbfix. *Right:* Detail of the chains within Switzerland.

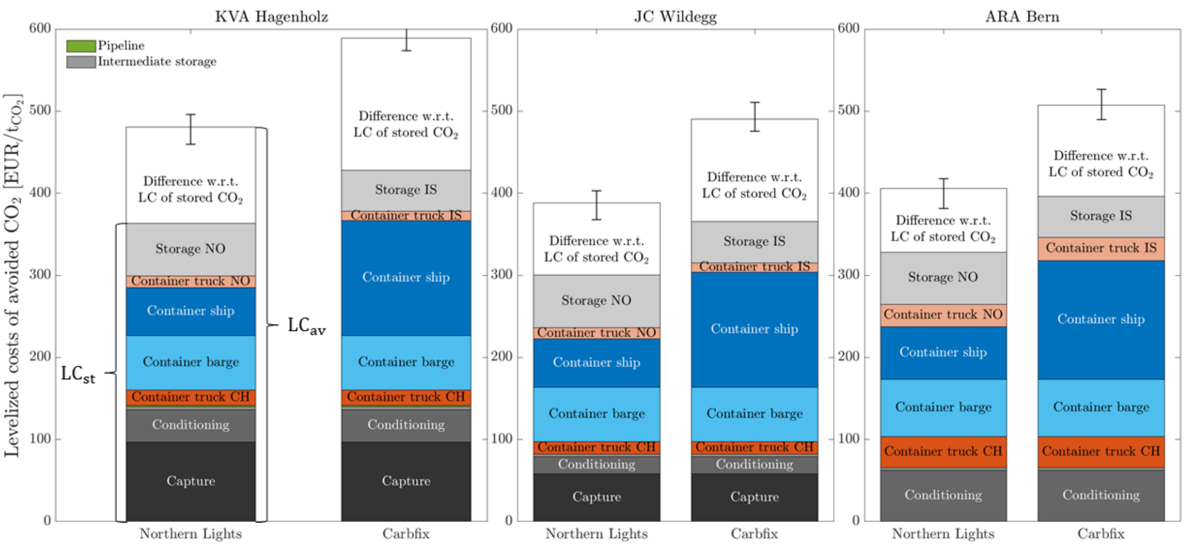


Figure 11 – Cost breakdown of the levelized costs of avoided CO_2 for the most economical supply chains for KVA Hagenholz, Jura Cement Wildegg, and ARA Bern to the storage sites of either Northern Lights or Carbfix.

As shown in Figure 11, the costs of avoided CO_2 vary among the emitters. The distribution of the costs among the different categories is different between the emitters because additional CO_2 capture is not needed at ARA Bern, thus not causing any supplementary costs. In the case of a plant that produces biogas but does not purify bio-methane from CO_2, some supplementary costs would occur for the capital and operational expenditures related to the installation and the operation of the biogas upgrading unit; however, these are outside of the scope of this study. Generally, as biomethane plants have a relatively small size and the CO_2 concentration is relatively high, membranes are used for capture. For KVA Hagenholz, and Jura Cement in Wildegg, the post-combustion capture of CO_2 accounts for approximately 15-25% of the overall costs. The transport part accounts for a large share of the costs, with barge and ship transport being the largest contributions. Similarly, the higher shipping costs to

Iceland are due to the longer distance. The small volume transported in each isotainer leads to minor economies of scale for this transport option, which can be observed in the small differences between the cost breakdowns of Jura Cement Wildegg and KVA Hagenholz. While the unitary transport costs do not differ much for different amounts of CO_2 transported, the investment costs for conditioning and temporary storage are considerably large for small volumes, resulting in the overall costs for ARA Bern being similar to those of Jura Cement Wildegg despite negligible capture costs.

The uncertainty related to the cost assessment is difficult to evaluate, and therefore the absolute values presented in Figure 11 should be interpreted with care. For that reason, this figure primarily serves as a comparative assessment among the different supply chains rather than for determining the exact costs related to the implementation of carbon dioxide supply chains. Furthermore, it is difficult to predict the future evolution of costs, as it also depends on the technology developments, on their learning curves, and on the evolution of the material and energy costs. Nonetheless, the willingness to act shown by certain emitters seems to be more important than the definition of an exact business case as criterion to make investment decisions on CCTS or CCUS.

In addition to the cost assessment, further considerations have to be made to obtain a comprehensive evaluation of the supply chains. Considering the similar structure of all chains, they share similar limitations and challenges. The complexity is high, as many transport exchanges take place, which necessitate a broad cooperation between the different service providers. This complexity can be observed in the realization of the demonstration chain in WP3, the only notable difference in the analysis here with respect to the actual implementation in WP3 being the much larger amount transported and the use of barge transport between Basel and Rotterdam. The used transport options in the chains presented here all present a risk of delays, due to congestion on the roads for trucks or in the harbors on the Rhine River for barges, respectively. As far as meteorological and climatic uncertainties are concerned, the potential for low water levels on the Rhine River can reduce the throughput of goods' transport for a certain period, or even interrupt it. In the winter, the bad weather conditions can also slow down ship transport. Finally, since cargo ships are operating connections with a lower frequency than the other means of transport along the chain, buffer isotainers need to be planned to prevent the consequences of a missed connection.

In the future, dedicated barges and ships might be used to cover the journeys on the Rhine and on the sea, thus importantly decreasing the costs of transport. Dedicated trucks with fixed tanks also exist. Those have not been considered for pioneering supply chains, as it would require a dedicated filling station for isotainers at the harbor of Basel, which is regarded as a significant greenfield infrastructure requirement.

In order to consider costs in a broader perspective, we compare the costs of transport in the short- and medium-term time horizon with the costs of transport considering a full pipeline network. For a pipeline network within Switzerland, Saipem reports transport costs of 30-35 EUR/tCO_2 (Saipem, 2021). Open Grid Europe (OGE) and Tree Energy Solutions (TES) plan a CO_2 pipeline network connected to the harbor of Wilhelmshaven with a capacity of 20-25 $MtCO_2$/y, which is planned to access the Swiss border in Wallbach between 2035 and 2040 (TES, 2023). The pricing model is not yet defined and could be based either on a postage stamp, on a zone pricing, or on a route pricing. Considering the capacity of the pipeline network and the distance, the cost of transport is estimated at 10 EUR/tCO_2 from the Swiss border to the north of Germany (Oeuvray, Burger, Roussanaly, Mazzotti, & Becattini, 2024). Finally, an offshore pipeline between Wilhelmshaven and a storage site off the Norwegian coast with a capacity of 10 $MtCO_2$/y is planned to be operated from 2028, and its capacity to be increased to 40 $MtCO_2$/y by 2040 (Wintershall Dea, 2022). For the 900 km from the German coast to the storage site the costs of transport are estimated between 10-15 EUR/tCO_2 (Wintershall Dea, 2022). In the case of Iceland as a final destination, it is less likely that an offshore pipeline will be built over such a long distance; however, we estimate a cost of 20 EUR/tCO_2 with low-pressure dedicated ships connecting continental Europe with Iceland. Overall, the total costs of transport are estimated to be 50 to 60 EUR/tCO_2 from Switzerland to the North Sea off the coast of Norway, and 60 to 65 EUR/tCO_2 from Switzerland to Iceland.

Beside the comparison with future long-term transport options, the option of geological storage abroad is compared with the possibility of storing CO_2 in concrete in Switzerland, which comprises both direct mineral carbonation of Recycled Concrete Aggregates (RCA) and slurry carbonation. Rosa et al. report a total potential for storage in concrete of 110 ktCO_2/y in Switzerland, considering 50% concrete waste recycling and a theoretical mineral carbonation potential of 45 kgCO_2/t_{RCA} (Rosa, Becattini, Gabrielli, Andreotti, & Mazzotti, 2022). Tiefenthaler et al. predict the amount of demolition concrete to remain constant until 2025, before rapidly growing until 2050 (Tiefenthaler, Braune, Bauer, Sacchi, & Mazzotti, 2021). Table 8 reports the total annual potential for CO_2 utilization and storage in recycled concrete.

Table 8: Reference values for the evaluation of the utilization and storage potential for CO_2 in recycled concrete.

	Lower bound - 2025	**Higher bound - 2050**	**(Rosa, Becattini, Gabrielli, Andreotti, & Mazzotti, 2022)**
Amount of concrete annually demolished	4 Mt[4]	40 Mt (Tiefenthaler, Braune, Bauer, Sacchi, & Mazzotti, 2021)	4.89 Mt
Concrete waste recycling	90% (Fachverband der Schweizerischen Kies- und Betonindustrie FSKB , 2022)		50%
Amount of RCA available for mineral carbonation	3.6 Mt_{RCA}	36 Mt_{RCA}	2.44 Mt_{RCA}
Total mineral carbonation potential[5]	15.5 kgCO_2/t_{RCA}	15.5 kgCO_2/t_{RCA}	45 kgCO_2/t_{RCA} (theoretical potential)
Total annual potential	55 ktCO_2	560 ktCO_2	110 ktCO_2

Based on these evaluations and on the direct and slurry mineralization potential reported above, we obtain a total potential for storage in concrete of 55-560 ktCO_2/y in Switzerland. This broad range indicates the uncertainty associated with the amount of CO_2 that can potentially be stored in recycled

[4] FSKB reports an amount of construction waste of 500 kg per inhabitant each year (Fachverband der Schweizerischen Kies- und Betonindustrie FSKB , n.d.), which yields an amount for recycling of 3.93 Mt_{RCA} per year when multiplied with the Swiss population in 2021 (Federal Statistical Office FSO, 2022). Similarly, a model developed under contract of BAFU reports 1.5 mio m^3 of demolished concrete in 2014 (Schneider, 2016), which corresponds to ca. 3.60 Mt_{RCA} in that year. We consider a recycling rate of 90% in the following computations.

[5] The potential of direct mineral carbonation is reported to be 13 kgCO_2/t_{RCA} in WP2. For the slurry carbonation, we obtain a range between 2.37 and 2.69 kgCO_2/t_{RCA} depending on the concrete design (Type A or C), while Neustark reports a value of 2.57 kgCO_2/t_{RCA} for low quality concrete prepared with 100% slurry instead of fresh water. Therefore, we use the reference value of 2.5 kgCO_2/t_{RCA} in the following computations. This sums up to a total potential of 15.5 kgCO_2/t_{RCA}.

concrete. The lower bound corresponds to the emissions of one to two large waste water treatment plants, while the upper bound could accommodate the emissions of several waste-to-energy plants.

Therefore, the comparative supply chains are designed for ARA Bern, whose total emissions are below this threshold. For transport, we assume an average distance of 10 km between the emitter and the mineralization site, as in the LCA performed in WP2 and in an earlier study (Rosa, Becattini, Gabrielli, Andreotti, & Mazzotti, 2022). Because of the limited amount transported and the flexibility necessary to be able to distribute CO_2 towards different concrete recycling locations where the storage can be performed, we assume container-based road transport. Figure 12 shows the cost breakdown for four reference supply chains from ARA Bern. The conditioning and intermediate storage are considered the same for all chains, while transport and storage depend on the solution, and determine the difference in levelized costs of avoided CO_2. Contrarily to Table 7, we assume dedicated transport options to be shared with other emitters, which might give a more representative appreciation of the costs in the medium-term. The storage costs at Northern Lights and for mineralization in concrete are currently very similar, but might of course evolve similarly or differently with time.

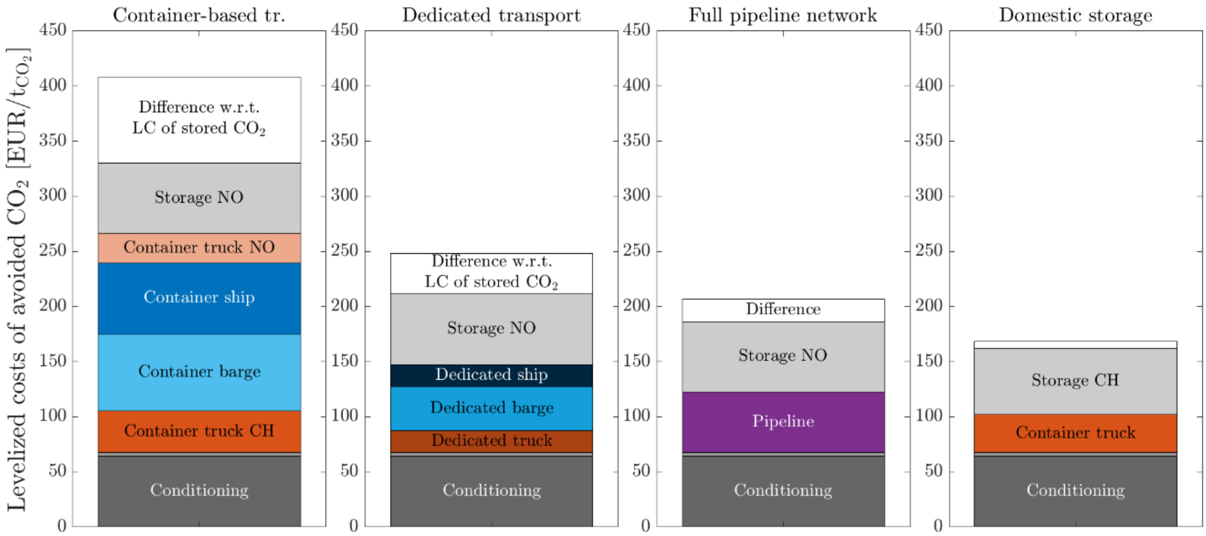


Figure 12 – Cost breakdown of reference supply chains for ARA Bern. From left to right: cost-effective pioneering supply chain with container transport; supply chain with dedicated transport; supply chain using a full pipeline network, all three with storage at the Northern Lights storage site (CCTS); supply chain with domestic storage in concrete (CCUS).

It is worth noting that even if the costs of capture (not applicable to ARA Bern), conditioning, intermediate and geological storage decreased, transport would probably remain the decisive factor. In Figure 12, the most economical chain is the supply chain with domestic storage in concrete, for which the transport distance is much shorter than for the other three chains that transport CO_2 over ca. 2’000 km to the storage site located in Norway. However, Figure 12 also shows the efficiency increase in costs and CO_2 avoidance when using dedicated transport or a full pipeline network.

Resource use

Beside costs, other aspects of the chains need to be considered, such as the CO_2 intensity of the supply chain, which is discussed in Subtask 1.3, and the risk and resilience, which are discussed in Subtask 1.4. Furthermore, the resources necessary for the operation of CCTS supply chains are a crucial element to ensure their implementation.

Energy

The energy necessary to operate CCTS chains can be divided into two categories: thermal and electrical energy. The thermal energy requirements encompass heat for capture and transport. Heat for capture is generally in the form of steam, while heat for transport is generally obtained from the combustion of fuel for the propulsion of trucks, barges, and ships. On the other side, electrical energy requirements include the power supply of capture units, heat pumps, conditioning units, pipeline pumping stations, and storage. Figure 13 shows the specific thermal and electrical energetic requirements that have been evaluated for the pioneering supply chains from the three emitters to geological storage in Norway, as shown in Figure 10.

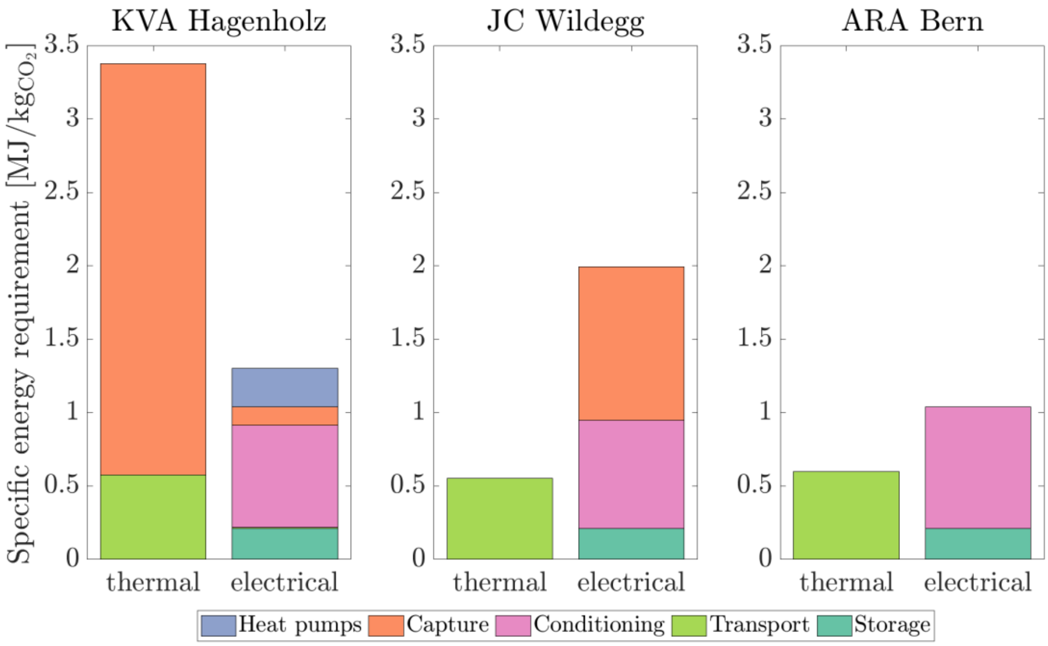


Figure 13 – Specific thermal and electrical energy requirements for each pioneering chain from KVA Hagenholz, JC Wildegg, and ARA Bern to the Northern Lights storage site.

Figure 13 shows that when applying post-combustion capture, the largest share of energy is needed for capture, while transport and storage have a smaller impact. The specific energy requirements for conditioning, transport and storage are equivalent for all three emitters. While the capture energy is assumed to be zero at ARA Bern because the separation from the biogas is already existing, KVA Hagenholz and Jura Cement Wildegg may operate post-combustion capture with different technologies at a capture rate of 90%, leading to a higher thermal energy demand and electricity demand for heat pumps at KVA Hagenholz, and a higher electrical duty at Jura Cement Wildegg. The details of the capture and conditioning energy consumption are discussed in the part of the report on Task 3. The transport options used for the pioneering chains are conventional and thus mainly operated with fossil fuels. The energy for the different transport chains is reported in Table 4-Table 10, which allows for a comparison between different transport options.

Figure 14 shows the total annual energy requirements to operate a CO_2 collection network capturing and transporting 7 $MtCO_2$/y up to the Swiss border. The annual thermal requirement is equivalent to the heat of combustion of 2 Mt of waste, considering the average heating value of waste (VBSA, 2022). The annual electrical requirement is similar in both cases and equivalent to 2.5% of the Swiss electricity final consumption in 2019 (BFE, 2019) or 80% of the electricity exported by WtE plants in 2021 (VBSA, 2022).

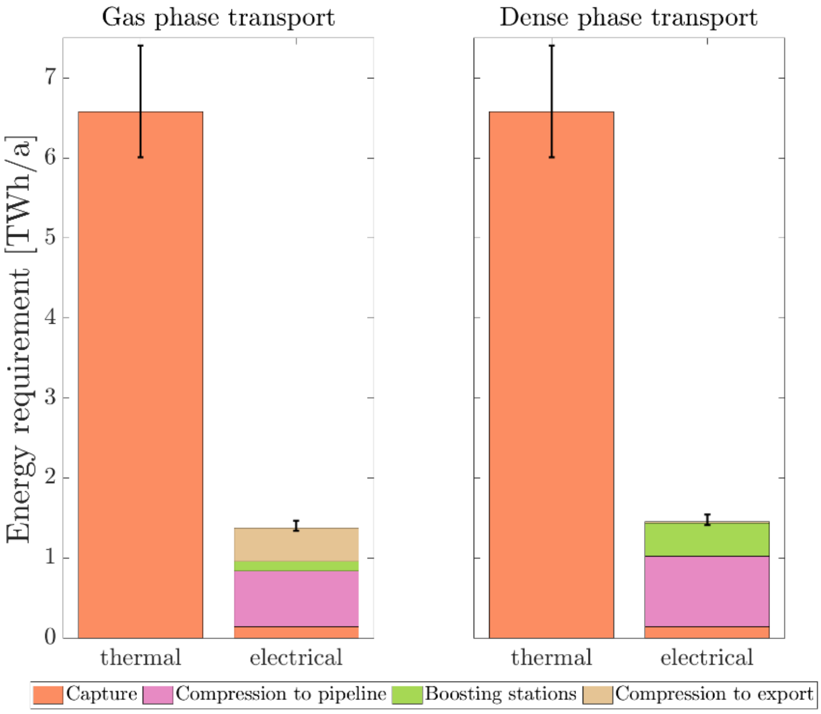


Figure 14 – Total annual energy requirement to operate a CCTS network within Switzerland with 90% capture rate at the 32 largest point-source emitters. Gas phase transport is on the left-hand side and dense phase transport is on the right-hand side.

Land footprint

The land footprint considered in this section comprises exclusively the installations associated to the stages taking place before the transport of the CO_2, which would generally be located at the emitter's site. This section aims at providing general considerations for future capture sites, based on the design performed in Task 3 for KVA Hagenholz and Jura Cement Wildegg.

From the areas reported in Table 9 below, we can compute an estimate of the area necessary to implement CCTS. While the capture technologies are different on each site, their specific land footprint is similar, and is therefore reported here for reference as average. Overall, the area required to implement capture, liquefaction, intermediate storage, and the handling of road or railway transport ranges from 40 to 50 m^2 per annual 1 $ktCO_2$ captured, as shown in Figure 15. In comparison, a DAC plant with a capacity of 1 Mt/y would occupy 0.4 km^2 (Fasihi, Efimova, & Breyer, 2019), which corresponds to 400 m^2 per annual 1 $ktCO_2$ captured, i.e., about 10 times more.

Table 9 : Space requirements for the installation of capture, conditioning, intermediate storage units and logistics handling at KVA Hagenholz and Jura Cement Wildegg based on the layout developed in Task 3 and the logistics report for KVA Hagenholz (Rapp AG, 2022).

	KVA Hagenholz	**Jura Cement Wildegg**
Annual emissions captured	382 kt	571 kt
Average captured mass flow in operation	12.7 kg/s	19.1 kg/s
Capture	1’600 m^2	2’300 m^2
Compression	825 m^2	530 m^2
Liquefaction (incl. compression)	1’100 m^2	810 m^2
Intermediate storage	700 m^2	1’000 m^2
Logistics – road transport	10’500 m^2	n.a.
Logistics – railway transport	17’000 m^2	n.a.

Figure 15 provides general land footprint considerations for emitters with a magnitude of several hundred ktCO_2/y. It is worth noting that while a linear factor can reasonably be applied for the capture, conditioning and intermediate storage plants, the logistics area might not grow linearly with the amount of CO_2 captured and transported. For instance, to ensure transport by truck, a drivable road access is needed, as well as ca. 270 m^2 such that a truck can turn around, which is unavoidable even for smaller amounts of CO_2. In the case that the transport chain is relying on container transport, the isotainers which are not in use have to be stored. An isotainer requires an area of ca. 15 m^2, and up to nine isotainers can be stacked on top of each other according to the norm ISO 1496/3. However, the operator of the plant might opt for smaller piles or for not stacking them for practicality reasons. Finally, a certain space has to be planned for the filling stations. Each station requires approximately 80 m^2 for the truck, the isotainer, and the hoses during the filling process. One filling station is sufficient for up to eight isotainer fillings per day; however, if several isotainers have to be filled at the same time, more stations have to be supplied.

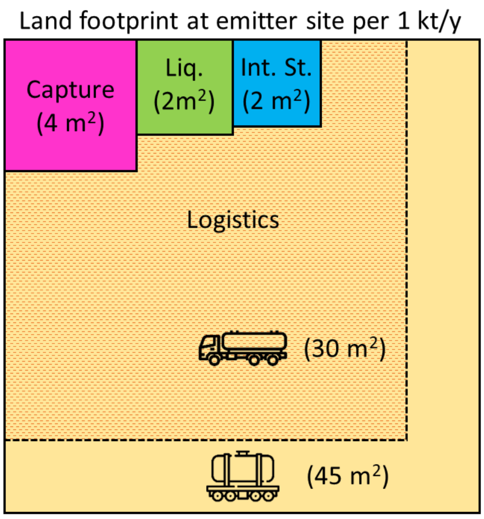


Figure 15 – Specific land footprint for an annual capture amount of 1 ktCO_2 including the capture, liquefaction, intermediate storage, and truck or train logistics, respectively.

Human resources

It is challenging to exactly forecast the human resources needed for the operation of CCTS plants. The workforce needed to operate the capture and conditioning plants does not grow linearly with the size of the plants. At ARA Bern, it is 0.2 FTE for the liquefaction plant, while at least 1 board operator and 2 field operators per shift are needed at KVA Hagenholz and Jura Cement in Wildegg. This sums up to 13 FTE when assuming 24/7 operation and ca. 2'000 h/FTE. The costs of labor represent 4-5 % of the annual costs of capture and conditioning combined. On the other hand, the labor force for the handling of isotainers grows approximately linearly with the plant size. Based on the operation at ARA Bern, ca. 1.5-2 FTE would be needed per each 100 ktCO_2 captured.

Perspectives on freight transport volumes

Besides the resources use described above, the transport of CO_2 will generate an increase in the use of existing transport infrastructure. This section aims at evaluating the impact of CO_2 transport on the Swiss infrastructure network, first considering the deployment of a CCTS chain for a single emitter, and finally evaluating the foreseen large-scale deployment of CCTS for all hard-to-abate emitters. With the construction of the third incineration line in 2027, 960 t_{MSW} will be daily delivered at KVA Hagenholz via 120 truck trips. At the same time, the 185 t of residues daily produced will be transported away by 10 truck journeys (ERZ). In Switzerland, truck transport sums up to approximately 160'000 journeys per day (OFS, 2022a; OFS, 2022b) for a little less than 1 million tons of goods transported (OFS, 2022). In comparison, the 1'000 tCO_2 daily captured at KVA Hagenholz would require the use of approximately 50 isotainers per day. At Swiss scale, approximately 520 isotainers would need to be used daily in order to connect all waste-to-energy plants in Switzerland (4.2 MtCO_2 emitted yearly (VBSA, 2019) with 90% capture efficiency).

Considering road transport, the Federal Roads Office has recently reported the average daily traffic of heavy goods vehicles (ASTRA, 2023). For the A3 in Effingen (AG), the average is ca. 2'300 trucks per day, while in Würenlos (ZH) on the A1, the average is ca. 8'500 trucks per day. Considering the transport of the CO_2 from KVA Hagenholz to Basel by isotainers loaded on a truck, this represents an increase of the heavy goods vehicles of about 2% on the A3 and of less than 1% on the A1, while using dedicated trucks would lead to an increase of less than 2% and of 0.5%, respectively.

For rail transport, 1.37 million containers, swap bodies and semitrailers have been transported by rail in 2021 (OFS, 2022b; OFS, 2022). Adding up the 18,250 annual containers of KVA Hagenholz would represent an increase of 1.3% for container transport by railway.

In the port of Basel, ca. 126,000 TEU containers have been transshipped in 2021 (OFS, 2022b; Port of Switzerland, 2021). Adding the isotainers from KVA Hagenholz would represent an increase of 15% in the container transport. Overall, the amount of goods treated at the port of Basel summed up to 5.4 Mt in 2021 and 4.6 Mt in 2022 (Port of Switzerland). Considering this amount, the mass added through the capture at KVA Hagenholz would represent a 7-8% increase.

It is worth noting that while the total transport of goods via containers in Switzerland was reported to be 720 Mtkm in 2021, the transport of bulk liquid summed up to 1,238 Mtkm (OFS, 2022), which is not considered in the foregoing comparisons that consider only transport by container. In the long-term, Switzerland is expected to export ca. 7 million tonnes of CO_2 in 2050 (The Federal Council, 2021), with a substantial share being transported as bulk. In 2022, 8.8 million tonnes of oil and derived products have been imported to Switzerland (Avenergy Suisse, 2023); it is noteworthy that oil and CO_2 have a similar density in the liquid phase. The main transport carriers for oil were pipeline (3.7 Mt), rail (2.9 Mt), barge (1.7 Mt), and road (0.6 Mt) (Avenergy Suisse, 2023). This comparison suggests that the deployment of CCTS supply chains is feasible at scale, because the amounts transported are similar for oil nowadays and CO_2 in the future.

3.1.3 Subtask 1.3 – Assessment of the life cycle environmental impact of CCTS and CCUS chains

For the life cycle assessment (LCA) of the early mover chains, inventories have been modelled for capture units, conditioning units, several transport modes, and geological storage sites. The inventories have been gathered from industry partners as well as from literature. Due to a lack of first-hand data, the LCA models rely on background data from ecoinvent 3.8 (Wernet, et al., 2016). Modelled technologies have been chosen based on their availability in the short term so that their deployment is theoretically possible within a few years.

The capture process for the KVA Hagenholz (KVAH) CCTS chain is assumed to be an amine-based post-combustion capture process based on the BASF OASE Blue process. In the base case, the heat for regeneration of the amine solution is supplied by heat pumps working at ambient conditions. The capture process for the Jura Cement Wildegg (JCW) CCTS chain is assumed to be a hot potassium carbonate post-combustion capture process based on the CO_2 Capsol process. The inventory data for the capture and the conditioning process are based on the engineering documents of the project partner Casale. The engineering documents can be found in the appendix for both the hot potassium carbonate process (Appendix III) and the amine-based process (Appendix IV).

For the BASF OASE Blue process, information on the used amines, their composition, and the amount of amine emitted to the environment is unavailable. In line with (van der Spek, Arendsen, Ramirez, & Faaij, 2016) and (Moser, et al., 2021) an aqueous solution of 2-amino-2-methyl-1-propanol (AMP) with a mass fraction of 20% and piperazine (PZ) with a mass fraction of 10% is assumed as a proxy. The amines emitted to the atmosphere with the CO_2-depleted exhaust gas were estimated with data from pilot studies (Moser, et al., 2021). Currently, characterization factors for converting the air emission of AMP and PZ to environmental impacts are unavailable for the impact assessment methods of the LCA. As an approximation, characterization factors from monoethanolamine (MEA) were used. In future work, the impact pathways of the amines should be investigated.

Findings and measurement data from the demonstration chains in WP3 are considered in the LCA in WP4 whenever possible. The used data includes, in particular, the specifications of the ISO tank containers, such as weight or filling volume and fuel consumption, to validate the transport models. A finding from the demonstration that is particularly important for the LCA is the gaseous phase remaining in the ISO tank container after unloading, which is transported back with the container to the emitter site. Additional inventory data was gathered from the literature: The steel demand for construction of the hot potassium carbonate capture process and the make-up stream of hot potassium carbonate were estimated with data from (Saunier, et al., 2019).

The LCA assesses the viability of early mover CCTS chains to avoid greenhouse gas emissions, i.e., whether operating the CCTS chain emits more greenhouse gases than it stores. The system boundary excludes the operation of the plants that result in the CO_2 point sources, as the plants are assumed to operate irrespective of any carbon capture effort (cf. Figure 16). The resulting system includes only the additional installations and processes that are required for retrofitting an existing plant with CCTS. Furthermore, the energy penalties resulting from integrating the capture unit and point source are considered, e.g., for KVA Hagenholz, the reduced electricity output of the waste-to-energy plant is compensated by electricity taken from the Swiss electricity grid. By subtracting greenhouse gases emitted over the life cycle of the CCTS chain from the CO_2 that is stored permanently, the avoided greenhouse gas emissions are calculated.

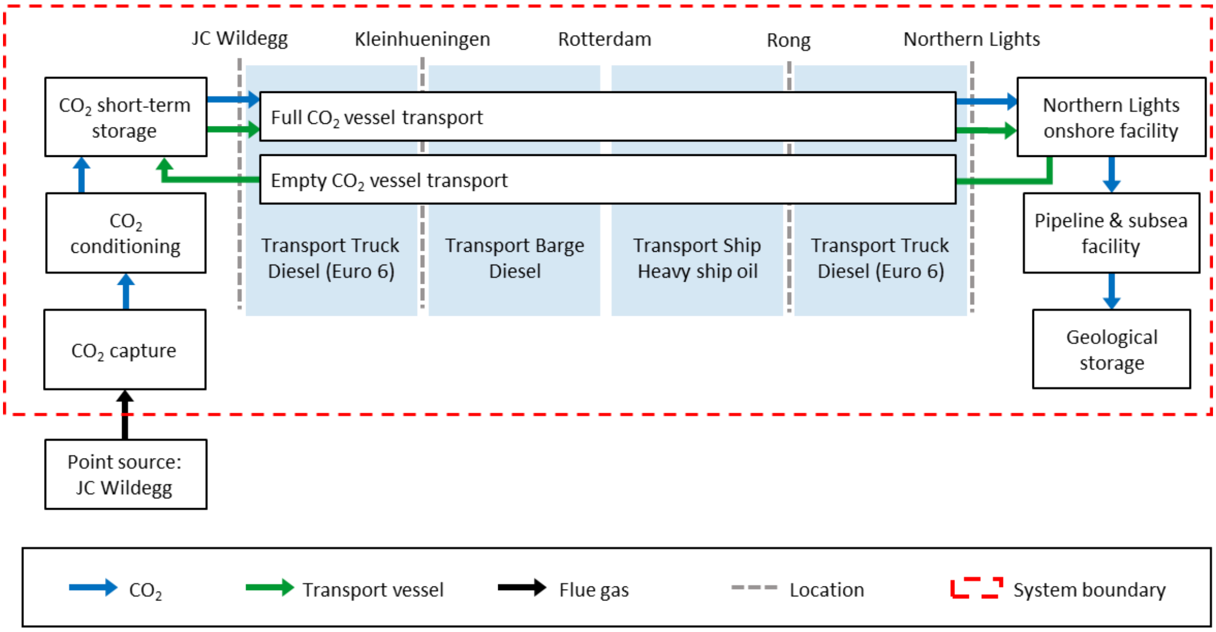


Figure 16 – Illustration of the system boundary of the CCTS chain in the life cycle assessment. Jura Cement Wildegg plant and the Northern Lights storage site are shown as examples of CO_2 sources and sinks.

Besides the global warming impact (GWI) caused by greenhouse gas emissions, other environmental impacts are calculated. For all impact categories, the Environmental Footprint method, version 3.0 (EF v3.0) is used (Fazio, et al., 2018). An overview of the impact categories considered and of their classification is given in Table 10. The classification clusters the impact categories and their indicators into three quality levels. With “I” (recommended and satisfactory) being the highest level, followed by “II” (recommended but in need of some improvements), and “III” (recommended, but to be applied with caution). More than the sixteen indicators shown in Table 10 exist but lack a recommendation level and are therefore neglected. By comparing the impacts caused by the CCTS chains environmental trade-offs can be highlighted. Furthermore, potential areas of burden shifting can be identified, where impacts in one impact category are reduced at the cost of another impact category.

Table 10: Impact categories from ILCD and their quality classification

Impact category	Indicator	Classification
Climate change	Radiative forcing as Global Warming Potential (GWP100)	I
Ozone depletion	Ozone Depletion Potential (ODP)	I
Human toxicity, cancer effects	Comparative Toxic Unit for humans (CTUh)	II/III
Human toxicity, non-cancer effects	Comparative Toxic Unit for humans (CTUh)	II/III
Particulate matter/ Respiratory inorganics	Intake fraction for fine particles (kg PM2.5-eq/kg)	I
Ionizing radiation, human health	Human exposure efficiency relative to U235	II
Photochemical ozone formation	Tropospheric ozone concentration increase	II
Acidification	Accumulated Exceedance (AE)	II
Eutrophication, terrestrial	Accumulated Exceedance (AE)	II
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	II
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	II
Ecotoxicity (freshwater)	Comparative Toxic Unit for ecosystems (CTUe)	II/III
Land use	Soil Organic Matter	III
Resource depletion, water	Water use related to local scarcity of water	III
Resource depletion, metals/minerals	Scarcity	II
Resource depletion, fossil	Scarcity	II

Global warming impact of early mover CCTS chains:

The global warming impact of the three CCTS chains from KVA Hagenholz, Jura Cement Wildegg, and ARA Bern to the Carbfix storage site in Iceland using the cost-effective dedicated transport solution is shown in Figure 17. The global warming impact for alternative transportation solutions is shown in Chapter 3.1.2 in Table 4 to Table 7. For all CCTS chains, the global warming impact, i.e., the greenhouse gas emission during the whole life cycle of the CCTS chain, is lower than the amount of stored CO_2. Therefore, each CCTS chain avoids greenhouse gas emissions. However, the differences between the chains using the cost-effective future transport solution are substantial, with the CCTS chain of KVA Hagenholz emitting 30% more than the CCTS chain of ARA Bern. The difference is a result of the capture and conditioning steps energy demand since the global warming impact of the transport and storage steps are similar across chains. However, when comparing CCTS chains throughout Europe, the transport step can lead to substantial differences between chains (Burger, et al., 2024).

The differences between the capture and conditioning steps of the CCTS chains are large: The KVA Hagenholz chain’s capture and conditioning steps emit 2.1 times as much as the ARA Bern chain. The main reason is that ARA Bern does not require an additional capture unit since it already includes a biogas upgrader, where CO_2 is separated. The biogas upgrader is not considered at ARA Bern because the assessment considers only additional efforts. For other wastewater treatment facilities, the impact of installing an additional biogas upgrader needs to be considered. For the KVA Hagenholz and JC Wildegg CCTS chains, the capture and conditioning step contributes 41% and 38% of the total global warming impact of the CCTS chain, respectively. The global warming impact of the capture and conditioning steps is dominated by the energy supply, with a share exceeding 85%.

As energy supply is responsible for a substantial share of global warming impacts, the LCA results are very sensitive towards the assumed heat and electricity source. In this study, we assume that the heat for the capture unit is supplied by heat pumps with a heat source at ambient temperature and that electricity is taken from the Swiss electricity grid mix.

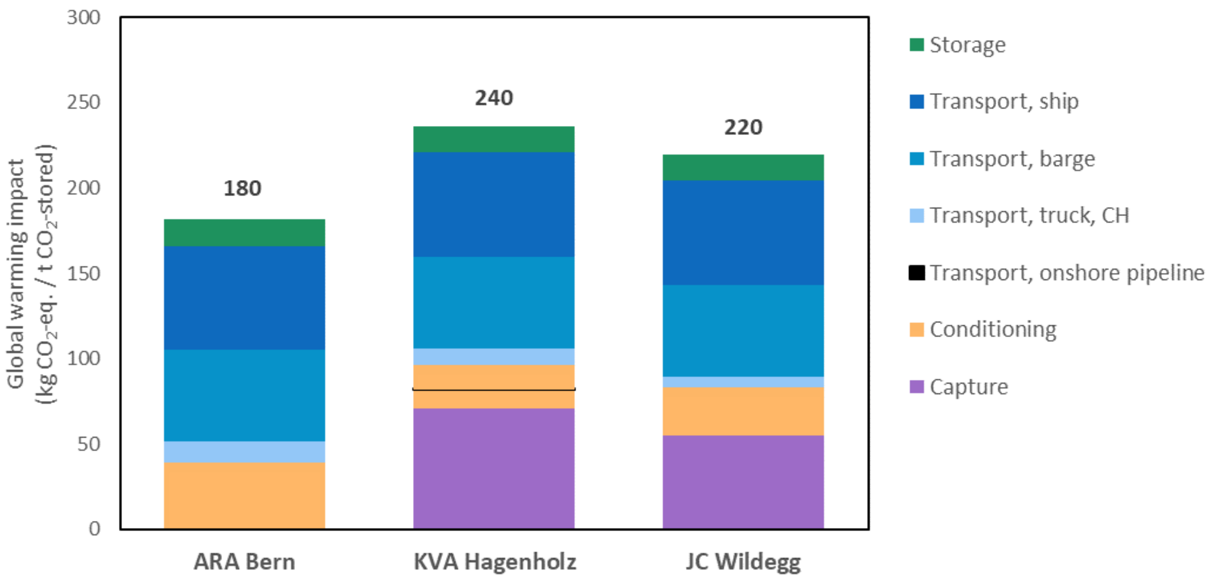


Figure 17 – Global warming impact of the chains for ARA Bern, KVA Hagenholz and JC Wildegg to the Carbfix storage site in Iceland, assuming the cost-effective future transport solution and heat supply by heat pumps working at ambient conditions.

Impact of heat sources on the global warming impact of early-mover chains

The global warming impact for alternative heat sources is shown in Figure 18. The heat demand of the hot potassium carbonate process is provided by internal recuperation of energy within the system; thus, no external heat supply is necessary. A heat integration with the waste-to-energy plant or an external heat source can be chosen for the amine-based capture process. In the case of heat integration, the reduced electricity output of the waste-to-energy plant is compensated by electricity taken from the Swiss electricity grid. External heat sources considered are wood, biogas and natural gas boilers, and heat pumps operating at ambient conditions. As a base case, the use of heat pumps operating at ambient conditions was assumed in Figure 17 and Table 3 to Table 7. Heat pumps are applicable to any waste-to-energy plant and are not restricted by the availability of biogas and biomass.

The heat supply via heat integration between the amine-based capture process and the waste-to-energy plant in Hagenholz reduces the global warming impact of the capture and conditioning unit by 44% compared to a heat supply via heat pumps and results in 36% less GWI than the capture and conditioning process for JC Wildegg. Heat integration can, therefore, substantially reduce GWI. However, it should be considered that the results considering heat integration depend on the availability of non-used heat and the energy penalty, so the reduced output of electricity and heat for district heating. Thus, the results depend on the local electricity and district heating demand the waste-to-energy plants have to fulfil, which change between different waste-to-energy plants and throughout the year. Therefore, the heat integration developed by Casale represents a winter case when the district heating output is typically the largest.

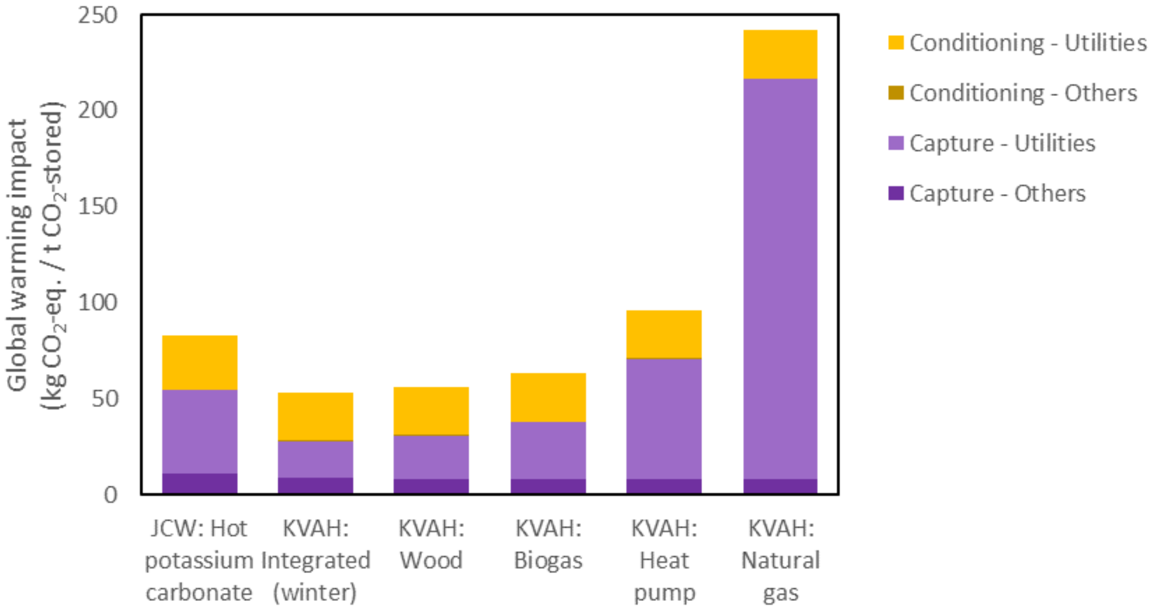


Figure 18 – Global warming impact for the capture and conditioning step of Jura Cement Wildegg (JCW) and of KVA Hagenholz (KVAH) for various heat sources. The consumer electricity grid mix of the Federal Office for the Environment is assumed for electricity supply.

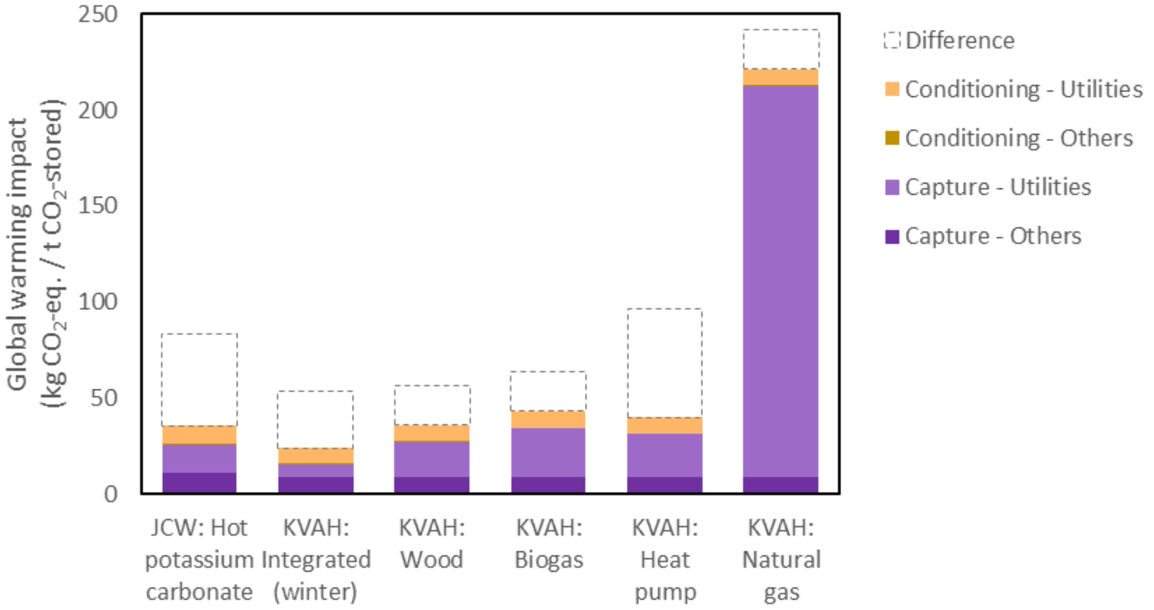


Figure 19 – Global warming impact for the capture and conditioning step of Jura Cement Wildegg (JCW) and of KVA Hagenholz (KVAH) for various heat sources. The Swiss electricity grid mix of ecoinvent 3.8 is assumed for electricity supply.

Impact of electricity mix on the global warming impact of early-mover chains

The environmental impacts of the consumed electricity strongly depend on the assumed electricity grid mix and assumptions on the import of electricity from neighboring countries. In the LCA results, the Swiss consumer electricity grid mix was assumed as given by the Swiss Federal Office of the Environment. For comparison, the commonly used Swiss electricity mix from ecoinvent results in a 67% smaller global warming impact per kWh, which consequently affects the global warming impact of the capture and conditioning step (Figure 19). Processes with comparatively high electricity consumption are also most impacted by the choice of electricity mix, such as the hot potassium carbonate process and the amine-based capture process with heat integration or heat pumps for heat supply. The choice of electricity mix further changes the ranking of the capture and conditioning alternatives with least GWI to the disadvantage of biomass and biogas boilers.

Global warming impact of ISO tank container and dedicated transport option

A comparison of the distance-specific GWI values for each transport mode is shown in Table 11. The GWI includes the transport of the filled container and the return trip of the empty container. The global warming impact of transport methods consuming electricity, e.g., train transport, depend on the respective country-specific electricity grid mix.

Table 11: Global warming impacts per ton-kilometer from iso-container and dedicated transport modes

Transport mode	**Global warming impact (g CO_2-eq/t km)**	
	ISO tank container transport	Dedicated transport
Truck	149	117
Train (NL)	96.2	85.4
Train (DE)	94.9	84.3
Train (CH)	26.9	23.9
Barge	93.8	63.8
Ship	18.9	27.5
Onshore pipeline (CH)	-	13.2

The global warming impact of dedicated transport methods is smaller compared to ISO tank container-based transport. This is mainly due to the large weight of the ISO tank container that needs to be transported along with the CO_2. As an exception, the global warming impact of dedicated ship transport increases compared to ISO tank container-based ship transport. This is due to the assumption that the dedicated transport via ship and barge loses 2% of the transported CO_2 over a transport distance of 1000 km (IPCC, 2005), thus increasing the global warming impact of the dedicated transport. For the dedicated ship transport, the loss of CO_2 outweighs the reduction of transported mass. However, this is not the case for the other environmental impact categories.

The results demonstrate that the early mover chains succeed in reducing the GWI of a point source. Contrary to previous studies (Volkart et al. 2013, Bisinella et al. 2022), the transport stage has a substantial impact and is responsible for approximately half of the impact of the whole chain (cf. Figure 17 and Table 3 to Table 7). While most studies previously assumed pipeline transport of CO_2, the CCTS chains investigated in this report rely on transport modes available earlier than pipelines with worse environmental performance (cf. Table 11).

There are two main reasons for the large contribution of the transportation step to the global warming impact compared to the literature: The large specific impact of the available transport modes and the long transport distance. The investigated transport modes are container-based. Initially, no pipeline is used for long distances. The specific global warming impact per ton-kilometer is larger for container-based transport modes than for pipeline transport (cf. Table 11). However, the global warming impact of transport is expected to decrease, first when switching from iso-container-based transport to dedicated-vessel transport and further when pipeline transport becomes available. For the CO_2 transport chains from the ARA Bern, the KVAH, and the JCW to the Northern Lights and the Carbfix storage facility, the GWI of the cost-effective dedicated transport chain is 31% or 22%, respectively, smaller than the ISO tank container-based transport chain (cf. Table 3 to Table 7). The large distance between point sources and the storage site further increases transport impacts. With the storage located in Iceland, the CO_2 needs to be transported more than 3'000 km.

Note that the difference in the impact of the CCTS chains for ARA Bern between the LCA conducted in this report to the LCA conducted in the report to 'WP3: Demonstration of CO_2 transport and geological storage (abroad)' is caused by the transport chain, which has changed from the ISO tank container-based transport to the dedicated transport options. While the LCA in WP3 aims to model the demonstration CCTS chain, WP4 extends the scope and considers alternative transport technologies in a generalized LCA. For instance, a barge is considered for transport along the Rhine for economic reasons in the LCA in WP4 with an overall lower climate impact when compared to transport by train considered in WP3.

Other environmental impacts of early-mover CCTS chains

Besides GWI, other environmental impact categories were investigated during the LCA. The impacts are presented relative to the environmental impacts of the CCTS chain for ARA Bern. Therefore, in Figure 20, the impacts from ARA Bern are always equal to one, and the impacts from the other point sources are indicated by a factor relative to ARA Bern. The ranking between the three early-mover chains is the same for nearly all impact categories: The ARA Bern CCTS chain shows the smallest impact in all 16 categories. In contrast, the KVA Hagenholz CCTS chain shows the largest impacts in 15 out of 16 categories. The main differences between the early-mover chains are the capture and conditioning steps since the transport and storage steps are similar across chains. Electricity consumption contributes most to the environmental impacts of the capture and conditioning step, with the heat supply being completely electrified. Thus, the ranking between the early-mover chains mainly follows the electricity demand of the processes. The only exception is the 'ecotoxicity, freshwater' impact of the JCW plant, which results primarily from potassium carbonate production.

The transport stage dominates half the impact categories by contributing over 50% to impacts in 7 of the 16 categories. Therefore, reducing direct emissions from the transport stage, e.g., by reducing the distance to the storage site, could substantially reduce impacts in multiple categories. For the CCTS chains for the KVAH and the JCW, the capture and conditioning step contributes more than 50% to 7 of the 16 impact categories.

As part of Subtask 1.3, the LCA results of the early mover chains were fed into the CCTS network optimization model in Task 3.5.

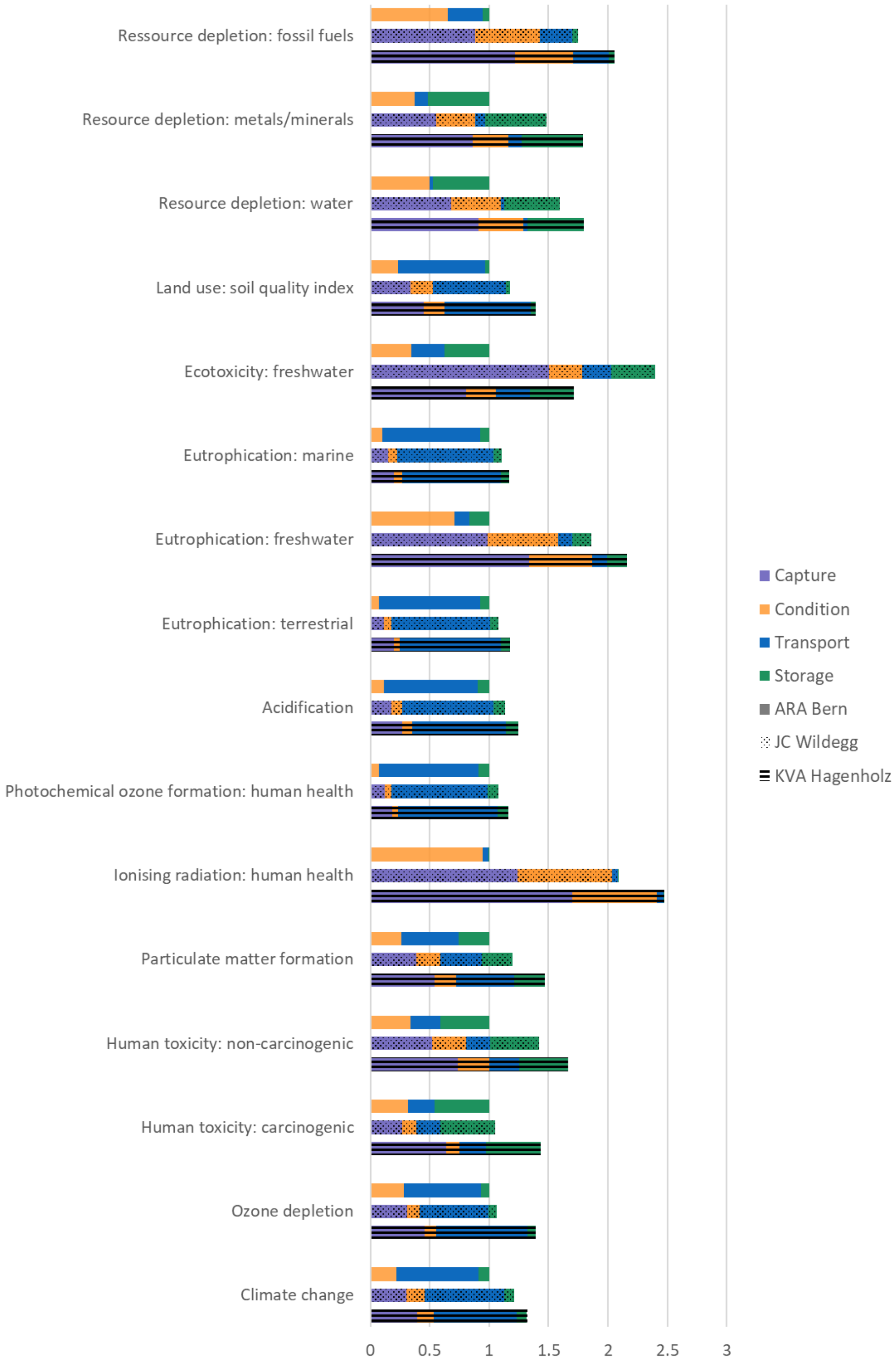


Figure 20 – Environmental impacts of the early-mover CCTS chains relative to the ARA Bern CCTS chain. The impact distribution between the capture, condition, transport, and storage steps is indicated by different colors. The impact value for the ARA Bern chain always sums up to 1.

3.1.4 Subtask 1.4 – Resilience analysis of CCTS and CCUS chains

Resilience of a CCTS supply chain is defined as its ability to permanently store the captured CO_2 during the time horizon of interest, and it is quantified in terms of expected amount of carbon not stored in case of failures or unexpected scenarios. Based on the methodology introduced in section 2.1, we conducted the following investigations into resilient CCTS supply chains.

Qualitative resilience assessment of early-movers supply chains. We find that system reliability and resilience can be increased by providing backup transport connections, installing temporary buffer storages, and providing a portfolio of storage options, including geological storage and carbon mineralization.

However, even though multiple alternatives are theoretically possible as response to a failure, not all are available at any given location. For example, space constraints at emitter sites or transfer hubs might be critical to the realization of resilience strategies. When planning with trucks as backup connection for a pipeline, the CO_2 needs to be in liquid state instead of supercritical, thus requiring a separate type of conditioning technology on site. Similarly for buffer storage which also requires CO_2 as a liquid and additionally requires space for the storage tanks. At locations where space is the limiting factor, for example at KVA Hagenholz, releasing the flue gas to the atmosphere might be the only option to respond to a failure. At transfer hubs, where a change in transport vehicle takes place, temporary storage appears to be the most suitable resilience option. First, we assume that transfer hubs have space available for cargo infrastructure, likely providing enough space for storage tanks or CO_2 containers. Second, the required equipment for conditioning the CO_2 is assumed to be available since a change in transport vehicle often requires compression or liquefaction, also under normal operation.

If the transport chain is based on standard containers, no additional infrastructure is required at the transfer hubs but the existing storage spaces for containers can be used. Although storing containers at transfer hubs is simple, the storage duration should be limited. Since the CO_2 inside a container is in liquid form, at temperatures around -36°C, the heat ingress from the outside into the container causes a pressure increase inside. The container specifications include a holding time, which specifies the duration for which the pressure increase does not exceed the maximum design pressure. Exceeding the holding time causes a safety valve to release CO_2 from the container. The container designs considered in this project have a holding time of at least 60 days, which is assumed to be enough for storing the containers during failure states.

Optimal design of cost and resilient CCTS supply chains for the Swiss WtE sector

We perform a single-year resilience analysis to determine the optimal CCTS supply chains in terms of (N-1)-resilience for the years 2030, 2040 and 2050. The single-year optimizations are constrained in such a way that the cost-optimal solutions match those obtained through the minimum-cost, multi-year optimization in Becattini et al. (2022).

Due to the large number of WtE plants present in the cost-optimal CCTS supply chain in 2030, 2040 and 2050, two different methods are adopted to handle the computational complexity resulting from the increased number of possible connections and failures. For all years, Delaunay triangulation is used to prune the connectivity matrix and to keep connections between close neighbors only. For the 2050 supply chain, where the entire network of WtE plants is part of the CCTS supply chain, the first method alone is not sufficient to handle the complexity of the optimization problem. Therefore, clustering is utilized to further reduce the dimensionality of the problem. The network is subdivided into smaller networks, which undergo their own resilience optimization. The resilient sub-networks are then reassembled. This procedure prevents nodes belonging to different sub-networks from forming backup connections.

Figure 21 shows the expected levelized cost of stored carbon (LCSC) (left-hand side bars and y-axis) and the expected CO_2 emissions (right-hand side bars and y-axis) for the cost-optimal (grey), the infrastructure-resilient (blue), and the environment-resilient (green) designs. The three cases are reported for years 2030, 2040 and 2050. The reduced network is also reported for reference. The configurations of selected CCTS supply chains are presented in Figure 22.

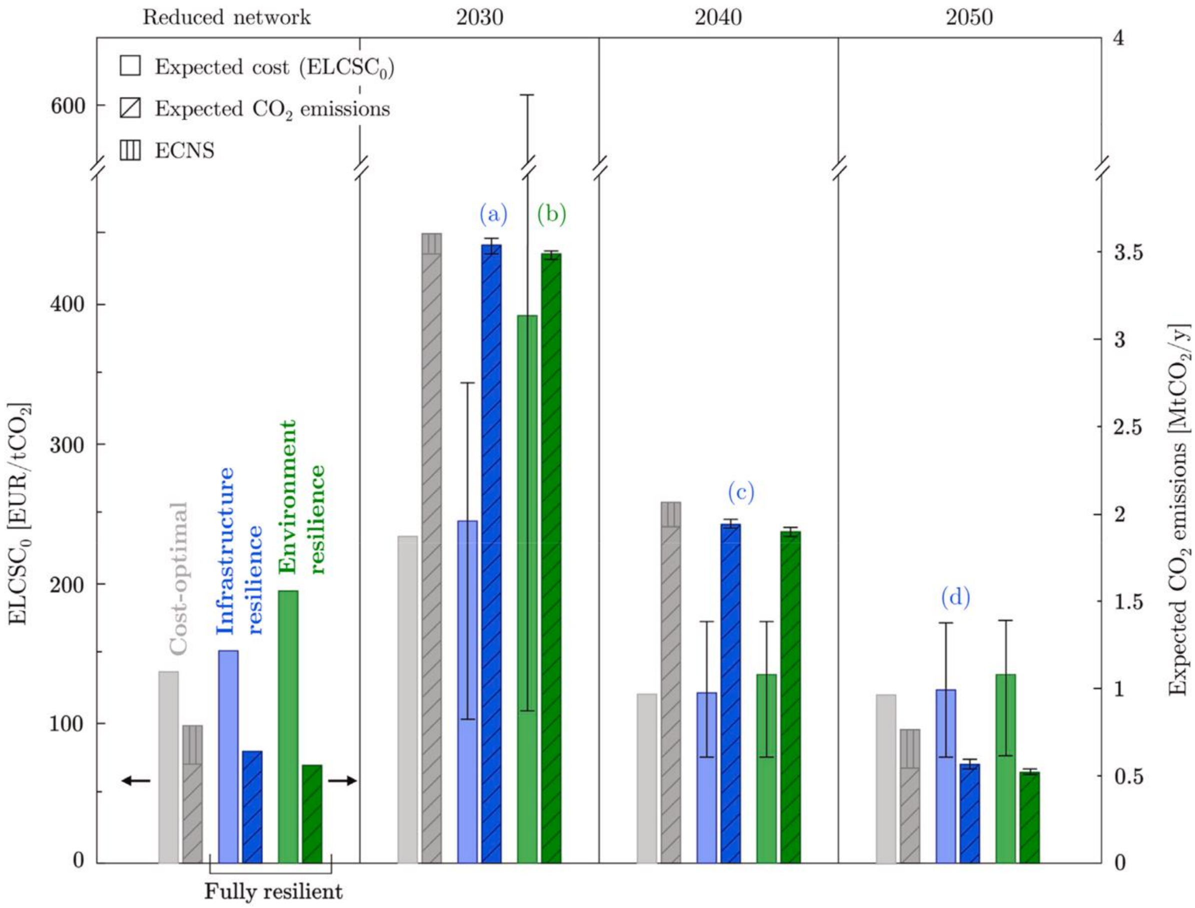


Figure 21 - Resilient CCTS supply chains for the Swiss WtE sector complying with a linear emission reduction pathway in 2030, 2040 and 2050. Expected LCSC (left-hand side bars and y-axis) and expected CO_2 emissions (right-hand side bars and y-axis) for the cost-optimal (grey),

In 2030, the CCTS supply chain maximizing infrastructure resilience (blue bars in Figure 21) is obtained at a nominal cost of 243 €/tCO_2 (+4% with respect to the cost-optimal solution), due to the additional investment costs required for the backup truck connections; when considering the expected costs in failure conditions, the total cost of the CCTS supply chain becomes 245 €/tCO_2 (+5%). This allows to avoid venting CO_2 into the atmosphere in the case of failures, hence reducing the expected CO_2 emissions of the cost-optimal supply chain by 50 ktCO_2 per year (about 1.5% of the CO_2 emissions of the WtE sector in 2030).

The CCTS supply chain maximizing environment resilience (green bars in Figure 21) comes at a much higher cost of 390 €/tCO_2 (+67% with respect to the cost-optimal solution), due to the additional investment costs required for the backup pipeline connections, which must be installed in addition to the cost-optimal connections (see Figure 22b).

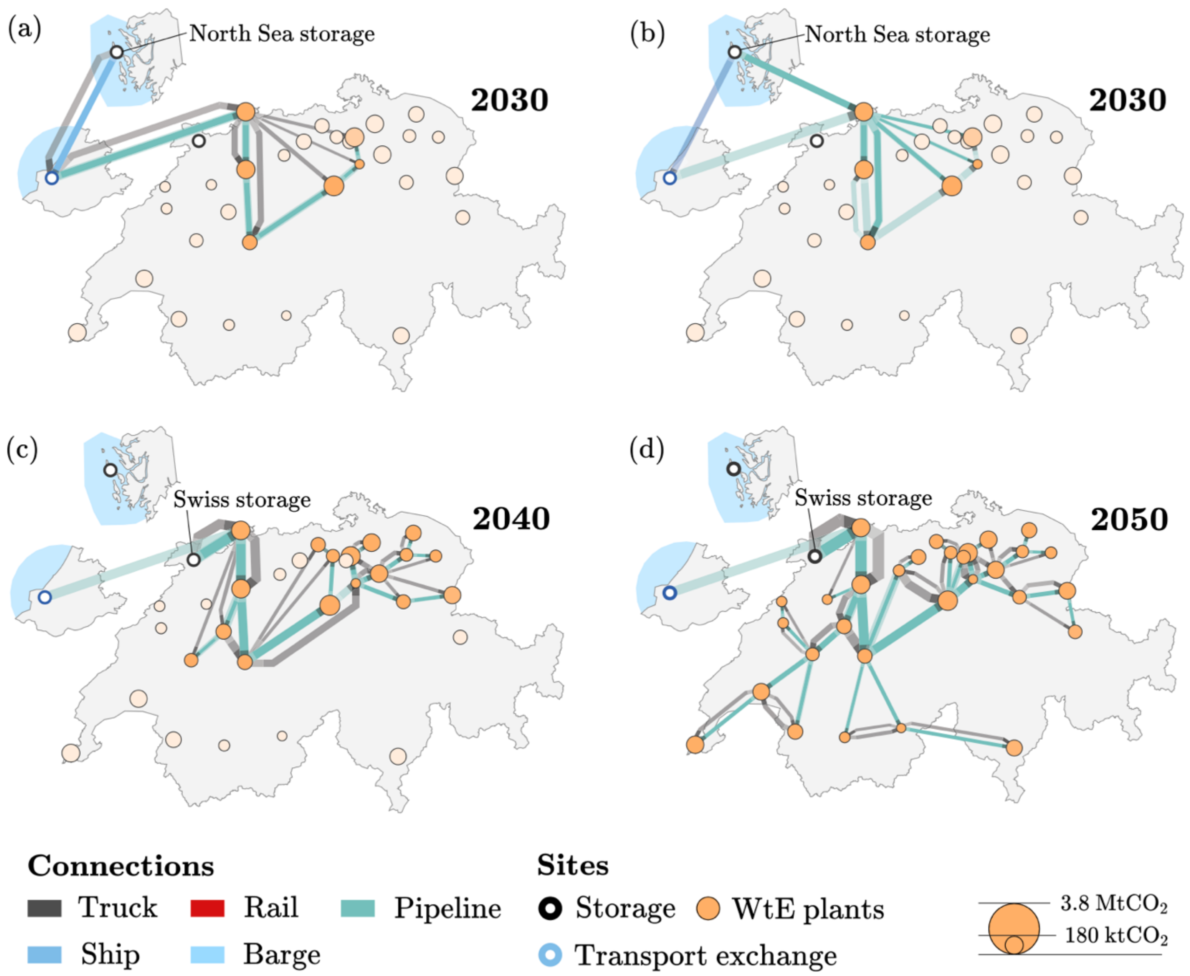


Figure 22 - Resilient CCTS supply chains for the Swiss WtE sector complying with the linear emission reduction pathway in 2030, 2040 and 2050. Schematic representation of the (N-1)-resilient design, based on the cost-optimal, multi-year solution. Infrastructure-resilient CCTS supply chains shown for years 2030 (a), 2040 (c) and 2050 (d), and environment-resilient CCTS supply chain shown for 2030 (b). The Swiss storage site is available in 2040 (b) and 2050 (d). Shaded colors indicate connections that are either no longer utilized, or that are backup solutions.

Infrastructure resilience is obtained via a truck network (see Figure 22), which allows to minimize the costs, whereas environment resilience is obtained via redundant pipelines (see Figure 22b), which allow minimizing the CO_2 emissions. The latter allows reducing the expected carbon emissions with respect to the cost-optimal solution by 100 ktCO_2 per year (about 3% of the CO_2 emissions of the WtE sector in 2030), but results in a drastic increase of costs.

The cost discrepancy between infrastructure and environment resilience becomes less pronounced in 2040 and 2050; this is because the differences between truck and pipeline are levelled off thanks to the assumed availability of the Swiss storage site, hence to the shorter distance for CO_2 transport, and to a greater utilization of the installed pipelines. The impact of the resilient designs on the CO_2 emissions of the supply chains increases from 2030 to 2050, as it depends on the amount of CO_2 transported. The infrastructure-resilience supply chain allows reducing the expected carbon emissions with respect to the cost-optimal solution by 200 ktCO_2 per year (about 25% of the CO_2 emissions of the WtE sector in 2050). Additional 50 ktCO_2 (up to 32% of the CO_2 emissions of the WtE sector in 2050) can be saved through the environment-resilience supply chain. For all cases, the expected operation costs and emissions do not differ significantly from the nominal values, due to the high reliability (i.e., low failure probability) of the available transport technologies.

Overall, the system benefits from using multiple modes of transport. Combined, the properties of the different modes of transport can be leveraged to design a resilient network at different scales. The low operation cost of pipelines makes them the most cost-effective solution for nominal operation. The low investment costs, high speed of transport, and wide availability of trucks make them the best backup technology, allowing for a drastic reduction in the cost of resilience compared to the other modes of transport.

Furthermore, we considered the effect of uncertainties on the design of the Swiss CCTS infrastructure. To this end, we defined a set of scenarios as part of and in alignment with subtasks 2.3 and 2.4, that define potential developments of the European CCTS infrastructure in the spatial and temporal dimension. The scenario definition is part of subtask 2.3 (see section 3.2.3) and the results are part of the network analysis in section 3.2.5.

3.2 Task 2 – Investigating techno-economic, environmental and reliability performance of a Swiss CO_2 network interconnected to an EU-wide shared CO_2 infrastructure as long-term solution

3.2.1 Subtask 2.1 – Further collection of data and information, and model development on the spatial and temporal dimensions

The largest point-source emitters of Switzerland have been collected to be included in the model, the cement, chemical and petrochemical, iron and steel, and waste-to-energy industries, which is reported in Table 12. The capture technologies included in the model are implemented by task 2.5.

Table 12: Annual CO_2 emissions of the largest emission sectors in Switzerland.

Industry	**Annual CO_2 emissions (2021)**
Waste-to-energy	4.0 Mt/a
Cement	2.3 Mt/a
Chemical and petrochemical	0.7 Mt/a
Steel	0.1 Mt/a

For the conditioning, the data from subtask 1.1 can be reused, and supplementary work is ongoing to obtain more detailed information on this stage of the chains. Indeed, there are two conditioning cases to differentiate: The first case deals with conditioning the carbon dioxide to the required specifications of transport after the capture stage. The second case deals with the potential need for reconditioning at transport exchanges between two transport modes differing in specifications. The second case has not yet been studied in literature and may impact the design of future supply chains.

With regard to modelled transport options, dedicated vessels and pipelines have been added including their temporal availabilities. For the transport option models, we have obtained data from a service provider on predicted costs for dedicated barges transporting carbon dioxide at medium pressure, i.e., 16 bara, while we are expecting to soon receive the same estimates for dedicated barges transporting it at low pressure, i.e., 8 bara. Presently, the cost estimates for dedicated ships at middle and low pressure, and for gas and dense phase pipelines are based on literature. Supplementary storage options will be added to the database based on the findings made in subtasks 2.4 and 2.5.

3.2.2 Subtask 2.2 – Clustering potential and strategies

For the Swiss point sources identified as part of subtask 2.1, their clustering potential is to be quantified in subtask 2.2. By clustering, the economies of scale for transporting the CO_2 may be utilized to decrease costs and environmental impacts for the individual point sources. By comparing results from task 2.5 and task 1.1, the benefit of using a shared infrastructure can be estimated. The costs for single emitters in task 1.1 do not fall below 200 €/tCO_2, even in optimistic scenarios. When a large-scale infrastructure is available and thus clustering the sources together becomes possible, the costs for transport decrease. Although the initial investment costs for a network infrastructure are substantial, so are the cost savings overall. For all scenarios in the network optimization (see tasks 2.3 – 2.5), the costs under the assumptions from tasks 2.3, 2.4, and 2.5 drop under 200 €/tCO_2 in the year 2040 at the latest. Therefore, even for scenarios with unfavorable conditions for CCTS deployment, clustering sources together makes sense from a financial perspective.

Two types of clusters are assessed:

1. *Clustering* of emitters. In this case, emitters are clustered together to utilize the same infrastructure for transporting the CO_2 to the export hub in Basel. Such clusters are preferably connected by pipeline, where emitters further away from the collection point in Basel transport captured CO_2 to the next emitter on the route to Basel. From there, a larger pipeline transports the CO_2 from both facilities towards the export hub. When clustering the CO_2 emitters and transporting CO_2 to the export hub in Basel the optimization was able to choose between two types of pipelines: a cheaper one with larger capacity, which could only be installed late in the time horizon, and a more expensive one with limited capacity that could be deployed from the beginning. The trade-off between lower cost and earlier installation showed a clear preference for earlier installation of the collection pipelines that connected the emitters with each other. Only close to the export hub in Basel, the larger pipeline was selected due to capacity limitations and larger cost savings. In section 3.2.5, more details regarding the two pipeline types are discussed. However, it seems clear that collecting CO_2 emissions with a shared infrastructure is beneficial at an early stage of the network already. From a resilience perspective, clustering emitters helps reducing the number of large connections that might cause global contingencies.

2. *Clustering of mineral carbonation CO_2 storage facilities*. Clustering also works in the opposite direction when the CO_2 sink has smaller capacities than the sources. In this project, the integration of mineral carbonation plants into the network is to be assessed. Storing CO_2 in recycled concrete aggregate has smaller demand for CO_2 (up to 2 ktCO_2 per year) than the point sources emit (between 100 and 500 ktCO_2 per year). Therefore, one capture unit at a point source can provide CO_2 to several domestic mineralization facilities where CO_2 is stored in recycled concrete aggregate. The transport within these clusters is done by truck or train, depending on the availability of a train station. Since the construction of carbonation plants is possible early in the optimization horizon, the clusters of carbonation plants around emitters are installed immediately in the cost-optimal solution.

In terms of resilience of emitter clusters, the system benefits from using multiple modes of transportation. Combined, their properties can be leveraged to design a resilient network at different scales. In this case, the low investment costs, high speed of transport and wide availability of trucks make them the best backup technology, allowing for a drastic reduction in the cost of resilience compared to the other modes of transport.

3.2.3 Subtask 2.3 – Definition of scenarios for an EU-wide shared CO_2 infrastructure.

In Europe, the near-term strategic T&S infrastructure focus is North of Switzerland. Switzerland is actively participating as a third country in projects in the North, all of which have the common goal of transporting CO_2 through Germany to storage sites in the North Sea. Additional project developments in this region provide resilience in case of setbacks, alterations, or capacity downsizing in one or more projects. Projects south of Switzerland have lower confirmed storage capacity and uncertainty regarding pipeline expansion possibilities. For Switzerland, the southern direction requires substantial additional pipeline infrastructure. Any potential setbacks in the southern projects could have considerable consequences due to the limited availability of viable transport and storage alternatives.

Based on project analyses, three potential scenarios stand out through which Swiss emissions can be transported to export terminals along the North Sea coast. These scenarios outline the countries and planned projects that would be part of each transport pathway. All scenarios provided are based on extending the Swiss pipeline network through Basel north to coastal terminals bordering the North Sea. Importantly, each scenario utilizes the German Carbon Transport Grid (GCTC) pipeline infrastructure to reach Northern Europe before splitting into three alternative pipeline networks made up of multiple network projects. The three coastal terminals are Wilhelmshaven in Germany, Rotterdam in the Netherlands, and Zeebrugge in Belgium.

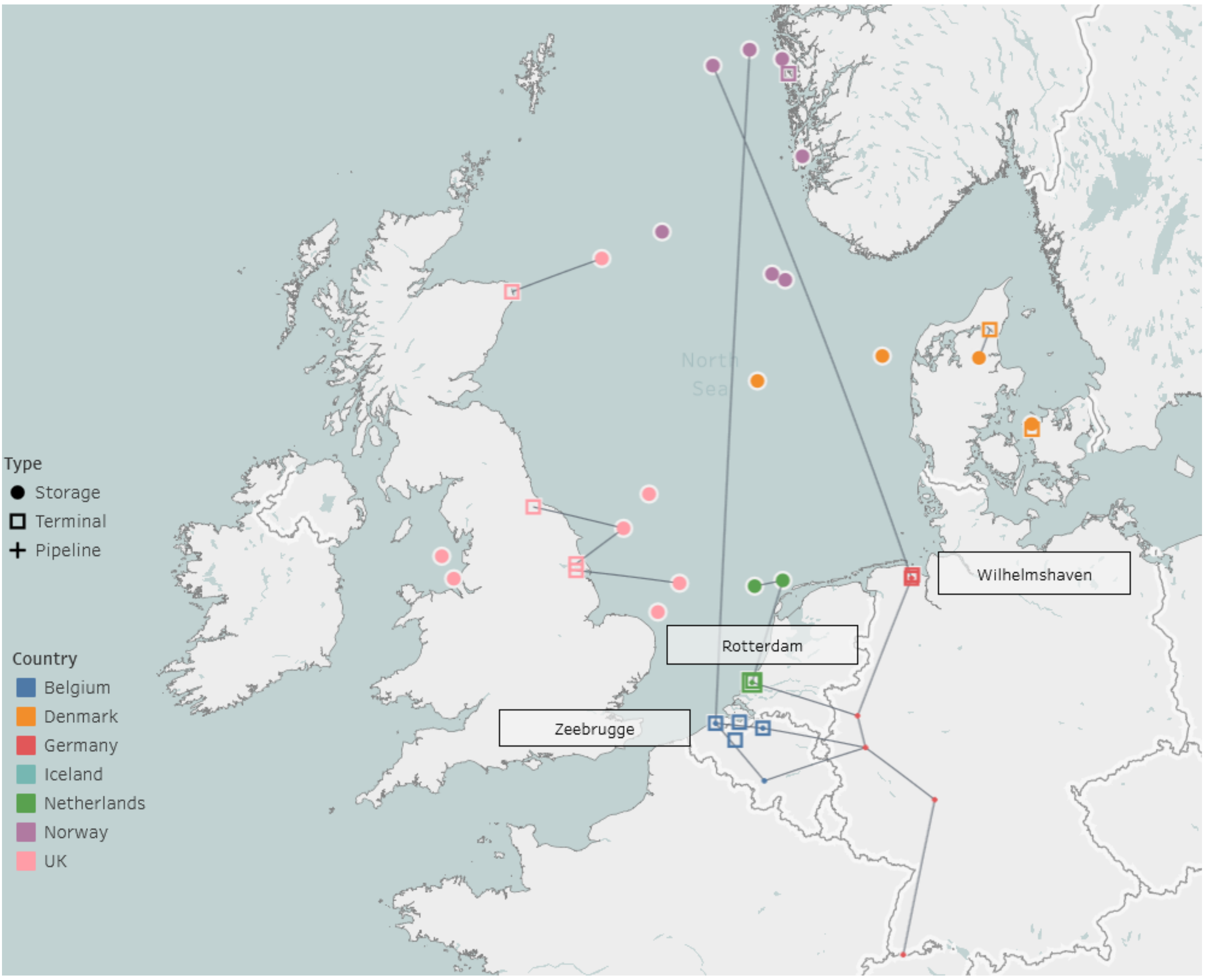


Figure 23: The Swiss CO_2 pipeline network may extend north towards three main export terminals in Germany, the Netherlands and Belgium. From there, CO_2 may be transported towards storage sites via pipeline or via multiple possible shipping routes, not shown on this map. The CO_2 is exported from the export terminals either to import terminals or directly to the storage site.

Pathways from these terminals to storage facilities are more diverse and include mostly offshore storage sites in the North Sea but also several onshore storage sites. North Sea offshore transport plans are set to connect all coastal countries through an intertwined network of projects, facilitating the storage of CO_2 across the region. Major pipelines planned through EU2NSEA, Aramis, and Bifrost have the potential to become central players within the European network, given their expected transport capacities. In addition to pipeline infrastructure, projects such as Northern Lights, NoordKaap, and Nautilus are at the forefront of a developing transshipment network that will be crucial in achieving the storage objectives of the European CO_2 transport network. Critically, transshipment projects will play an important role in addressing CO_2 overflows at export terminals or shortages at storage sites that could inject more CO_2. Here, the rigidity of the pipeline network will be counterbalanced through a fluid and expansive transshipment network connecting terminals to storage sites and terminals to other terminals. Many other transport and storage projects, for example, in the UK (Acorn CCS, Bacton Thames Net Zero, Northern Endurance Partnership), Denmark (NORNE, Greensand), Norway (Poseidon, Trudvang, Polaris, Errai, Stella Maris) and Iceland (Coda Terminal) have the potential to add additional storage capacities for the European T&S network and receive CO_2 imports from the aforementioned three terminals.

These scenarios are based on publicly disclosed project plans, which are backed by reputable public and private actors, instilling a degree of confidence. Nonetheless, it is crucial to acknowledge that the European project landscape is characterized by uncertainty and rapid evolution. While these aspects are not extensively explored in this report, they are of great importance for the realization of these network plans.

Many of the projects are still pending final approval, and they are still confronted with a multitude of technical, regulatory, financial, and social challenges that remain to be dealt with by industry players and governments alike. Storage capacities are still being investigated and confirmed, with projects inherently at risk of going over budget and past the projected timeline. Moreover, public opinion on CCTS is not reliably supportive, particularly for those regions that will be most directly impacted by planned infrastructure developments. It is foreseeable that numerous projects will have to adapt their plans and strategies to address these multifaceted challenges. The interdependencies of projects, especially relevant for the cross-border onshore pipeline infrastructure developments in Germany, the Netherlands, and Belgium, make assessing risks of potential setbacks difficult. Nevertheless, intermediate and hybrid transport solutions may serve as bridges until an established network links the Swiss CO_2 pipeline network with storage sites. Various other operational aspects are also important to address to translate the plans into reality. This includes the task of incorporating, managing and allocating flows and responsibilities between public and private actors in a shared network. Not only will CO_2 demand have to be effectively allocated, but competition may arise from, e.g., hydrogen projects.

Constantly evolving developments are evident, exemplified by the recent emergence of projects beyond Northern Europe. When assessing prospective CO_2 T&S pathways from Switzerland, it is imperative to integrate the most recent projects and their plans into the evaluation process. The upcoming final PCI list, which will be announced in November 2023, will provide more precise indications of the projects prioritized by the EU in shaping the Trans-European CO_2 network. Although the announced projects discussed and analyzed in this report are credible and backed by reputable actors, the nascent stage at which the planned network currently finds itself will inherently be accompanied by external pressures that may destabilize current plans. For details on the results, see Appendix I.

Acknowledging that integrating the Swiss network into the EU-wide CO_2 infrastructure described above can reduce transportation cost, this subtask assesses development scenarios of a potential European transnational CO_2 grid. Export of Swiss CO_2 will depend on the European infrastructure in the near future since no domestic geological storage currently exists, and the export routes rely to a large degree on the realization of announced projects. To analyze the uncertainty of the evolution of a European CO_2 infrastructure, modelling scenarios have been developed. These scenarios are compatible with the optimization model used in subtask 2.5 to investigate potential pathways of the infrastructure and its effect on Swiss CCTS supply chains.

All modelling scenarios and their assumptions are described in Table 13, and are based on the analysis of the European infrastructure in this subtask and the results from subtask 2.4, where real-world constraints are defined. The reference scenario represents the 'neutral' assumptions from the real-world constraints.

Table 13: Scenario overview. Differences to the reference scenario are described.

Scenario name (number of scenarios)	Assumptions
Reference scenario	Annual limits on capture units, storage capacity, pipeline capacity, and CO_2 emissions. The capture units are limited per sector, divided into waste, cement, chemical, and others. The reference scenario represents a middle ground in the expected availability of the respective technologies. First large-scale pipelines (trunklines) can be built in 2039. Switzerland has a domestic geological storage facility with a maximum injection capacity of 3 $MtCO_2$ per year.
Early / late pipeline construction (2)	The backbone pipelines within Switzerland can be built earlier (after 2035) or later (after 2043) than in the reference scenario. Uncertainty in the time and duration of backbone pipeline construction is assessed with the scenario.
No foreign pipeline (1)	Foreign pipelines are unavailable within the optimization horizon. Since Switzerland is assumed to have limited influence on the timing, routing, and development of foreign pipelines within, the domestic infrastructure may also depend on foreign decisions. The 'no foreign pipelines' scenario assesses how Swiss CO_2 can still be transported abroad.
Rhine congestion (1)	The barge transport on the river Rhine is not allowed. Due to high transportation demand and low water situations, the Rhine may not have enough capacity for large scale CO_2 transport. Alternative options and the effect of such a congestion on the Swiss CCTS/CCUS system is assessed.
No Swiss storage (1)	Domestic geological storage of CO_2 is impossible within the optimization horizon. As the exploration of a domestic storage site is in a very early stage, it may not become operational within the optimization horizon.
Early / late installation of capture units (2)	The amount of CO_2 that can be captured from each sector (waste, cement, chemical, other) is constrained and develops faster/slower than the reference scenario over the optimization horizon.
Early / late availability of storage sites (2)	The capacity of storage sites is available earlier/later than in the reference scenario. The capacity limit can represent both technical injection capacity of the storage site or the capacity contractually reserved for Swiss emitters. The scenario with late storage availability also assumes a delayed development of a potential Swiss storage site. Therefore, no Swiss storage is available in this scenario.
Unforeseen storage shutdown (1)	The three closest storage sites to Switzerland encounter unforeseen issues in their operation or the availability of underground storage space and have to shut down from year 2036 onwards.
Unconstrained (1)	The limits imposed by the real-world constraints are removed. The availability of pipelines, capture units, and storage sites is not time dependent but the full expected capacity is available from the start of the optimization horizon. Pipelines have a construction time of 5 years instead of a year in which they become available.

With the presented scenarios, the optimization model can assess situations which are more favorable for a fast rollout of the CCTS infrastructure as well as delays and complications.

We also consider an “unconstrained scenario”, where no real-world constraints are imposed on capture units, storage sites, and availability of transport modes. We also consider an “unconstrained scenario”, where no real-world constraints are imposed on capture units, storage sites, and availability of transport modes. The “unconstrained scenario” represents a very optimistic case in which large infrastructure deployments are possible immediately and over large geographies. We use it as a benchmark to assess the impact of different real-world constraints on the costs and optimal design of real-world CCTS supply chains.

3.2.4 Subtask 2.4 – Development of real-world constraints for infrastructure rollout, financial implications of rollout scenarios and feedback into industry roadmaps

The overall objective of this subtask is (i) to identify real-world constraints for different CCTS network infrastructure rollout scenarios, (ii) to develop an understanding of the financial implications of these scenarios (such as connection costs for additional emitters), and (iii) to analyze cost and investment applications for an evolving transportation network (such as the switch to pipeline transport in the long term). The findings are communicated to the industry to further develop industry roadmaps and to facilitate CCTS/CCUS adoption.

As a starting point for this subtask, real-world constraints for different CCTS/CCUS network infrastructure rollout scenarios are identified, developed, and fed into the modelling work described in Subtask 2.5. A set of real-world constraints based on currently available reports and studies was collected and aligned with Subtask 2.5 to gain an understanding of the modelling work setup to facilitate the convergence between real-world constraints and the model. As a next step, the set of real-world constraints was further developed through data analysis, workshops with relevant stakeholders, and interviews with potential additional external sources. At the same time, regular alignments with Subtask 2.5 took place to ensure fit for inclusion into the modelling work. Refinements to the model can be categorized as follows:

- System configuration (i.e., “general setup of the model”): Compilation and location of emitters, availability and location of transport exchange sites, availability and location of storage sites, and availability of pipeline as well as non-pipeline transport modes
- Input parameters (i.e., “considerations for scenarios”): Availability of capture sites, emissions development for waste-to-energy, cement, and chemical industry, distribution of capture sites to different sections of the pipeline network, turnover capacity of transport exchange sites, availability of non-pipeline transport modes, node distances for non-pipeline transport, availability of flowlines and trunklines east and west, node distances for pipeline transport, capacity of storage sites, electricity price and electricity carbon intensity.

3.2.5 Subtask 2.5 – Scenario-based optimal integrated designs of a Swiss CO_2 network

The optimization model developed at ETH is used to determine the optimal design of both CCTS supply chains. Based on the data from subtask 2.1 and the real-world constraints from subtask 2.4, several uncertain scenarios are defined (Table 13 in Subtask 2.3). The network optimization determines a temporally and spatially resolved evolution of the CO_2 infrastructure and the optimal investment strategy for the CCTS and CCUS supply chains.

Due to the complexity of the investigated system, the MILP optimization model described in Task 5 is simplified into an LP optimization model. In an LP optimization model all costs, investment and operational, scale linearly with the decision variables. Therefore, economies of scale with larger size of installations, cannot be properly represented. LPs cannot include binary variables to model yes/no decisions, and thus no minimum capacities of technologies can be included. Although these limitations influence the outcome, their effect can be controlled by acting on the input data that is provided to the optimization. With the aim of quickly analyzing multiple scenarios, the fast-solving time of LP optimization was considered to outweigh the higher modelling accuracy achievable with a MILP optimization model.

The model optimizes the CCTS infrastructure over a time horizon of 26 years from 2025 to 2050. The objective of the optimization is the lowest net present cost of the infrastructure. The optimization is constrained by an annual CO_2 emissions limit, which decreases over time. An emissions limit ensures the progressive decarbonization of the optimized system and compliance with long term climate targets. The emissions limit is based on the Swiss Federal climate strategy (The Federal Council, 2021) but has been adapted to fit the scope of the optimization model: First, the model only accounts for the emissions from the included industrial point sources. Second, the optimization model accounts for potential negative emissions and considers biogenic and fossil CO_2 emissions as distinct types. From these differences and the assumption that the emissions limit will decrease linearly, an annual emissions limit is derived. The decrease of emissions starts from 2030 onwards, since at least one waste to energy plant is required to capture its emissions by then (Martin Albicker, 2023). Besides the emission limit, the optimal solution is mainly influenced by the time and size of available capture units, pipelines, and storage sites. In this context, available means that the optimization can choose to install a certain technology but does not necessarily install it.

In the reference scenario – which follows the neutral scenario from the real-world constraints (cf. subtask 2.4) – we determine a CCTS supply chain design that complies with the emissions target. As the emissions constraint is only imposed after 2030, the first capture units are installed in year 2030. The captured CO_2 is mainly transported to the Aramis storage site (cf. Figure 24) which is the closest site to Switzerland and assumed to be operational after 2028 in the reference scenario. Approximately 2% of the CO_2 is also stored domestically in concrete. Under current cost assumptions, the domestic storage of CO_2 in concrete is deployed as soon as emissions need to be reduced. However, with a maximum sequestration capacity of about 2 $ktCO_2$ per year, the carbonation plants are small compared to the sequestration capacity of the whole system. Once the capacity of the closest geological storage site (Aramis in the Netherlands) is reached, the CO_2 is transported to the next closest one (Luna in Norway). As soon as the Swiss storage site becomes available (in 2043 in the reference scenario), it is preferred as it is cheaper to store CO_2 domestically rather than to transport it abroad. Over the whole optimization time horizon, approximately 48% of the CO_2 is stored at Aramis, 28% in the domestic geological storage, 18% in the Luna storage location, and 2% domestically in recycled concrete aggregate. The remaining 4% are stored at the storage sites Errai and Smeaheia in Norway.

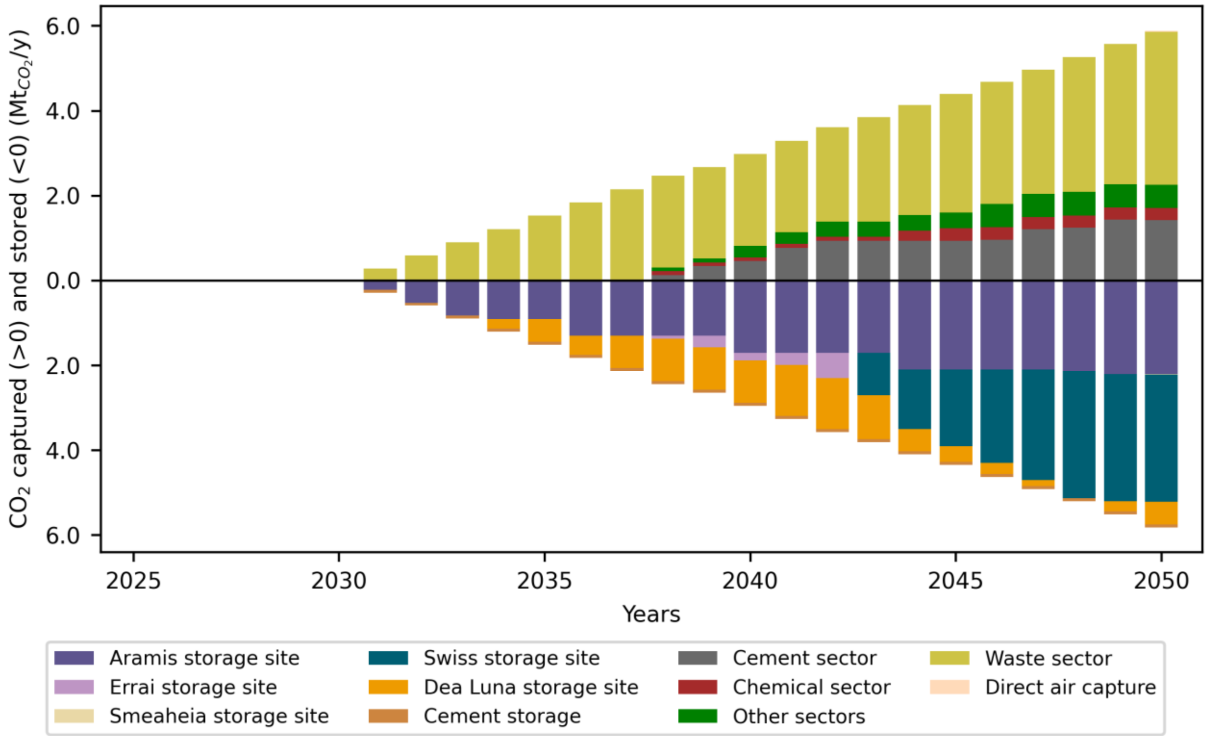


Figure 24 – Temporal development of captured and stored CO_2 for the reference scenario. The positive bars show which sector provides the CO_2 and the negative bars show at which site the CO_2 is stored.

On the capture side (Figure 24), the waste to energy (WtE) sector is the first to install capture units based on the assumptions of the real-world constraints for the reference scenario.

For transport, pipeline is the preferred option for onshore transport if available and ship is preferred offshore. Within Switzerland, the layout of pipelines was aligned with the engineering study conducted by SAIPEM for optimal CO_2 pipeline connections (Saipem, 2021). Following the study, two different types of pipelines are included in the optimization: a larger pipeline type ('trunkline'), which aims at building a backbone transmission system with large capacity; and a smaller pipeline type ('flowline'), which aims at collecting smaller quantities directly from the point sources. The time of installing trunklines is aligned with the results of subtask 2.4 and has a large influence on the results. In the scenario 'late pipeline', the network relies mostly on trains to compensate the absence of pipelines. In this scenario, the domestic storage is not connected by pipelines and thus requires trains for the CO_2 supply. Due to the late availability of pipelines, the costs increase by approximately 20%, mostly caused by additional train and truck transport.

In the reference scenario, the Swiss transport network starts to develop around the export hub in Basel due to lower transport costs. The CO_2 collected in the point sources around Basel is exported and stored geologically. In addition, small-scale transport is deployed to supply the mineralization plants which develop early in the optimization due to their low cost. The mineralization plants are supplied with truck transport or trains where possible.

The transport from the point source emitters to Basel starts with train transport from the emitters that have a train station available and truck transport from emitters close to Basel. The layout of the network as a function of the year can be seen in Figure 25, which shows the optimal time and location for building individual technologies based on the assumptions made in our scenarios. For the exact pipeline routing, the reader is referred to the pipeline routing study of Saipem (Saipem, 2021), on which this study is built.

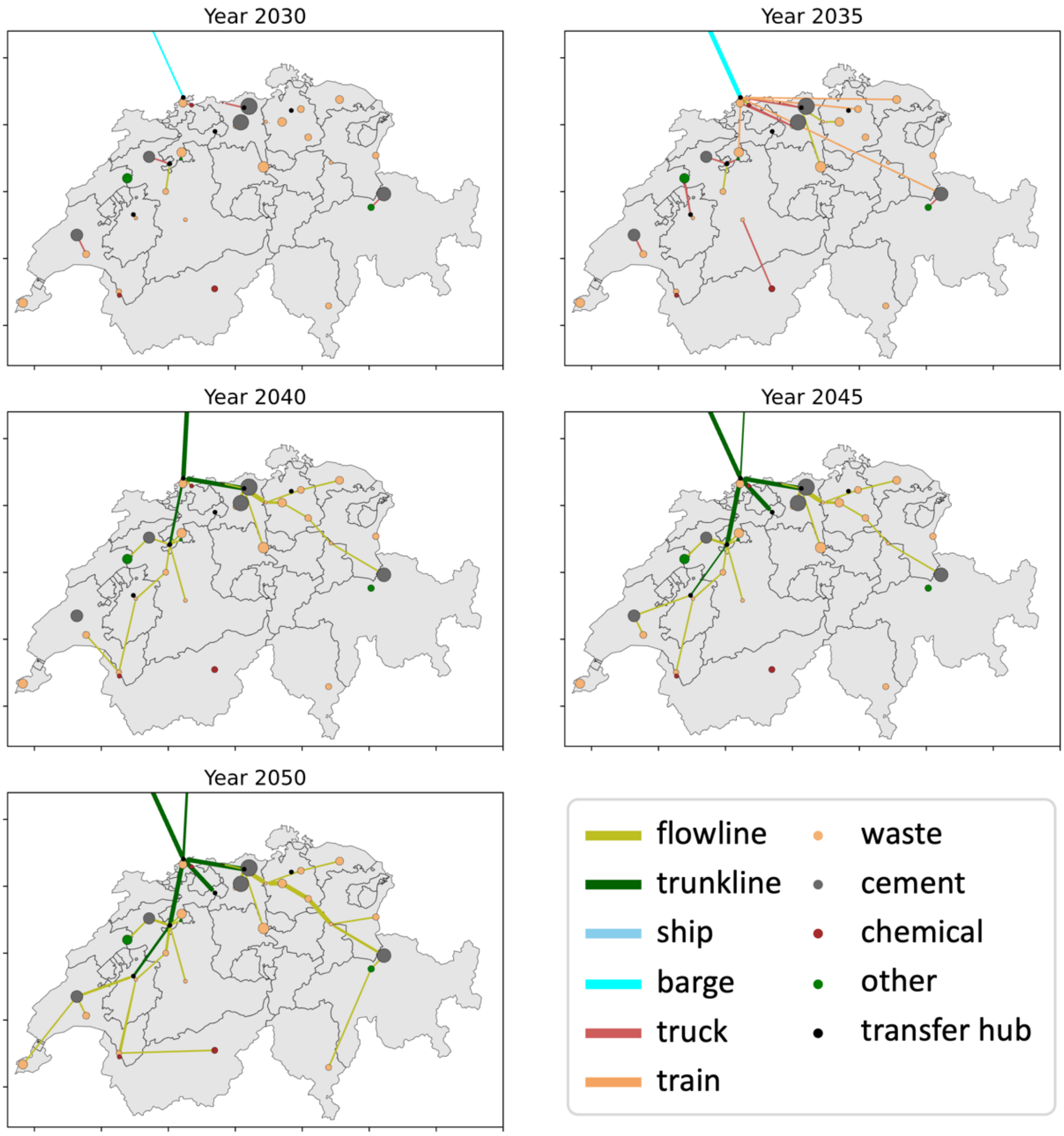


Figure 25 - Spatial evolution of the cost-optimal CCTS supply chain within Switzerland in the reference scenario. The transport routes represented by straight lines are only an indicator of the connection. In the model, the distances do not assume the direct distance between nodes but use factors, specific to each transport mode, to approximate the real distances for each transport route.

The analyzed scenarios can be clustered in favorable and unfavorable conditions for the deployment of CCTS supply chains compared to the reference scenario. Figure 26 compares the average annual costs of the supply chains across scenarios.

All favorable scenarios assume that CCTS infrastructure can be built earlier and with larger capacity than in the reference or unfavorable scenarios. Favorable scenarios result in costs that are 2 – 27% lower than in the reference scenario (cf. Figure 26). The lower costs observed in these scenarios result from the system being able to utilize the cheapest transport option, in particular pipelines, earlier or for shorter distances than in the reference scenario. Therefore, less CO_2 has to be transported by truck, train, barge, and ship, which are more expensive than pipelines. For example, the earlier availability of pipelines results in a savings of approximately 10% compared to the reference scenario. Additionally, the emissions from the pipeline are lower compared to other transport modes. Thus, there is more flexibility for the optimization to operate until the emission limit is reached. Furthermore, the scenarios with favorable conditions do not require direct air capture (DAC) to compensate for emissions that the infrastructure cannot capture from point sources within Switzerland, which also results in lower total costs of the supply chain (cf. Figure 26).

The costs are higher in scenarios with unfavorable conditions for CCTS development: In the scenario "late capture" for example, the capture units cannot be installed early enough to comply with the annually decreasing emission limit. Therefore, to still comply with the emission limit, DAC units have to be used to compensate for the continued flue gas emissions. Operating DAC units is more expensive than capturing CO_2 from point sources, leading to an increase in total cost. The "late capture" scenario is the only one with significant amounts of CO_2 captured with DAC, since the capture capacities in all other scenarios are sufficient to reach the emission targets.

Among the analyzed scenarios, only the "late storage" scenario cannot stay within the emissions limit, producing infeasible optimization results. Although all available technologies are installed, in year 2049, the CO_2 emissions are approximately 70 ktCO_2 higher than allowed and in year 2050 this overshoot increases to 350 ktCO_2. As the optimization does not produce feasible results, no total cost can be assigned to the scenario. The "late storage" scenario represents a situation, in which insufficient storage capacity exists for the system to sequester CO_2. The reason for such limited storage capacity may be a delayed exploration of the sites, slow increase of the injection capacity, unexpected issues encountered during exploration, or a failure of Swiss emitters to contractually secure storage capacity for Swiss CO_2. In such a scenario, DAC cannot serve as alternative solution since the CO_2 from the DAC facilities needs to be stored in geological storage sites, too. Therefore, a reliable Swiss CCTS system requires storage capacity that is guaranteed in the future. Urgent action would be needed to start securing storage capacity already today.

While such storage capacity can be provided by foreign storage sites alone, the development of a Swiss geological storage site enables cost savings and ensures that around half of the CO_2 can be sequestered domestically. The reduced amount of exported CO_2 limits the dependence on foreign CCTS infrastructure development. This finding assumes that the Swiss geological storage site can, after a ramp-up phase, inject 3 MtCO_2 per year in 2050.

The scenarios "no foreign pipeline" and "Rhine congestion" deal with issues of foreign transport infrastructure and their effect on the Swiss decarbonization. In case there is no pipeline that can transport the CO_2 from Switzerland, barges are used to transport the CO_2 to a North Sea harbor. If the Rhine has no capacity for CO_2 transport via barge due to low water or high transport demand, the optimization chooses transport via train as a near-term solution. Under the assumptions taken, both scenarios still lead to feasible results, although the costs are approximately 11% higher than in the reference scenario.

Regardless of the transport infrastructure outside of Switzerland, a domestic pipeline infrastructure is built in all scenarios. Thus, the domestic pipeline system represents a robust design decision under the scenarios analyzed in this work.

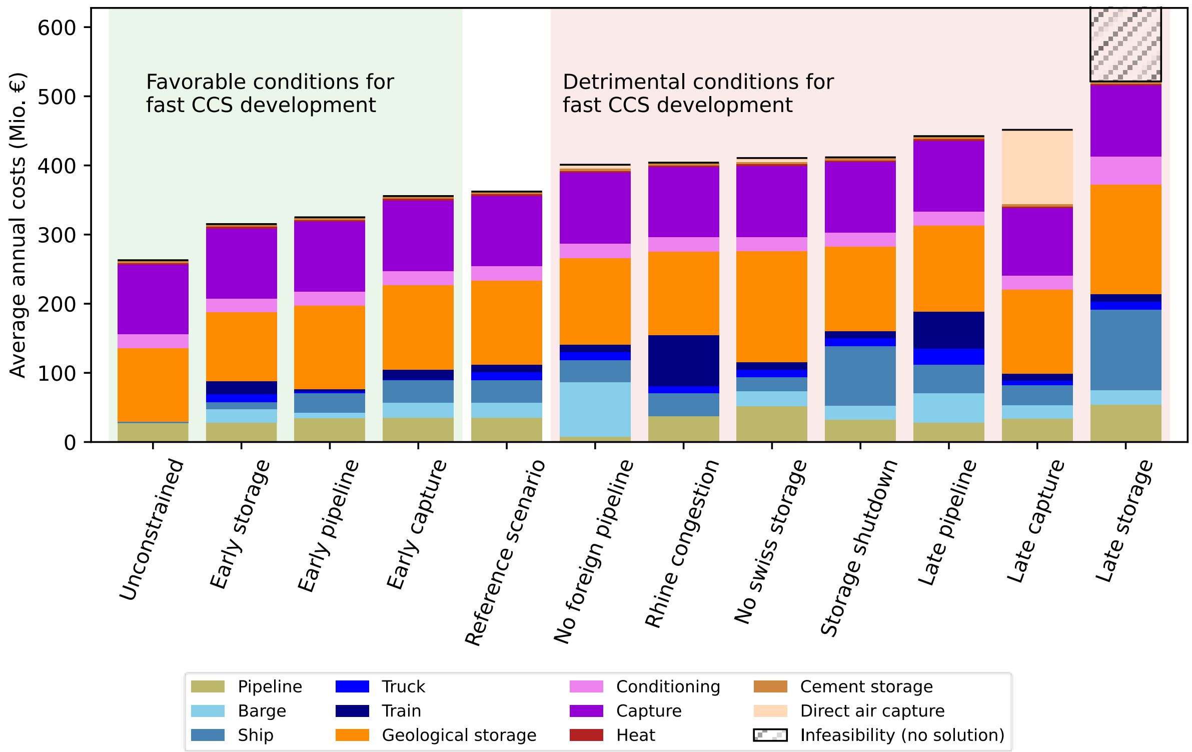


Figure 26 - Average annual cost for installing and running a CCTS/CCUS infrastructure under each scenario. The costs are divided by the technology causing them. The infeasible solutions include the cost for infrastructure to sequester as much CO_2 as possible, but without meeting the emission limit.

The results show that a domestic pipeline network is a robust decision across scenarios. Even for scenarios where pipelines are only available rather late in the optimization horizon (from year 2043 on, cf. Table 13), domestic pipelines to Basel and exporting ones to the North Sea hubs are built in the cost-optimal solution. Whether a pipeline exists from the export hub in Basel to the North Sea does not influence the decision to build a domestic pipeline network. If the export pipeline from Basel can, for some reason, not be built, the collection of CO_2 within Switzerland would still rely on pipelines. Instead of an export pipeline, barges on the Rhine are used to export the CO_2. The switch from domestic pipelines to barges requires reconditioning in Basel. By building reconditioning equipment at the export hub, the Swiss system can be adapted to the change of external conditions, i.e., the foreign pipeline not being built.

Direct air capture could be used to achieve net-zero emissions by capturing the residual CO_2 emissions that cannot be captured from point sources within Switzerland. However, it is only used in one of the scenarios as a measure against delays in the infrastructure deployment. For a system where capture units can only be installed very late in the optimization horizon, DAC units are used to reach the emission target. In that case, the DAC units are installed and operated directly at the storage sites to minimize transport distance.

Finally, we also define different decarbonization trajectories and assess their impact on the optimal layout and rollout of the supply chains (Becattini, Gabrielli et al., 2022). More specifically, we define a linear (LER) and a cumulative emissions reduction (CER) pathway. The former implies limited planning flexibility, where the CCTS supply chains must comply with a specified target evolution of yearly emissions. Such evolution in yearly emissions goes from the current emissions without CCTS at the beginning of the time horizon to the minimum attainable emissions at the end of the time horizon. The latter implies greater planning flexibility, where the CCTS supply chains must only comply with the cumulative emissions target over the entire time horizon and with the minimum attainable emissions at the end of the time horizon. For equal emissions reduction, the greater flexibility of the CER pathway enables lower costs of stored and avoided carbon, i.e., about 15% smaller, than those accrued along the LER pathway. However, the CER policy is less robust and may lead, in case of delays, to failure in achieving the climate goals, because of a lack of time for corrective actions.

As the analysis in this work package is based on a linear program optimization, important aspects of the approximation resulting from the linear optimization model are discussed in the following:

- Installation costs. Investment and operating costs are assumed to scale linearly with size, capacity, and distance of transport modes. Therefore, economies of scale cannot be considered. For pipelines, this poses a challenge since their investment cost depends almost exclusively on the distance, leading to a large decrease in unitary cost for higher volumes of transported CO_2 (Oeuvray, Burger, Roussanaly, Mazzotti, & Becattini, 2024). To account for economies of scale, we define two pipeline sizes and restrict the routes where pipelines can potentially be built both in time and space in alignment with the results from subtask 2.4.
- Export pipelines. Parallel pipelines connecting Basel to the North Sea in Figure 25 are an assumption made in the input data to investigate how many harbors at the North Sea would be required. Installing parallel pipelines seems highly unlikely and requires further investigation. Potentially, one pipeline from Basel may be connected to two pipelines going to separate CO_2 hubs at the North Sea. The routing of the export pipeline from Basel and its connection to other foreign pipelines is outside the scope of this work.
- Minimum capacity. When choosing the optimal size of a technology, no minimum capacity is imposed upon the optimization model. Therefore, technologies like pipelines or capture units may be installed on a rather small scale by the optimization problem.

3.2.6 Subtask 2.6 – Business models for WtE, cement, and chemical and pharma industries.

The topic of business models for CCTS and CCUS for Switzerland is rather new and unexplored in both academia and practice – especially regarding the unique challenge Swiss emitters face for the implementation of CCTS value chains with long transport routes and storage abroad. The current regulatory landscape in Switzerland, the foreseen pathways for decarbonization, as well as the opportunities and limitations for certain setups for the management and organization of such value chains constitute building blocks that shape the options for business model development. This report provides an extensive overview of these building blocks, showcasing the different options and considerations emitters have when developing their business models.

As for the four building blocks of the report, the following conclusions emerge and can serve as a starting point for further in-depth analysis (for details on the results, see Appendix II):

First, the regulatory framework significantly impacts the viability of CCTS and CCUS business models. The inclusion or exclusion of specific industries or origins of CO_2 in the Swiss ETS, the adoption of the revised CO_2 Act, as well as price and demand dynamics on the VCM make it very difficult for emitters to assess the stability and durability of future revenue streams.

Second, the value chain structures for CCTS and CCUS exhibit fundamental differences, especially in terms of activities, costs, and associated costs. Since CCTS requires cross-border transport, CCUS is the pathway with significantly lower costs and complexity. Due to this, an individual emitter is likely to opt for CCUS. However, if the national perspective is taken and the available short- and long-term storage potentials of both pathways are considered, it becomes evident that only a few, rather small emitters will be able to pursue CCUS.

Third, the management and organization of the capture, transport, and storage activities vary with integrated, shared, and outsourced options presenting different cost-risk profiles. Capture activities are closely tied to industrial processes, making complete outsourcing unlikely, while transport and storage are more amenable to outsourcing since they involve substantially different activities, require know-how of multiple industries and processes, and face high risks and investment costs. In general, two setups for the management and organization of full value chains can be foreseen: (i) an integrated capture setup, in which the emitter owns and operates a capture facility and completely outsources the transport and storage activities to one or several third parties; and (ii) a capture cluster, in which several emitters jointly own and operate one CO_2 capture facility and completely outsource transport and storage activities to one or several third parties. The specific setup for value chain management depends on the chosen CCTS or CCUS pathway and the potential for other emitters to collaborate in capture clusters. Further, the choice of setup is influenced by project-specific factors, such as cost reduction and risk mitigation, rather than industry affiliation.

Fourth, considering the current costs of CCTS and CCUS value chains and the uncertainties regarding the stability and longevity of revenues, as of today, there is no fundamentally viable business model for the implementation of CCTS or CCUS. In other words: In most cases and for most emitters, there is no business case yet to pursue this activity. Therefore, it is all the more important to identify supporting revenue or financing streams to establish economic viability and accelerate deployment. These can be either detached from the actual CCTS or CCUS business activity – for example, by increasing customer charges for prices of the emitter’s products or services generated within their core business – or by leveraging additional policy instruments that support the financing of early movers – for example, under the Climate and Innovation Act.The topic of business models for CCTS and CCUS for Switzerland is rather new and unexplored in both academia and practice – especially regarding the rather unique challenge Swiss emitters face for the implementation of CCTS value chains with long transport routes and storage abroad. The current regulatory landscape in Switzerland, the foreseen pathways for decarbonization, as well as the opportunities and limitations for certain setups for the management and organization of such value chains offer building blocks that shape the options for business model development up to a certain degree. This report provides an extensive overview of these building blocks, showcasing the different options emitters have when developing their business models.

3.3 Task 3 – Integration of post-combustion CO_2 capture with Waste-to-Energy (WtE) and cement plants

The detailed results of the integration analysis and the technoeconomic analysis of both subtask 3.1 and subtask 3.2 are all reported in the engineering documents, which are attached in Appendix III and Appendix IV, respectively. The following is a summary of the main findings alongside some complementary analyses that have been carried out.

3.3.1 Subtask 3.1 – CO_2 capture integration with Jura cement plant

Several carbon capture solvent licensors have been contacted by Casale, introducing the project and signing relevant Non-Disclosure Agreements. In a first meeting with Jura Cement, two alternative solutions have been presented and compared: an amine-based system according to BASF OASE Blue solvent and a hot potassium carbonate system based on CO_2 Capsol technology. Both solvents are safe from an environmental point of view, and suppliers developed special formulations to minimize solvent losses due to volatility or degradation in contact with oxygen and other oxidants. Nevertheless, amine losses are more sensitive to poisoning since the VOC concentration in flue gas of the cement process are high. Moreover, due to the lack of available heat, the general impression was that the integration of the hot potassium carbonate system in the cement plant is easier than that of the amine-based system from an energetic point of view. Specifically, amine systems would require up to 85 t/h of steam for regeneration. Even by applying heat pumps extensively, it is possible to recover a maximum of only 50-60% of this heat from the process. For this reason, it was agreed that a first set of documents would be prepared by Casale based on the CO_2 Capsol process. A simplified schematic of the capture technology and the cement production process are shown in
Figure 27 and the flue gas conditions of Jura Cement are shown in Table 14. Jura cement has two modes of operation, compound operation, where the raw mill is turned on and the heat of the exhaust gas is used for drying the raw materials, resulting in a flue gas with a higher flowrate and lower CO_2 concentration, and direct operation, where the raw mill is turned off. The compound operation runs for 80% of the time, and the plant has down time in January.

Table 14: Flue gas conditions at stack of Jura Cement in Wildegg

	Compound operation	**Direct operation**
Flue gas flow rate	241’340 Nm^3/h	210’000 Nm^3/h
Temperature at stack inlet	200°C	200°C
Pressure at stack inlet	0.98 bar	0.98 bar
Molar composition [%]		
CO_2	15.5%	21.3%
N_2 + Ar	64.2%	60%
O_2	7%	7%
H_2O	11.2%	14%
SO_x	91-126 mg/Nm^3	355-370 mg/Nm^3
NO_x	425 mg/Nm^3	460 mg/Nm^3
Other impurities*	Balance	Balance

*Particulate matter, NH_3, benzene, volatile organic compounds, formaldehyde, HCl and CO

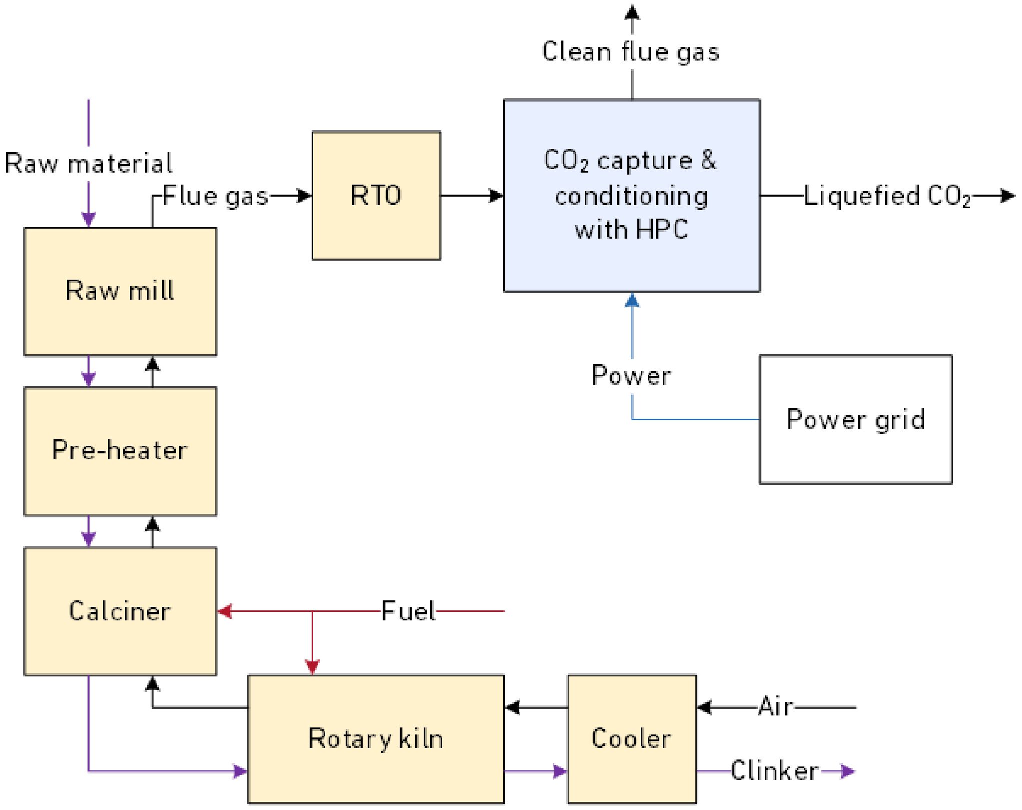


Figure 27 - Schematic of the hot potassium carbonate CO_2 capture technology applied to a cement production plant. The capture process can run in electricity mode, where no heat is required, which is suitable for a cement plant where heat availability is limited.

After this submission, other alternatives will be considered and compared:

- Different technologies for CO_2 capture, such as membranes and Shell CANSOLV®
- Modifications to the cement plant to operate with lower amount of flue gases and higher CO_2 content

3.3.2 Subtask 3.2 – CO_2 capture integration with Hagenholz waste-to-energy plant

Here, too, based on the design basis of KVA Hagenholz, several carbon capture solvent licensors, including BASF, Mitsubishi Heavy Industries, Shell and CO_2 Capsol, have been contacted by Casale. Non-Disclosure Agreements were signed with three licensors in the end: BASF, Capsol and Shell. Discussions took the whole month of March 2022 mainly due to the fact that part of the deliverables of DemoUpCARMA project will be made available to public consultation and that third parties shall comply with the provisions of the Consortium Agreement and of the Grant Agreement. Casale decided to move forward with the OASE Blue amine-based solvent by BASF, based on which the engineering design documents were prepared. A simplified schematic of the amine-based CO_2 capture process applied to a waste-to-energy plant is shown in Figure 28 and the flue gas conditions at stack are shown in Table 15 below.

Table 15: Flue gas conditions at stack of KVA Hagenholz

Flue gas flow rate	207’180 Nm^3/h
Temperature at stack inlet	40°C
Pressure at stack inlet	1 atm
Molar composition [%]	
CO_2	12.4%
N_2	Balance
O_2	5%
H_2O	6%
SO_x	<6 mg/Nm^3
NO_x	60 mg/Nm^3
Other impurities*	< 30 Nm^3

*Particulate matter, NH_3, CO, TOC, HCl, HF, HBr, heavy metals, Hg, Cd, dioxins and furans

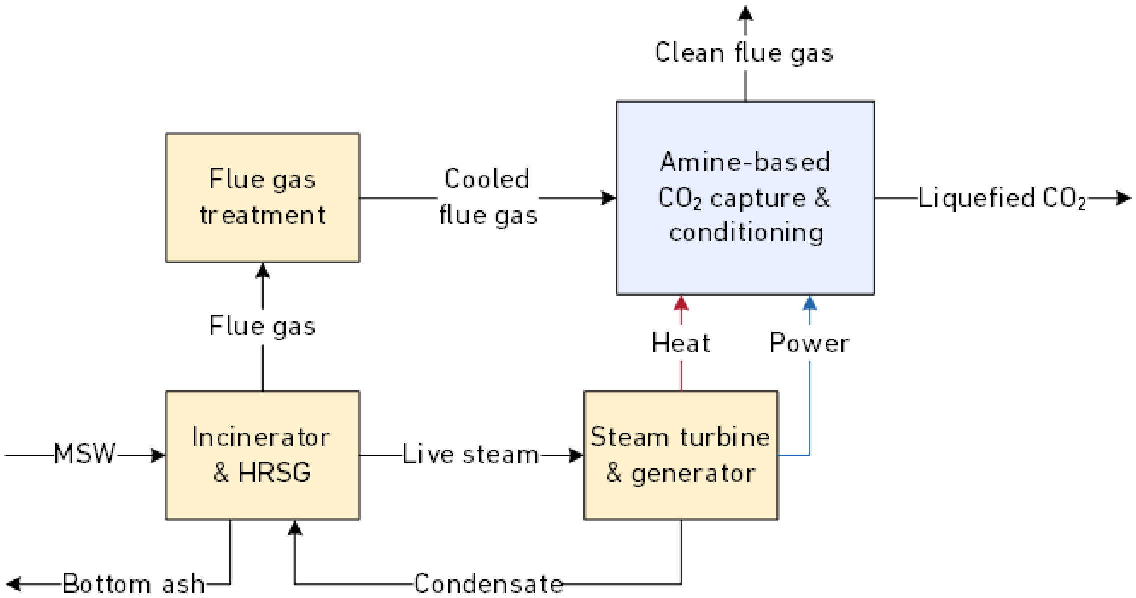


Figure 28 - Schematic of amine-based CO_2 capture process applied to a waste-to-energy plant, where both heat and power are extracted from the steam turbine and generator of the WtE plant

The general finding was that district heating network would not be affected by the capture integration, even in winter, due to (i) sufficient waste heat available, both at the WtE plant and at the CO_2 capture plant, and (ii) the electricity production on site, which enables the use of heat pumps. The heat required to regenerate the OASE Blue solvent at 90% capture efficiency was estimated to be around 35.3 MW, most of which can be recovered directly and via heat pumps to be sent to district heating. The electricity consumption of the capture process of the heat pumps was estimated at 3.2 MW_e. All values are reported in detail in the design documents and summarized in Table 17. A first space demand evaluation has been done. Capture can be done on site, but there is no space on the Hagenholz site for a logistic hub. Absorbed CO_2 must be compressed or liquefied and transported to an external storage and loading area. Potential sites are evaluated, and rail connections are investigated. ETH conducted a preliminary screening of CO_2 conditioning conditions for both pipeline and liquid transport. Based on Northern Lights and SAIPEM studies, the following cases were reported:

Table 16: CO_2 conditions and specifications for different transport modes

	Pipeline			**Liquefaction**		
	LP	HP	Dense phase	HP liquid bulk	LP liquid bulk	Liquid batch
Pressure [bar g]	10	35	145	15	7	22
Temperature [°C]	< 45			-30	-46	-37
CO_2 Purity [%mol]	0.998			0.9997		
H_2O [%mol]	should be perfectly dry			< 30 ppm		
O_2 [%mol]	100 ppm			< 10 ppm		
Others [%mol]	~ 0.002			~ 300 ppm		

ERZ/Ramboll have defined two pipeline conditions from Hagenholz to Werdhölzli to be considered:

- 10 bar / ambient gaseous
- 17 bar / -30°C liquefied

Sensitivity analysis of flue gas temperature

To account for seasonality, it was decided to go for a solution with varying inlet temperature. A flue gas temperature of 40°C would allow for maximum heat recovery via heat pumps for the district heating system in wintertime, while in summer, an elevated operating temperature of 55°C would not only allow easier direct heat recovery without heat pumps, but also minimize the surface area for the re-coolers to cool-off the heat.

Thus, calculations for four process setups have been performed in the study:

1. Absorption at 40°C, CO_2 stripping with vapor compression
2. Absorption at 40°C, CO_2 stripping without vapor compression
3. Absorption at 55°C, CO_2 stripping with vapor compression
4. Absorption at 55°C, CO_2 stripping without vapor compression

It was shown that a vapor compression unit adds more complexity and yields higher costs without major energy benefits, therefore a solution without vapor compression was chosen.

Furthermore, to investigate the effect of the flue gas temperature on the capture performance, ETH conducted multiple sensitivity analyses of the absorption process while varying inlet flue gas temperature from 40°C to 55°C on the chemical engineering software, Aspen Plus. The operating conditions such as the L/G ratio, which is the liquid-to-gas ratio of the solvent mass flow rate and flue gas flow rate, and the specific reboiler duty, which is the amount of heat required in the reboiler of the regeneration section per kg of CO_2 capture, were adjusted in the sensitivity analysis, so as to keep the capture efficiency constant at a fixed column height. The reference case was the absorption process at 40°C, capturing 90% of the CO_2 with a 15-meter column. The results are shown below.

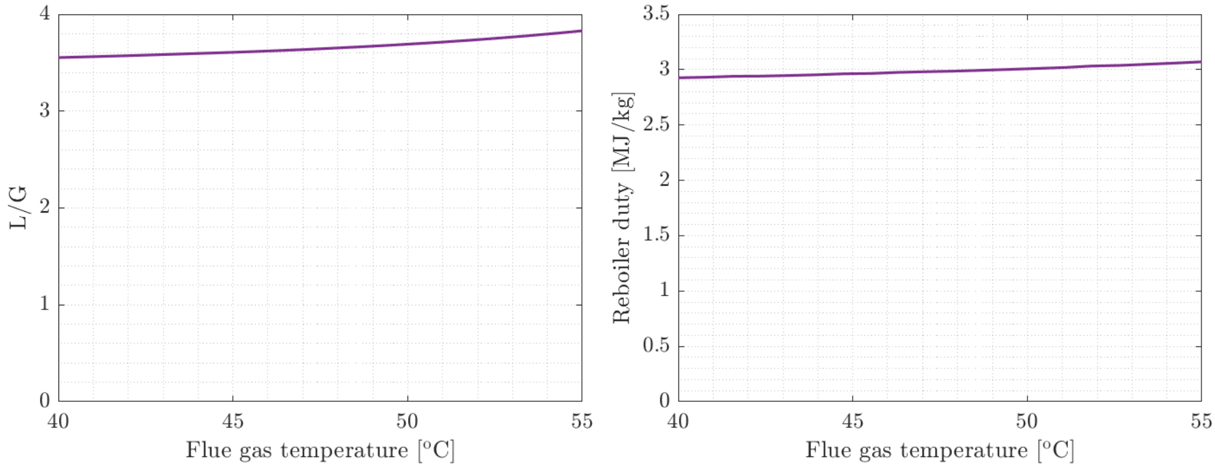


Figure 29 - Effect of flue gas temperature on the required L/G ratio of the solvent (left), and on the specific reboiler duty (right)

It has been shown that in order to maintain the CO_2 capture efficiency at the reference case of 90% while increasing the temperature from 40°C to 55°C, the solvent flow rate must increase by 8%, which results in a reboiler duty increase of 5%. These values were in line with the plant performance report of one of the licensors. They indicate that it may be worthwhile to operate at elevated temperatures in summer to reduce cooling duty and heat exchanger area, and whereas the energy penalty is not very high. However, increasing the temperature has a significant impact on the amine (piperazine) slip in the flue gas leaving the absorber, as seen in Figure 30, and this must be taken into account with an appropriate water-wash design.

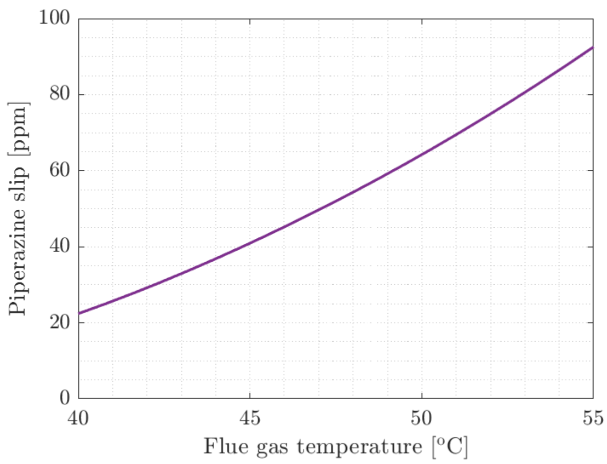


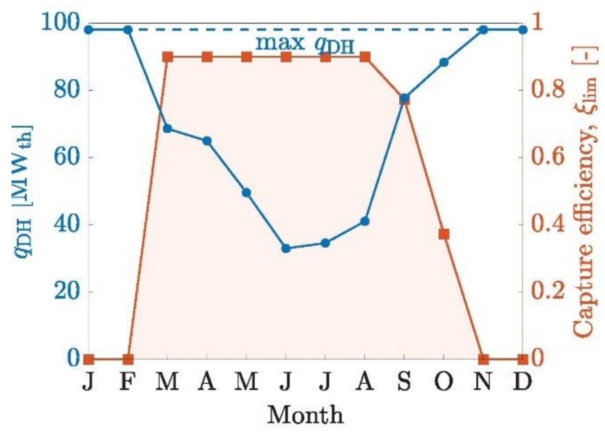
Figure 30 - Effect of flue gas temperature on the piperazine slip out of the absorber column

Modelling the integration of CO_2 capture with WtE plants

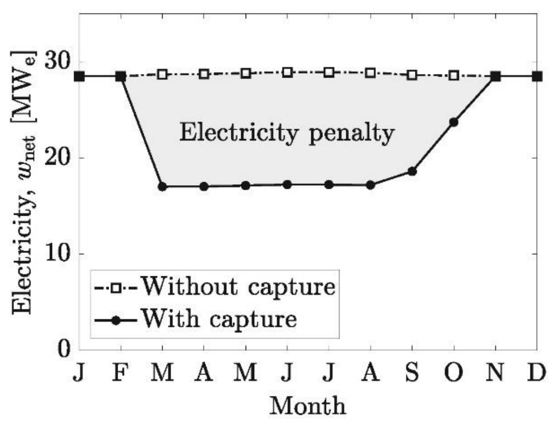
Waste-to-energy (WtE) plants in Switzerland play a particularly important role in the country's net-zero strategy; they decreasing the reliance of the heating sector on fossil fuel-based energy sources by delivering district heating to local district heating networks. They are in the hard-to-abate sector due to their primary role as a waste treatment facility, and the municipal solid waste that they burn contains

50% biogenic carbon, thus providing the potential for negative emissions when integrated with CO_2 capture and storage. To explore this integration, ETH has conducted a more general analysis of the CO_2 capture integration and developed a model that quantitatively describes the relationship between the energy output of a given WtE plant and the capture performance of a chosen CO_2 capture technology. The full methodology and model derivation is available in the work published by (Otgonbayar & Mazzotti, Modeling and assessing the integration of CO_2 capture in waste-to-energy plants delivering district heating, 2024). The findings were also presented at the 16th Greenhouse Gas Control Technologies conference in Lyon, France on 25th October (Otgonbayar & Mazzotti, Optimization of solvent-based post-combustion capture processes for waste-to-energy, 2022) and in the 12th Trondheim Conference on Carbon Capture, Transport and Storage on 22nd June.

The developed model can analyze the impact of combining an existing WtE plant with a post-combustion capture process, while still fulfilling the district heating (DH) and/or electricity demand of the plant. It takes as input the waste incineration process parameters as well as the CO_2 capture energy consumption values and can thus be applied to different WtE plants and different CO_2 capture technologies. For the following case study, the performance of the BASF OASE Blue solution will be assessed for the Hagenholz WtE plant (flue gas conditions reported in Table 15). The specific reboiler duty and the specific electrical duty (including the conditioning step) of the OASE Blue solvent at 90% capture efficiency are reported in the engineering documents and are found to be 2.8 MJ_{th}/kg and 0.7 MJ_e/kg, respectively. The model includes variable capture efficiencies and can, for a given district heating demand that needs to be fulfilled, determine the corresponding maximum feasible capture efficiency. The overall maximum capture efficiency is limited to 90% since energy consumption data is not available for higher efficiencies. For lower capture efficiencies, constant specific reboiler and electrical duty is assumed, and energy consumption scales linearly with amount of CO_2 captured. In practice, this can be achieved by adjusting the flue gas flow rate via a bypass stream, as investigated in previous works (Paul Akula, 2021) (David Luke Oates, 2014).



(a)

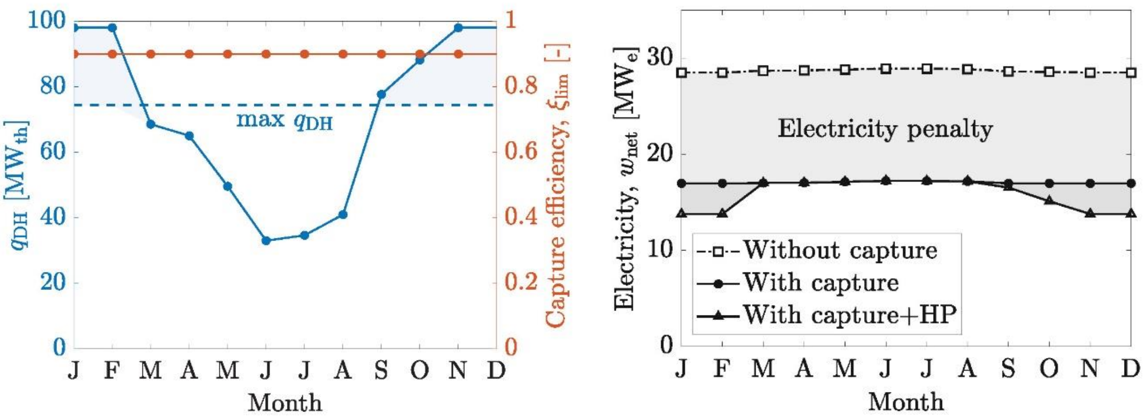


(b)

Figure 31 - (a) Monthly district heating supply of KVA Hagenholz in blue and the corresponding maximum feasible capture efficiency in red, (b) monthly net electricity output of the WtE plant before (square marker) and after capture (circle marker)

The left plot in Figure 31 shows the district heating supply curve of KVA Hagenholz in blue and the maximum capture efficiency in red. The WtE plant is projected to export up to 100 MW of heat to district heating in winter, and around 28 MW_e of electricity to the power grid. It can be seen that in the summer months, when the district heating demand (and thus supply) is low, 90% capture is feasible as shown in the left plot in Figure 31. On the other hand, DH supply increases in the winter months, limiting the maximum possible capture efficiency and allowing for no capture when all of the heat is required from November to February. The corresponding electricity output after subtracting the electricity consumption is shown as a solid line in the right graph. The analysis shows that by using only excess heat that is available on site, negative emissions can be achieved, as up to 55% of the generated CO_2 on average can be captured and stored annually. This incurs a reduction in electrical efficiency of around 25%.

Alternatively, all of the required heat can be sent to the capture process to ensure 90% capture throughout the year, which would limit the heat available for district heating, as show in the dashed blue line in Figure 32. The remaining heat can be provided by heat pumps that upgrade low-grade waste heat from the CO_2 capture process, e.g., from the flue gas, the desorber overhead condenser and/or the compressor intercoolers. Considering a heat pump coefficient of performance of 7.4, which is the value provided by heat pump vendors (also reported in the deliverable), the electricity output after the heat pumps is shown in triangle markers. It is shown that it is possible to capture the remaining CO_2 even in winter with an overall electrical efficiency reduction of 45% and an average heat pump duty of 1.3 MW_e.



(a) (b)

Figure 32 - (a) Monthly DH supply curve in blue solid line and maximum heat supply in blue dashed line, and the maximum associated capture efficiency in red; (b) monthly net electricity output of the WtE plant before capture (square marker), after capture without heat pumps (circle marker), and after capture with heat pumps (triangle marker)

The energy output values of KVA Hagenholz according to the model have been compared with values obtained in Casale's feasibility study and are reported below and show a good agreement.

Table 17: Energy consumption values of the integration according to the model, compared with Casale's values

	Casale	Model	Relative error
District heating supplied	97.5 MW	97.7 MW	0.2%
Electricity output before CO_2 capture	27.8 MW_e	28.5 MW_e	3%
Heat sent to CO_2 capture plant	35.3 MW		
Missing heat for district heating	30.8 MW	33.0 MW	7%
Heat pump duty	2.9 MW_e	3.2 MW_e	10%
Total electricity penalty of CO_2 capture	14.3 MW_e	14.8 MW_e	2%
Penalty percentage of WtE output	0.51	0.52	1%

4 Conclusions

In this work package, we designed CCTS supply chains for three early movers (KVA Hagenholz, Jura Cement, and ARA Bern), wherein we investigated CO_2 capture, liquefaction, transport, and geological storage in the Northern Lights in Norway, or Carbfix in Iceland. A techno-economic assessment as well as a life cycle analysis (LCA) was carried out for each of the chains to assess their feasibility for near future deployment. Due to the near-time horizon, these supply chains will rely on CO_2 transport via conventional transport options such as truck and train on land, and barge and ship on water, as a CO_2 pipeline network has not yet been established. Data was successfully gathered directly from industrial stakeholders for nearly the entire supply chain, encompassing capture, conditioning, intermediate storage, and permanent storage. Data from industrial stakeholders regarding transport options were for the most part accessible, except for dedicated ship transport and pipeline transport; for these, we referred to literature values.

Recognizing the unique specificities of each early mover, optimal CO_2 capture integration has been designed for the emitters for which CO_2 capture is necessary, and general guidelines were derived, which can be applied other similar cases. Different technologies were proposed for the different emitters, mainly based on the plant operating conditions and available heat on site; considering the limited heat resources at Jura Cement, an electricity-driven process was deemed more suitable, while KVA Hagenholz has enough steam available on site to run a more conventional amine-based capture process. It was found that CO_2 capture can be integrated at the WtE plant without compromising the large district heating demand, even in winter. This is attributed to the substantial waste heat available both at the WtE plant and the CO_2 capture plant, which can be efficiently recovered either directly or through heat pumps. Based on these findings, plant performance results such as energy requirements, spatial requirements and costs were determined for each early mover, which were integrated into the techno-economic assessment of the corresponding supply chains.

The cost of the pioneering supply chains was estimated for multiple different transport scenarios from present-day container-based solutions to more future-based dedicated transport options, and ranged from 280 €/t to 440 €/t. It was found that in the near-term, transport costs represent the largest share of the supply chain costs, around 60%, as economies of scale for these long distances are very limited with the existing modular transport options. However, cost of transport is expected to decrease significantly with more efficient transport options, with a 60% decrease when switching to dedicated transport options and over 70% decrease when switching to pipeline network, which could result in an overall halving of the levelized cost of avoided carbon of the entire supply chain (cost per unit CO_2 avoided – independent of its origin – when accounting for the emissions associated with the deployment of the chain). Although all components that are needed to deploy the CCTS supply chains in the near future are already available to us, numerous challenges and bottlenecks exist that extend beyond cost considerations when it comes to implementing these pioneering chains at the required scale. Extensive foresight and planning are essential to account for factors such as space requirements, logistical arrangements, and the impact on transport volume and infrastructure. Existing traffic on highways and container transport at ports are expected to increase. However, the increase in the former is estimated to be around 1-2% only, and the overall scale of CO_2 transported is comparable with current oil transport in Switzerland. Space requirements are also a non-trivial matter, with some plants such as KVA Hagenholz not having enough space on-site to carry out the CO_2 conditioning and logistical activities such as temporary storage and loading. Although alternative solutions need to be found, e.g., transporting the CO_2 to Werdhölzli for liquefaction, it was found that the additional cost was marginal compared to that of the supply chain.

Despite using conventional fossil-fuel based transport options over long distances, the LCA results demonstrate that the early mover chains succeed in reducing the global warming potential (GWI) of a point source since the greenhouse gas emission during the whole life cycle of the CCTS chain are significantly lower than the amount of stored CO_2, constituting around 15-30%. The largest contributors to GWI of the CCTS chain are the capture and transport steps. The GWI of the capture and conditioning is dominated by the energy supply and thus is very sensitive towards the assumed heat and electricity source. The transport stage is responsible for approximately half of the GWI of the CCTS chain due to the large specific impact of the available transport modes and the long transport distance. Nevertheless, similar to the costs, this is expected to decrease, first when switching from iso-container-based transport to dedicated-vessel transport and further when pipeline transport becomes available. Regarding other environmental impact categories, the transport stage dominates half the impact categories by contributing over 50% to impacts in 7 of the 16 categories. For the CCTS chains for the KVAH and the JCW, the capture and conditioning step contributes more than 50% to 7 of the 16 impact categories.

Furthermore, a resilience analysis was carried out for the early mover supply chains as well as for clusters of emitters. Findings show that early movers and emitter clusters can rely on backup connections to increase their resilience. Compared to the cost-optimal solution, resilient designs of the CCTS network increase the total cost from approximately 5% to 70%. The amount of cost increase depends on the type of backup connection with trucks being the solution for minimum cost and backup pipelines causing the least emissions. When including additional strategies for resilience, temporary storage appears as a viable alternative for making CCTS chains resilient. However, the installation of buffer storage depends on the availability of space and is not possible at every point source. Thus, for some emitters, compensation via costly negative emissions technologies might be the only solution in case of a failure in the CCTS network. At transfer hubs, the conditions favour temporary storage due to the availability of space, conditioning equipment, and potentially storage tanks for liquid CO_2. However, the implementation of such resilience strategies by the emitter is subject to regulation and climate policy instruments in place. As the specific policy design cannot yet be foreseen, mandatory CO_2 compensation is not assumed in the optimization model. Depending on the regulation of a CCTS infrastructure, its design and operation may be oriented on the experiences of existing infrastructure, such as the natural gas network or the electricity grid. Furthermore, the infrastructure might not be installed based on a nation-wide design but by single actors. A CCTS network evolving from such installations will have different behaviour under failure scenarios than the analysed system.

The project also investigates the transition from early-mover supply chains to integrated Swiss CCTS and CCUS supply chains, i.e., where CO_2 is captured from Swiss industrial emitters and is stored either in underground geological storage (CCTS) or in concrete (CCUS). Industrial emitters include cement plants, waste-to-energy plants, chemical plants, and other relevant emitters. Geological storage sites include all the major planned storage sites in Europe, whereas storage in concrete is assessed with respect to the potential in Switzerland. CO_2 transport options include pipelines, ships, barges, trains, and trucks. The optimal design and rollout of the Swiss supply chains are determined via a mathematical optimization model. The optimization model determines a temporally and spatially resolved evolution of the CO_2 infrastructure and the optimal investment strategy for the CCTS and CCUS supply chains.

Overall, we find that when a large-scale infrastructure is available and clustering the sources together becomes possible, the costs for transport decrease between 20 and 60% compared to the early mover chains from section 3.1.2. Although the initial investment costs for a network infrastructure are substantial, so are the cost savings overall. Findings show that pipelines are the most cost-effective mode of transport when large volumes of CO_2 (higher than about 1.5 $MtCO_2/y$) must be handled, especially when considering multi-year time horizons. Ship and barge connections are competitive with pipeline connections, whereas rail and truck connections are cost-effective only when considering limited planning horizons or small volumes of CO_2 to be transported. It is also worth highlighting that different supply chain infrastructures are obtained in terms of timing, structure, and cost of the CO_2 network when different decarbonization trajectories are considered. Considering cumulative emissions limits is cheaper than imposing a stricter decrease in emissions, e.g., a linear trajectory. However, a cumulative reduction policy may lead to failure in achieving the climate goals in case of delays, because of a lack of time for corrective actions.

Acknowledging that integrating the Swiss network into an EU-wide CO_2 infrastructure, we also assess development scenarios of a potential European transnational CO_2 grid, possible deployment scenarios of carbon capture, transport, and storage, as well as scenarios concerning potential operation issues. We aim at assessing situations that are more favorable for a fast rollout of the CCTS infrastructure as well as delays and complications.

The cost-optimal evolution of the Swiss CCTS network under different uncertain scenarios shows that reaching the imposed emissions target requires early installation of infrastructure, especially the capacity for CO_2 capture and storage. For installing capture units too late, negative emissions technologies can be employed, although their availability might be limited. The resulting system is more expensive and may be more dependent on foreign conditions. If storage capacity is not available or cannot be secured early, the emission target cannot be reached. While the availability of a Swiss storage site reduces costs, it is not a showstopper to the decarbonization pathway. Similarly, late installations of large-scale transport result in an increase in cost but do not prevent the CCTS system from reaching the emission target. Under all scenarios, the domestic collection of CO_2 is done with pipelines, even if the export to the North Sea has to rely on barges.

Finally, the project explores opportunities and challenges related to business models for CCTS and CCUS supply chains, showcasing the different options and considerations emitters have when developing their business models. Our analysis suggests that: (1) The regulatory framework significantly impacts the viability of CCTS and CCUS business models. (2) Since CCTS requires cross-border transport, CCUS is the pathway with significantly lower costs and complexity from a business model perspective, hence individual emitters might opt for CCUS. However, rather small emitters will be able to pursue CCUS due to the limited potential for CO_2 utilization. (3) The management and organization of the capture, transport, and storage activities vary with integrated, shared, and outsourced options presenting different cost-risk profiles. (4) As of today, there is no business case yet to pursue CCTS and CCUS. Therefore, it is all the more important to identify supporting revenue or financing streams to establish economic viability and accelerate deployment.

5 Outlook and next steps

The findings of this WP have provided valuable insights into the feasibility and challenges of carbon capture, utilization, and storage (CCUS) and carbon capture, transport, and storage (CCTS) solutions in Switzerland. In light of these findings, we outline the following key next steps that are crucial for advancing the adoption of CCUS and CCTS technologies. These actions should be undertaken by the members of the DemoUpCARMA consortium through collaborations with stakeholders from research, industry and administration.

- Pilot CO_2 capture:
  - Initiate pilot-scale testing of CO_2 capture technologies using small, mobile units that can be deployed at different sites. This approach allows for practical testing of various capture methods, providing valuable data for decision-making.
  - Collaborate with technology providers, emitters, and research institutions to conduct these pilot tests and gather real-world data to inform future implementation.
- Advance large-scale deployment:
  - Plan and implement one or two early-mover large-scale CO_2 capture facilities, targeting emission sources with significant CO_2 output (equal or larger than 100'000 tCO_2/y).
  - Recognize that large-scale plant development requires substantial time and investment. Therefore, it is essential to begin these planning and implementation efforts promptly to meet long-term emission reduction goals.
- Establish a responsible body for pipeline development:
  - Take concrete actions to establish a dedicated governing body responsible for the development and management of CO_2 transport pipelines.
  - Collaborate with international partners, particularly in neighbouring countries, to align pipeline infrastructure with broader transnational CO_2 transport networks.
- Promote enabling policies for sustainable business models:
  - Advocate for policies (such as Carbon Contracts for Differences) that create a framework conducive to viable business models for CCUS and CCTS (see report of WP5 for further information on this topic).
- Advance research and development:
  - Continue fostering research to stay at the forefront of evolving CO_2 capture and transport technologies. Regularly update the life cycle analysis (LCA) and techno-economic assessment (TEA) to adapt to changing conditions and identify opportunities for improvement.
- Establish a common basis for LCA and TEA:
  - Collaborate with stakeholders from industry, research and the administration to develop a common framework for these estimation and analysis. This will provide a reliable and standardized basis that can be used by all parties involved in CCUS and CCTS projects, fostering transparency and effective decision-making.

6 National and international cooperation

The data collection has been conducted in collaboration with

- ARA Bern: Wastewater treatment plant (https://www.arabern.ch/)
- ASTAG: Swiss Commercial Vehicle Association (https://www.astag.ch/)
- Carbfix: CO_2 storage company based on mineralization in basaltic rock (https://www.carbfix.com/)
- Casale: Chemicals and industrial equipment supplier (https://www.casale.ch/)
- ChemOil: Rail logistics provider for hazardous goods (https://www.chemoil.ch/)
- Contargo: Container logistics service provider (https://www.contargo.net/)
- Dan-Unity CO_2: Carbon dioxide shipping provider (https://dan-unity.dk/)
- ERZ: Service provider for cleanliness in public spaces, waste, water and wastewater, and district heating in the city of Zürich (https://www.stadt-zuerich.ch/ted/de/index/entsorgung_recycling.html)
- Jura Cement Wildegg: Cement plant (https://www.juramaterials.ch/)
- KVA Linth: Waste-to-energy plant (https://www.kva-linth.ch/)
- Linde: Industrial gases and engineering company (https://www.linde.com/)
- North Sea Container Line: Container logistics company (https://www.ncl.no/)
- Neustark: CO_2 utilization and storage company based on mineralization in concrete (https://www.neustark.com)
- Northern Lights: CO_2 storage company (https://norlights.com/)
- Samskip: Container logistics service provider (https://www.samskip.com/)
- SBB Cargo: Railway freight transport provider (https://www.sbbcargo.com/)
- Sea-Cargo: Logistics provider (https://sea-cargo.no/)
- VBSA: Association of Operators of Swiss Waste Recycling Plants (https://vbsa.ch/)
- Victrol: Waterway freight transport provider (https://www.victrol.be/)

Further national and national cooperation initiatives related to the DemoUpCARMA project as a whole will be described in the WP1 report or in the final Executive Summary.

7 Publications

Becattini, V., Gabrielli, P., Antonini, C., Campos, J., Acquilino, A., Sansavini, G., Mazzotti, M. (2022). Carbon dioxide capture, transport and storage supply chains: Optimal economic and environmental performance of infrastructure rollout. *International Journal of Greenhouse Gas Control*, 117, 103635, https://doi.org/10.1016/j.ijggc.2022.103635

Burger, J., Nöhl, J., Seiler, J., Gabrielli, P., Oeuvray, P., Becattini, V., Reyes-Lúa, A., Riboldi, L., Sansavini, G., Bardow, A. (2023). Environmental impacts of carbon capture, transport, and storage supply chains: Status and the way forward. *International Journal of Greenhouse Gas Control*, 132 104039, https://doi.org/10.1016/j.ijggc.2023.104039.

Gabrielli, P., Campos, J., Becattini, V., Mazzotti, M., Sansavini, G. (2022). Optimization and assessment of carbon capture, transport and storage supply chains for industrial sectors: The cost of resilience. *International Journal of Greenhouse Gas Control*, 121, 103797, https://doi.org/10.1016/j.ijggc.2022.103797

Oeuvray, P., Burger, J., Roussanaly, S., Mazzotti, M., & Becattini, V. (2024). Multi-criteria assessment of inland and offshore carbon dioxide transport. *Journal of Cleaner Production*. 443, 140781, https://doi.org/10.1016/j.jclepro.2024.140781

Otgonbayar, T., & Mazzotti, M. (2024). Modeling and assessing the integration of CO_2 capture in waste-to-energy plants delivering district heating. *Energy*, 290, 130087. doi:10.1016/j.energy.2023.130087

8 References

ASTRA. (2023, February 22). *Monats- und Jahresergebnisse.* Retrieved July 21, 2023, from ASTRA: https://www.astra.admin.ch/dam/astra/de/dokumente/verkehrsdaten/2022/jahresergebnisse-2022.xlsx.download.xlsx/Bulletin_2022_de.xlsx

Avenergy Suisse. (2023). *Jahresbericht 2022.* Zurich: Avenergy. Retrieved from https://www.avenergy.ch/images/pdf/Jahresberichte/Jahresbericht_2022_de.pdf

Becattini, V., Gabrielli, P., Antonini, C., Campos, J., Acquilino, A., Sansavini, G., & Mazzotti, M. (2022). Carbon dioxide capture, transport and storage supply chains: Optimal economic and environmental performance of infrastructure rollout. *International Journal of Greenhouse Gas Control, 117*, 103635.

Becattini, V., Riboldi, L., Anantharaman, R., Bardow, A., Burger, J., Frattini, L., . . . Zotica, C. (2024). Rolling-out pioneering carbon dioxide capture and transport chains from inland European industial facilities: a techno-economic, envionmental, and regulatory evaluation. *manuscript in preparation*.

BFE. (2019). *Schweizerische Gesamtenergiestatistik 2019.* Bern: BFE.

Burger, J., Nöhl, J., Seiler, J., Gabrielli, P., Oeuvray, P., Becattini, V., . . . Bardow, A. (2024). Environmental impacts of carbon capture, transport, and storage supply chains: Status and the way forward. *International Journal of Greenhouse Gas Control, 132*, 104039. doi:https://doi.org/10.1016/j.ijggc.2023.104039

Clean Air Task Force. (2023). Retrieved from Europe Carbon Capture Activity and Project Table: https://www.catf.us/ccstableeurope/

Comité National Routier (CNR). (2016). *Comparatif des conditions d'emploi et de rémunération des conducteurs routiers internationaux en Europe.* Paris: CNR.

David Luke Oates, P. V. (2014). Profitability of CCS with flue gas bypass and solvent storage. *International Journal of Greenhouse Gas Control*, 279-288.

Durán, I., Rubiera, F., & Pevida, C. (2017). Separation of CO_2 in a Solid Waste Management Incineration Facility Using Activated Carbon Derived from Pine Sawdust. *Energies, 10*(6), 827. doi:https://doi.org/10.3390/en10060827

Enertime. (2022). *Very High Temperature Heat Pump and Steam Generation Heat Pump* . Retrieved from Enertime: https://www.enertime.com/en/solutions/heat-pumps

ERZ. (n.d.). *Fahrten vom und zum KVA Hagenholz.*

European Energy Exchange (EEX). (2023, 09 29). *EEX EUA Primary Auction Spot.* Retrieved from https://www.eex.com/de/marktdaten/umweltprodukte/eex-eua-primary-auction-spot-download

Eurostat. (2022, 12 19). *Labour cost index by NACE Rev. 2 - Index (2016=100).* Retrieved from ec.europa.eu: https://ec.europa.eu/eurostat/databrowser/view/teilm140/default/table?lang=en

Fachverband der Schweizerischen Kies- und Betonindustrie FSKB . (2022). *Jahresbericht 2022.* Langnau: Vögeli AG.

Fachverband der Schweizerischen Kies- und Betonindustrie FSKB . (n.d.). *Beton - Recycling und Rückbau*. (FSKB) Retrieved August 22, 2023, from https://www.fskb.ch/beton/recycling-und-rueckbau/

Fasihi, M., Efimova, O., & Breyer, C. (2019). Techno-economic assessment of CO_2 direct air capture plants. *Journal of Cleaner Production, 224*, 957-980. doi:https://doi.org/10.1016/j.jclepro.2019.03.086

Fazio, S., Biganzioli, F., Laurentiis, V. d., Zampori, L., Sala, S., & Diaconu, E. (2018). Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods. Version 2, from ILCD to EF 3.0. *European Comission*.

Federal Statistical Office FSO. (2022). *Switzerland's population in 2021.* Neuchâtel: FSO.
Feron, P. H., Cousins, A., Jiang, K., Zhai, R., & Garcia, M. (2020). An update of the benchmark post-combustion CO_2-capture technology. *Fuel*, 117776.
Fraga, D. M., Skagestad, R., Eldrup, N. H., Korre, A., Haugen, H. A., Nie, Z., & Durucan, S. (2021). Design of a multi-user CO_2 intermediate storage facility in the Grenland region of Norway. *International Journal of Greenhouse Gas Control, 112*, 103514. doi:https://doi.org/10.1016/j.ijggc.2021.103514
Friday O. Ochedi, J. Y. (2021). Carbon dioxide capture using liquid absorption methods: a review. *Environmental Chemistry Letters*, 77–109.
Gabrielli, P., Campos, J., Becattini, V., Mazzotti, M., & Sansavini, G. (2022). Optimization and assessment of carbon capture, transport and storage supply chains for industrial sectors: The cost of resilience. *International Journal of Greenhouse Gas Control, 121*, 103797. doi:https://doi.org/10.1016/j.ijggc.2022.103797
Gabrielli, P., Gazzani, M., & Mazzotti, M. (2020). The role of carbon capture and utilization, carbon capture and storage, and biomass to enable a net-zero-CO_2 emissions chemical industry. *Industrial & Engineering Chemistry Research, 59*(15), 7033-7045.
Hansson, J., Hackl, R., Taljegard, M., Brynolf, S., & Grahn, M. (2017). The Potential for Electrofuels Production in Sweden Utilizing Fossil and Biogenic CO_2 Point Sources. *Frontiers in Energy Research, 5*. doi:https://doi.org/10.3389/fenrg.2017.00004
International Energy Agency (IEA). (2023). *Carbon Capture, Utilisation and Storage*. Retrieved from IEA: https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage
International Energy Agency. (2023, March). Retrieved from CCUS Projects Database: https://www.iea.org/data-and-statistics/data-product/ccus-projects-database
IPCC. (2005). *Carbon Dioxide Capture and Storage.* Cambridge University Press.
IPCC. (2022). *Climate Change 2022: Mitigation of Climate Change.* Cambridge, UK and New York, NY, USA: Cambridge University Press.
Knoope, M. M., Guijt, W., Ramírez, A., & Faaij, A. P. (2014). Improved cost models for optimizing CO_2 pipeline configuration for point-to-point pipelines and simple networks. *International Journal of Greenhouse Gas Control, 22*, 25-46.
Martin Albicker, M. E. (2023). *Carbon Capture & Storage (CCS). Kostenschätzung fpr ein CCS-System für die Schweiz bis 2050.* Basel: Bundesamt für Umwelt (BAFU).
Moser, P., Wiechers, G., Schmidt, S., Moretz-Sohn Monteiro, J. G., Goetheer, E., Charalambous, C., . . . Susana, G. (2021). ALIGN-CCUS: Results of the 18-month test with aqueous AMP/PZ solvent at the pilot plant at Niederaussem – solvent management, emissions and dynamic behavior. *International Journal of Greenhouse Gas Control*.
Oeuvray, P., Becattini, V., & Mazzotti, M. (2022). Carbon Capture, Transport and Storage (CCTS) supply chain assessment for early movers. *16th International Conference on Greenhouse Gas Control Technologies.* Lyon.
Oeuvray, P., Burger, J., Roussanaly, S., Mazzotti, M., & Becattini, V. (2024). Multi-criteria assessment of inland and offshore carbon dioxide transport. *Journal of Cleaner Production*, 140781. doi:10.1016/j.jclepro.2024.140781
OFS. (2022). *Marchandise transportée des véhicules indigènes et étrangers selon le genre de véhicule (Prestations des véhicules de transport de marchandises. Séries chronologiques).*
OFS. (2022, November 22). *Prestation de transport selon le genre de marchandises et le type de fret. Véhicules lourds suisses.* Retrieved from https://www.bfs.admin.ch/bfs/fr/home/statistiques/catalogues-banques-donnees/tableaux.assetdetail.23404741.html

OFS. (2022). *Transport combiné de marchandises*. Retrieved from https://www.bfs.admin.ch/bfs/fr/home/statistiques/mobilite-transports/transport-marchandises/combine.html

OFS. (2022a). *Prestation de circulation des véhicules indigènes et étrangers selon le genre de véhicule (Prestations des véhicules de transport de marchandises. Séries chronologiques).*

OFS. (2022b). *Transport de marchandises en 2021.* Retrieved from https://www.bfs.admin.ch/bfs/fr/home/statistiques/mobilite-transports/transport-marchandises.html

OGE. (2023, September 27). *Our CO_2 transportation grid starts*. Retrieved from https://oge.net/en/co2/co2-grid

Otgonbayar, T., & Mazzotti, M. (2022). Optimization of solvent-based post-combustion capture processes for waste-to-energy. *16th Greenhouse Gas Control Technologies Conference.* Lyon.

Otgonbayar, T., & Mazzotti, M. (2024). Modeling and assessing the integration of CO_2 capture in waste-to-energy plants delivering district heating. *Energy, 290*(130087), 1-14. doi:10.1016/j.energy.2023.130087.

Paul Akula, J. E. (2021). Model Development, Validation, and Optimization of an MEA-BasedPost-Combustion CO_2 Capture Process under Part-Load and VariableCapture Operations. *Industrial & Engineering Chemistry Research*, 5176-5193.

Pérez-Calvo, J.-F., & Mazzotti, M. (2022). Techno-economic assessment of post-combustion CO_2 capture using aqueous piperazine at different flue gas compositions and flowrates via a general optimization methodology. *International Journal of Greenhouse Gas Control, 114*, 103587. doi:https://doi.org/10.1016/j.ijggc.2022.103587

Port of Switzerland. (2021). *Güterumschlag Schweizerische Rheinhäfen.* Retrieved from https://port-of-switzerland.ch/wp-content/uploads/2022/02/220210-MM-SRH-SVS-Umschlagszahlen-2021.pdf

Port of Switzerland. (n.d.). *Jahresbericht 2022.* Basel: Schweizerische Rheinhäfen.

Rapp AG. (2022). *CO_2-Transport ab KHKW Hagenholz.*

Rosa, L., Becattini, V., Gabrielli, P., Andreotti, A., & Mazzotti, M. (2022). Carbon dioxide mineralization in recycled concrete aggregates can contribute immediately to carbon-neutrality . *Resources, Conservation & Recycling, 184*, 106436.

Roussanaly, S., Deng, H., Skaugen, G., & Gundersen, T. (2021). At what Pressure Shall CO_2 Be Transported by Ship? An in-Depth Cost Comparison of 7 and 15 Barg Shipping. *Energies, 14*(18), 5635.

Saipem. (2021). CO_2 Collection Network in Switzerland - Final Presentation.

Saunier, F., Fradette, S., Clerveaux, F., Lefebvre, S., Madore, É., Veilleux, G., . . . Surprenant, R. (2019). Comparison of life-cycle assessment between bio-catalyzed and promoted potassium carbonate processes and amine-based carbon capture technologies. *International Journal of Greenhouse Gas Control*.

Schneider, M. (2016). *Das Kies, Aushub- und Rückbaumaterial (KAR)-Modell für die Schweiz.* Bern: BAFU. Retrieved from https://www.bafu.admin.ch/dam/bafu/de/dokumente/abfall/externe-studien-berichte/studie_kar_modell.pdf.download.pdf/Studie%20KAR-Modell%20f%C3%BCr%20die%20Schweiz.pdf

Sustainability in Business Lab. (2021). *Feasibility of a demonstrator for the carbon capture and storage value chain in CH with a waste-to-energy plant.*

TES. (2023). *Industrial scale Green Hydrogen, Green Gas supply and CO_2 offtake.* Retrieved from https://www.alpenforce.com/sites/default/files/2023-01/Legeret_TES.pdf

The Federal Council. (2021). *Switzerland's Long-Term Climate Strategy.* Bern.

Tiefenthaler, J., Braune, L., Bauer, C., Sacchi, R., & Mazzotti, M. (2021). Technological Demonstration and Life Cycle Assessment of a Negative Emission Value Chain in the Swiss Concrete Sector. *Frontiers in Climate, 3*, 729259.

United Nations Environment Programme. (2015, December 12). Paris Agreement to the United Nations Framework Convention on Climate Change.

van der Spek, M., Arendsen, R., Ramirez, A., & Faaij, A. (2016). Model development and process simulation of postcombustion carbon capture technology with aqueous AMP/PZ solvent. *International Journal of Greenhouse Gas Control*, 176-199.

VBSA. (2019, May). *Beitrag der Abfallwirtschaft zur künftigen Klimapolitik der Schweiz - Diskussionsgrundlage zum Konzept «Carbon Hub».* Retrieved from https://vbsa.ch/wp-content/uploads/2019/05/Klimastrategie_VBSA_Diskussionsgrundlage_def.pdf

VBSA. (2022). *Einheitliche Heizwert- und Energiekennzahlenberechnung der Schweizer KVA nach europäischem Standardverfahren.* Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation UVEK.

Wang, X., & Song, C. (2020). Carbon Capture From Flue Gas and the Atmosphere: A Perspective. *Frontiers in Energy Research, 8*. doi:https://doi.org/10.3389/fenrg.2020.560849

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment, 21*, 1218-1230. doi:https://doi.org/10.1007/s11367-016-1087-8

Wintershall Dea. (2022, October 18). *Wintershall Dea and HES Wilhelmshaven Tank Terminal intend to jointly develop a* CO_2 *Hub in Wilhelmshaven*. Retrieved from https://wintershalldea.no/en/newsroom/wintershall-dea-and-hes-wilhelmshaven-tank-terminal-intend-jointly-develop-co2-hub-wilhelmshaven

Yen, J. Y. (1971). Finding the K Shortest Loopless Paths in a Network. *Management Science, 17*(11), 661-786.

9 Appendix

- Appendix I - Definition of scenarios for an EU-wide shared CO_2 infrastructure
- Appendix II - Business models for waste-to-energy, cement, and chemical and pharma industries
- Appendix III - Optimal design and assessment of post-combustion CO_2 capture integration with Jura Cement (engineering documents)
- Appendix IV - Optimal design and assessment of post-combustion CO_2 capture integration with KVA Hagenholz (engineering documents)