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Federal Department of the Environment, Transport, Energy and Communications DETEC

Swiss Federal Office of Energy SFOE
Energy Research and Cleantech Division

Final report dated 3 April 2024

DECARBIN

The impact of energy and climate policy on the decarbonization of industry in Switzerland

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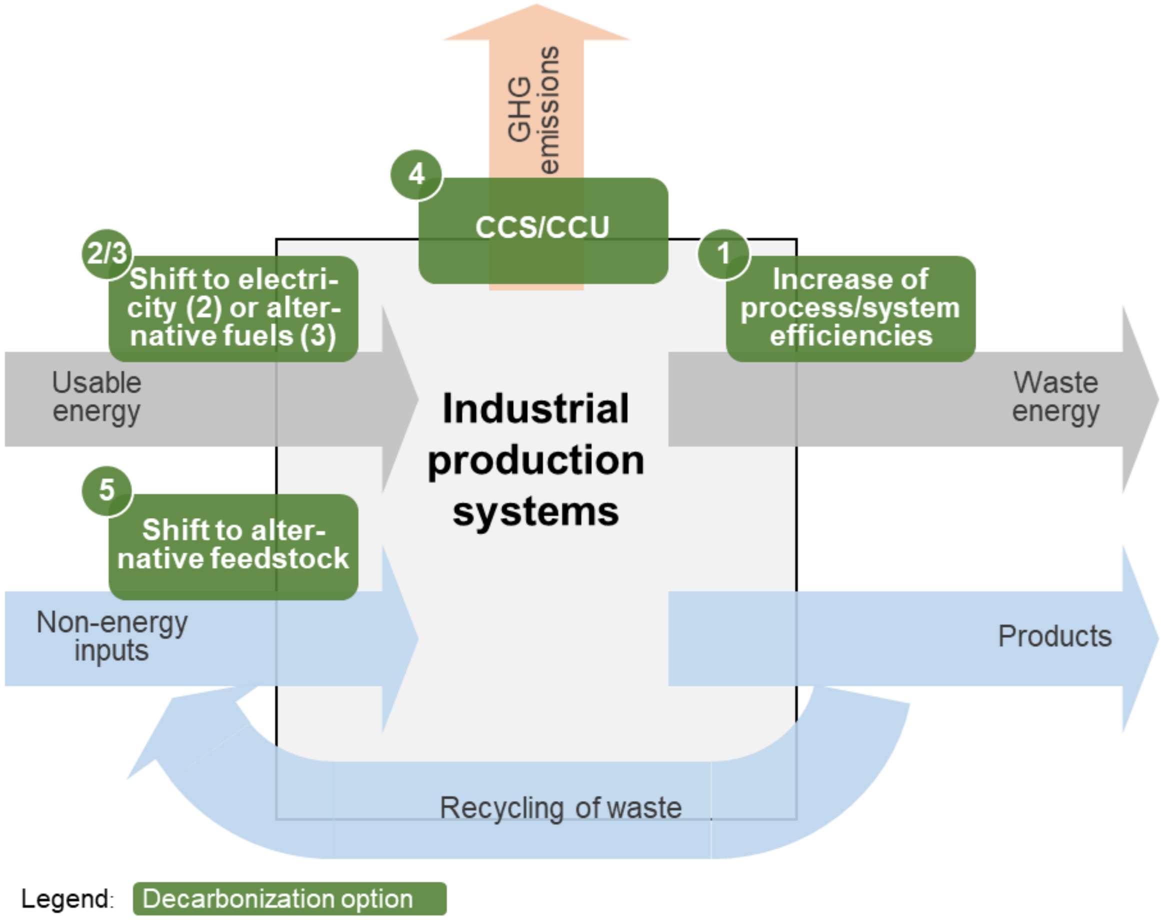

Source: ©DECARBIN 2024

Date: 03 April 2024

Location: Bern

Publisher:
Swiss Federal Office of Energy SFOE
Energy Research and Cleantech
CH-3003 Bern
www.bfe.admin.ch

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SFOE contract number: SI/502114-01

Zusammenfassung

Der Industriesektor trug 2018 rund 18% zu den Schweizer CO2-Emissionen bei. Die Technologien zur drastischen Reduktion der Emissionen in emissions- und energieintensiven Industrien sind allerdings teilweise noch nicht marktreif. Gleichzeitig sind diese Industrien für die Schweizer Wirtschaft von grosser Bedeutung. Grosse Schweizer Unternehmen sind in emissionsintensiven Sektoren wie Zement, Spezialchemie oder Pharma tätig. Weiter kann die wirtschaftliche Attraktivität und damit der Einsatz dieser neuen, emissionsarmen Technologien das Schweizer Energiesystem stark beeinflussen. Daher ist es eine wichtige Aufgabe für die Schweizer Politik, den Übergang zu einer kohlenstoffarmen Industrie effizient zu gestalten, ohne dabei den wirtschaftlichen Wohlstand, die Versorgungssicherheit und den sozialen Zusammenhalt in der Schweiz zu gefährden. Die Ergebnisse des DECARBIN Projekts unterstützen eine evidenzbasierte Gestaltung von Politikmassnahmen in diesem wichtigen, aber wenig erforschten Bereich der Energie- und Klimapolitik. Im Projekt wurde eine Sektor-Technologie-Matrix entwickelt, die zusammenfasst, welche Optionen aus technologischer Sicht am besten geeignet sind, die emissionsintensivsten Industriesektoren in der Schweiz – Baustoffe (einschliesslich Zement), Chemie & Pharma, Metalle und Lebensmittel – zu dekarbonisieren. Dabei wurden die Vermeidungsoptionen entlang von fünf Gruppen gegliedert: (1) Erhöhung der Prozess-/Systemeffizienz, (2) Umstellung auf strombasierte Prozesse (Elektrifizierung), (3) Umstellung auf alternative Brennstoffe, (4) Kohlenstoffabscheidung und -speicherung (CCS) oder -nutzung (CCU) und (5) Umstellung auf alternative Rohmaterialien. Darüber hinaus wurden zwei techno-ökonomische Modelle entwickelt, um den Einfluss von Energie- und Klimapolitik auf Investitionsentscheidungen in der Industrie zu untersuchen. Die Modelle berechnen und vergleichen den Wert von Investitionen in verschiedene Technologien zu verschiedenen Zeitpunkten für verschiedene Unsicherheits- und Politikszenarien. Die Ergebnisse zeigen, dass Elektrifizierung und eine Umstellung auf Biomasse gangbare Wege zur Dekarbonisierung der Chemie- und Molkereiindustrie sind. Dekarbonisierungspfade für die Zementindustrie beinhalten eine Kombination von CCS mit Biomasse. Wasserstoff spielt keine bedeutende Rolle in den drei modellierten Industrien. Bezüglich des Bedarfs an unterschiedlichen Energieträgern in der Schweiz sollte also mit erhöhter Strom- und Biomassenachfrage gerechnet werden. Aus der Sicht von Politik/Verwaltung, ergeben sich mehrere Implikationen. Erstens sollte die Verwendung von Biomasse in der Schweiz aufgrund möglicher starker Nachfragesteigerungen einer kritischen Bewertung unterzogen werden. Die Nutzung von Biomasse in Niedrigtemperaturanwendungen (wie heute weit verbreitet) erscheint angesichts der Verfügbarkeit und Wirtschaftlichkeit von Wärmepumpen in Verbindung mit dem Mangel an Alternativen in Hochtemperaturanwendungen unvernünftig. Zweitens wird die Aufrechterhaltung eines stabilen und steigenden CO2-Preises als entscheidend erachtet. Carbon Contracts for Difference, wie sie in Deutschland erprobt werden, könnten eine Option sein, um diese Preise zu garantieren. Drittens betonen die Ergebnisse die Bedeutung niedriger Stromkosten, insbesondere um die Elektrifizierung wirtschaftlicher zu machen als Biomasse, zumindest für Prozesse bei sehr hohen Temperaturen. Der Zugang grosser industrieller Verbraucher zu den EU-Strommärkten könnte als potenzieller Hebel dienen. Viertens wird weitere Forschung und Entwicklung im Bereich von Hochtemperaturwärmepumpen empfohlen. Schliesslich werden CCS-CAPEX-Subventionen zur Beschleunigung von Investitionen als möglich, aber nicht als zwingend notwendig erachtet. Unabhängig von politischen Interventionen besteht ein bemerkenswertes Risiko der Verlagerung von Industrien ins Ausland aufgrund hoher CO2-Transportkosten.

Summary

Industry contributed about 18% of Swiss CO2 emissions in 2018 but technologies for drastically reducing emissions in carbon- and energy-intensive industrial production are partly not mature yet. At the same time, these industries are of significant importance for the Swiss economy. Major Swiss companies are engaged in industrial production in subsectors such as cement, specialty chemicals or pharmaceuticals. Moreover, the economic attractiveness and hence the deployment of these new, low-carbon technologies can strongly affect the Swiss energy system. Hence, managing the low-carbon transition of emitting industries effectively, without jeopardizing economic prosperity, security of supply and social cohesion, is a momentous task for Swiss policymakers. As such, the DECARBIN project results support evidence-based policymaking in this important but little-researched domain of energy and climate policy. The project has developed a sector-technology matrix summarizing which options are best suited (from a technological point of view) to decarbonise the most emission-intense industry sectors in Switzerland, i.e., the minerals (including cement), chemicals, metals and food sectors. Abatement options were structured along five groups: (1) Increase of process/system efficiencies, (2) shift towards electricity-based processes (electrification), (3) shift towards alternative fuels, (4) carbon capture and storage (CCS) or use (CCU), and (5) shift to alternative feedstock. Furthermore, two techno-economic models were developed to investigate the influence of energy and climate policy on investment decisions in industry. The models calculate and compare the value of investments in different technologies and at different points in time for different uncertainty and policy scenarios. The findings indicate that electrification and a shift to biomass are viable pathways for decarbonizing the chemical and dairy industries. Meanwhile, the cement industry's strategy involves a combination of CCS with biomass. Hydrogen does not play a significant role in the decarbonization strategies of any of the three industries. In other words, our results imply an increased demand for electricity and biomass in the mid-term future. From a policy perspective, several implications emerge. Firstly, the use of biomass in Switzerland should undergo critical evaluation due to potentially strong increases of demand. Using biomass in low-temperature applications (as widely observed today) seems unreasonable given the availability and economic efficiency of heat pumps coupled with the lack of clearly viable alternatives in high-temperature applications. Secondly, maintaining a stable and increasing CO2 price is identified as essential. Carbon contracts for difference, as experimented with in Germany, might be one option to guarantee these prices. Thirdly, the results emphasize the importance of low electricity costs, particularly in making electrification more economically viable than biomass for all but very high-temperature processes. Access of large industrial consumers to EU electricity markets could act as a potential lever. Fourth, further research and development in very high-temperature heat pumps is recommended. Finally, while CCS CAPEX subsidies can expedite investments, they are not deemed necessary. Regardless of policy interventions, there is a noteworthy risk of industry re-localization based on lower CO2 transport costs of non-Swiss plants.

Résumé

L’industrie a contribué à environ 18 % des émissions de CO_2 en Suisse en 2018, mais les technologies permettant de réduire drastiquement les émissions dans les processus industriels à forte intensité énergétique et intensité carbone ne sont en partie pas encore matures. Parallèlement, ces industries revêtent une importance significative pour l’économie suisse. De grandes entreprises suisses sont actives dans la production industrielle dans des sous-secteurs tels que le ciment, les produits chimiques de spécialité ou les produits pharmaceutiques. En outre, l’attractivité économique et donc le déploiement de ces nouvelles technologies à faibles émissions de carbone peuvent avoir une forte influence sur le système énergétique suisse. Gérer efficacement la transition bas-carbone des industries émettrices, sans compromettre la prospérité économique, la sécurité d’approvisionnement et la cohésion sociale, constitue donc une tâche majeure pour les décideurs politique suisses. À ce titre, les résultats du projet DECARBIN soutiennent l’élaboration de politiques fondées sur des données probantes dans ce domaine important mais encore peu étudié de la politique énergétique et climatique. Le projet a développé une matrice secteur-technologie résumant les options les plus adaptées (du point de vue technologique) pour décarboner les secteurs industriels les plus émetteurs en Suisse, à savoir les secteurs des minéraux (y compris le ciment), des produits chimiques, des métaux et de l’alimentation. Les options de réduction des émissions ont été structurées selon cinq groupes : (1) amélioration de l’efficacité des processus/systèmes, (2) transition vers des procédés électrifiés, (3) transition vers des carburants alternatifs, (4) captage et stockage (CCS) ou utilisation (CCU) du carbone, et (5) substitution des matières premières. En outre, deux modèles techno-économiques ont été développés pour étudier

l'influence de la politique énergétique et climatique sur les décisions d'investissement dans l'industrie. Les modèles calculent et comparent la valeur des investissements dans différentes technologies et à différents moments, selon divers scénarios d'incertitude et de politique. Les résultats indiquent que l'électrification et une transition vers la biomasse constituent des voies viables de décarbonation pour les industries chimique et laitière. En revanche, la stratégie de l'industrie cimentière repose sur une combinaison de CCS et de biomasse. L'hydrogène ne joue pas de rôle significatif dans les stratégies de décarbonation des trois industries. Autrement dit, nos résultats impliquent une augmentation de la demande d'électricité et de biomasse à moyen terme. Du point de vue des politiques publiques, plusieurs implications se dégagent. Premièrement, l'utilisation de la biomasse en Suisse devrait faire l'objet d'une évaluation critique en raison de la potentielle forte augmentation de la demande. L'utilisation de la biomasse dans des applications à basse température (telle qu'observée aujourd'hui) semble peu judicieuse, compte tenu de la disponibilité et de la rentabilité économique des pompes à chaleur, ainsi que du manque d'alternatives clairement viables pour les applications à haute température. Deuxièmement, le maintien d'un prix du CO_2 stable et croissant est identifié comme essentiel. Les contrats carbone pour différence, expérimentés en Allemagne, pourraient être une option pour garantir ces prix. Troisièmement, les résultats soulignent l'importance de faibles coûts de l'électricité, en particulier pour rendre l'électrification plus économiquement viable que la biomasse, sauf pour les procédés à très haute température. L'accès des grands consommateurs industriels aux marchés de l'électricité de l'UE pourrait constituer un levier potentiel. Quatrièmement, il est recommandé de poursuivre la recherche et le développement sur les pompes à chaleur à très haute température. Enfin, bien que des subventions pour les dépenses d'investissement (CAPEX) dans le CCS puissent accélérer les investissements, elles ne sont pas jugées nécessaires. Indépendamment des interventions politiques, il existe un risque notable de relocalisation industrielle en raison des coûts moindres de transport du CO_2 des installations situées hors de Suisse.

Main findings

- Technologies facilitating the decarbonization of the industrial sector are largely available but have not been widely implemented in Switzerland, primarily due to economic considerations.

- Electrification and a transition to biomass stand out as feasible approaches for reducing carbon emissions in the chemical and dairy industries. Conversely, a hybrid approach involving CCS and biomass could effectively decarbonize cement production. In essence, the selection of technology hinges on factors such as process temperatures, energy carrier costs, capital expenditures, and the cost of capital.

- Anticipated decarbonization investments and the subsequent reduction of CO2 emissions in the chemical and cement industries are expected post-2035, with the timing of these investments heavily influenced by carbon pricing dynamics.

- Policymakers are strongly encouraged to conduct a thorough evaluation of biomass utilization in Switzerland, prioritize the establishment of a stable and increasing CO2 price (via the CO2 levy and price in the emissions trading system), and recognize the importance of maintaining low electricity costs.

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Abbreviations

A – Alternative state

CAPEX – Capital expenditures

CCfD – Carbon contracts for difference

CCS – Carbon capture and storage

CCU – Carbon capture and use

Cf – Compare

COP – coefficient of performance

EM – Emissions

EU ETS – EU Emissions Trading System

FU – Fuel

GHG – Greenhouse gas

I – Investment

IAEE – International Association of Energy Economics

NPV – Net present value

O&M – Operations and maintenance

OPEX – Operational expenditures

PIK – Potsdam Institute for Climate Impact Research

R – Reference state

ROV – Real Options Valuation

SCCER CREST – Competence Center for Research in Energy, Society and Transition

SCCER EIP – Swiss Competence Center for Energy Research, Efficiency in Industrial Processes

SCCER HaE – Swiss Competence Center for Energy Research, Heat and Electricity Storage

SFOE – Swiss Federal Office of Energy

ST – Storage and transport

UHT – Ultra-high-temperature

UNFCCC – United Nations Framework Convention on Climate Change

VAT – Value added tax

WACC – Weighted average costs of capital

WP – Work package

1 Introduction

1.1 Background information and current situation

The Federal Council aims to achieve a climate-neutral Switzerland by 2050 (Bundesrat, 2019). While the decarbonization of the transport and building sectors is under way in Switzerland (Bundesrat, 2021) and in many other industrialized countries, technologies for drastically reducing emissions in carbon- and energy-intensive industrial production are partly not mature yet (IEA, 2023). Industry contributed about 18% of Swiss CO2 emissions in 2018 (BAFU, 2020a) and consumed about 20% of final energy in Switzerland in 2020 (BFE, 2021). At the same time, carbon- and energy-intensive industries are of significant importance for the Swiss economy. Major Swiss companies are engaged in industrial production in subsectors such as cement, specialty chemicals, pharmaceuticals, metals, and machinery. Hence, managing the low-carbon transition of emitting industries effectively, without jeopardizing economic prosperity and social cohesion, is a momentous task for Swiss policymakers.

To date it remains unclear, which options exist for deep decarbonization of Swiss industries and how these are affected by energy and climate policy. The main technological options to this end are (1) Increase of process/system efficiencies, (2) shift towards electricity-based processes (electrification), (3) shift towards alternative fuels, (4) carbon capture and storage (CCS) or use (CCU), and (5) shift to alternative feedstock. The economic viability of these decarbonization options is strongly affected by energy and climate policies, and the international competitiveness of Swiss industrial production depends on the design of such policies (Dröge et al., 2009).

At the same time, the economic attractiveness and hence the deployment of technologies for the different options can strongly affect the Swiss energy system (see e.g. Agora Energiewende (2019) for the case of Germany) and the progress in achieving the goals of the Energy Strategy 2050 (Prognos AG et al., 2021). For example, an electrification of industrial processes could partly offset the anticipated reduction of the electricity demand from efficiency gains (Panos et al., 2021; Prognos AG et al., 2021), whereas deployment of CCS could increase the total energy demand and the need for a dedicated infrastructure for CO2 transport. In other words, Swiss energy and climate policy will affect industry decarbonization, which in turn will affect the energy system. To date, however, it remains unclear to which extent and in which way. In the DECARBIN project, we aimed to uncover these effects and develop recommendations on policy mix designs that effectively and efficiently induce a decarbonization of the Swiss GHG emitting industry sectors while avoiding unintended negative feedbacks on the Swiss energy system. As such, the DECARBIN project results aims at supporting evidence-based policymaking in this important but little-researched domain of energy and climate policy.

While the research questions in the DECARBIN project have not been addressed before, we can still build on previous research. For a long time, the industrial sector received little attention with respect to reaching climate goals in Switzerland – e.g., the Swiss marginal abatement cost study of 2009 (McKinsey, 2009) did not calculate abatement costs for industry. In the 2nd phase of the SCCER since 2017, research from the competence centre for Efficiency in Industrial Processes (EIP) assessed the techno-economic feasibility of efficiency options in industry, for example efficiency measures for Swiss industrial motor systems (Zuberi et al., 2017), the Swiss cement industry (Zuberi & Patel, 2017), the Swiss metals industry (Bhadbhade et al., 2019), the Swiss chemical and pharmaceutical industry (Zuberi & Patel, 2019), and the Swiss food & beverages industry (Bhadbhade & Patel, 2020). Such efficiency measures are an important part of the transition pathway, but they cannot deliver the full decoupling of industry production from carbon emissions. DECARBIN therefore builds on SCCER EIP results and extend the analysis to technologies that are relevant for a deep decarbonization in the mid- to long-term. For Switzerland, these technological options have only partially been analysed, e.g. CCS in cement within SWIDEM, SCCER EIP and DecarbCem (Nakhle et al., 2022; Obrist et al., 2021; Zuberi & Patel, 2017), heat pumps (Arpagaus et al., 2018; Arpagaus & Bertsch, 2020; Obrist et al., 2023) and technologies along the “power-to-x” path in a study commissioned by Innosuisse and the SFOE (Kober et al., 2019), or are currently being analysed (e.g., in DecarbCH for heating and cooling technologies (Patel & Guidati, 2021)).

On the international level, the systematic assessment of industry decarbonization also started only recently (with the exception of earlier studies on CCS in steel and cement industries (see e.g. Kajaste & Hurme, 2016; Van Ruijven et al., 2016)). Several overviews of technology options have recently been published (Agora Energiewende & Wuppertal Institut, 2019; C. Bataille et al., 2018; C. G. F. Bataille, 2020; Guidehouse, 2020; Levesque et al., 2020; PBL Netherlands Environmental Assessment Agency, 2021; Wesseling et al., 2017). The impact on the energy vector has also been analysed (Gierkink et al., 2021; Lechtenböhmer et al., 2016). These studies, however, cover industry sectors that are relevant for other geographies (including aluminium, steel, etc.), with a focussed analysis of relevant options and cost for the emitting industry sectors in Switzerland still pending. To quantitatively assess technology options for Switzerland, we will therefore build on our solid experience in techno-economic modelling (compare e.g. Schmidt et al., 2019), using the concept of abatement costs (Schmidt et al., 2012) that has recently been applied for industry decarbonization technologies in the German study by Agora Energiewende (2019).

1.2 Research questions

While decarbonization of the industry sector is arguably much harder than the decarbonization of other sectors (e.g., electricity generation, transport), the eventual decoupling of industry production is imperative in order to reach net zero in 2050. Thus far, literature on industry decarbonization, the link to the energy sector, and the role of policy is very limited, particularly for the case of Switzerland. This leaves Swiss policy makers with a high level of uncertainty, and risks taking uninformed policy decisions that may have unintended negative consequences for the Swiss energy system.

The DECARBIN project aims to address this very gap and to assist Swiss policy makers in designing an efficient energy and climate policy mix specifically for the decarbonization of the Swiss industry sector. To this end, our work shall help to understand the effects of different energy and climate policies on competing industry sector decarbonization options; to assess how specific policy designs would affect the international competitiveness of Swiss industrial production plants vis-à-vis production plants in the European Union, and to estimate how a large-scale deployment of industry decarbonization technologies would in turn affect the Swiss energy system and the Energy Strategy 2050.

To address this gap, we pose the following research questions:

1. Which technological decarbonization options are most relevant for carbon-intensive industry sectors in Switzerland?

The industry sector in Switzerland differs structurally from the industry sector in other countries (e.g., France, Germany), and a clear understanding of relevant decarbonization options for the industry sub-sectors most pertinent in Switzerland today and in the long-term is a prerequisite for meaningful policy advice. Extending the work from SCCER EIP by further technological options that could become relevant through 2050, a sector-technology matrix will form the basis for subsequent analyses, and can also inform the energy policy debate towards net zero 2050 in Switzerland more generally.

2. How sensitive are these options' abatement costs towards energy and climate policy and how would different policy mixes affect the competition between options? How does policy influence the international competitiveness of industrial production in Switzerland, and what does this imply for Switzerland's energy system?

From a policy point of view, it is crucial to understand how different decarbonization options are affected by energy and climate policy choices. The key variable in that regard are abatement costs, i.e., the cost per ton CO2 reduction. The abatement cost of options such as electrification, CCS, alternative fuel-based processes etc. depend on various energy policy parameters, and DECARBIN aims to highlight the most important dependencies in that regard.

Building on the results concerning the first question, DECARBIN puts great emphasis on analysing the outcome of policies with respect to technology choices, industry competitiveness, and energy system implications. Ultimately, Swiss policy makers need to know the effect of policy mixes (consisting of energy policies, general climate policies, and potentially industry-specific decarbonization policies) in the context of the Energy Strategy 2050. Concerning industry decarbonization, the project analyses in detail three aspects: How do policy mixes affect the competition between the different decarbonization options in relevant industry subsectors, how do specific policy designs affect the competitiveness of Swiss industrial production on a European level, and what do policy mixes – and the subsequent deployment of decarbonization technologies – imply for the Swiss energy system at large.

In general, DECARBIN combines quantitative methods (especially techno-economic modelling) with qualitative methods (technology expert interviews, policy design analysis) that allow to answer the scientific questions asked. Taken together, answering the scientific questions posed by DECARBIN shall not only advance the academic literature, but directly support evidence-based policymaking in this important but little-researched domain of energy policy.

1.3 Project setup

The DECARBIN project was coordinated by Prof. Schmidt and Prof. Steffen. In addition, Paul Tautorat was hired as a PhD student at the beginning of the project (April 1st, 2021). Furthermore, four master students joined the DECARBIN team for their theses (cf. Table 1).

Table 1 Overview of student theses conducted in the DECARBIN project

Topic	Student (program)	Methodology	Duration
Policies for the decarbonisation of the industrial sector	Paul Tautorat (doctorate ETH)	- Various	4/21-ong.
Automated mapping of industry decarbonization literature using an unsupervised learning approach	Björn Lalin (MAS ETH in Science, Technology and Policy)	- Topic modelling - Literature mapping	6/21-1/22
Influence of energy and climate policy on the economics of decarbonization options in the cement industry	Natalija Ljubic (MSc EPFL in Energy Science and Technology)	- Techno-economic modelling - Expert interviews	9/21-3/22
Influence of energy and climate policy on decarbonization investments in the food & beverages industry	Taha Ramazanoğlu (MSc ETH in Energy Science and Technology)	- Techno-economic modelling - Expert interviews	9/22-12/22
Influence of energy and climate policy on decarbonization investments in the chemical and pharmaceutical industry	Jasper Iversen (MSc ETH in Management, Technology and Economics)	- Techno-economic modelling - Expert interviews	10/22-4/23

The DECARBIN project is structured in three work packages (WPs, cf. Figure 1). Despite this being the final report commissioned at the end of WP3, some detailed modelling results will only be part of the planned academic publications (one in preparation on the Swiss chemical industry and a second one on the European cement and steel industries (incl. the Swiss plants)).

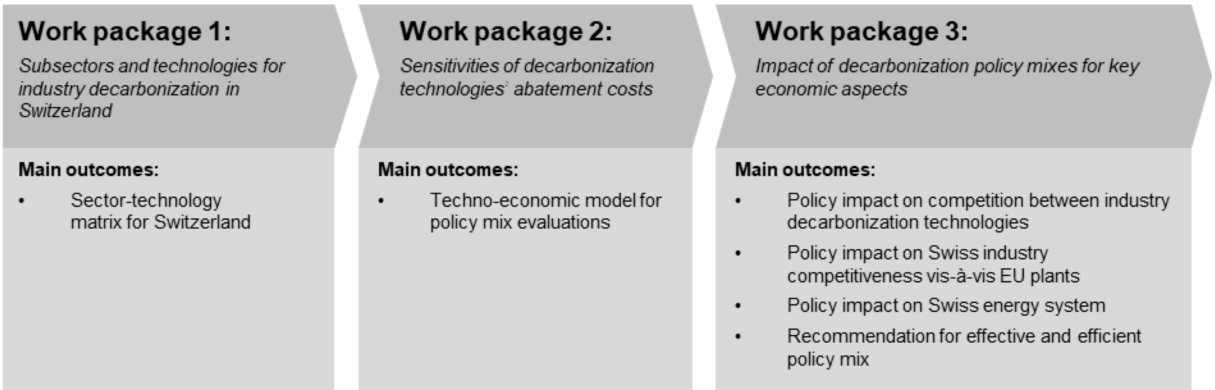


Figure 1 DECARBIN work packages

The results from each work package are subject to quality control. In the case of WP1, earlier versions of the sector-technology matrix, i.e., the prioritized industry sectors and the abatement options, were discussed by the authors' research groups. In addition, preliminary results were presented to representatives of the SFOE at different occasions. Written feedback from SFOE on WP1 was received and incorporated accordingly. Furthermore, expert interviews with researchers and practitioners from the respective industries were conducted to improve the results (cf. Table 2 for a list of conducted interviews).

In addition, the DECARBIN project introduced an advisory board, in order to ensure a high quality of the work, to efficiently leverage existing research, and to simplify collaborations. Two advisory board meetings took place in September 2021 and May 2023. Final results from the ROV-model, however, have not been presented to the advisory board, yet. On top of the authors, four members participated in the meeting:

- Dr. Tom Kober (Paul Scherrer Institut)
- Prof. Dr. Marco Mazzotti (ETH Zurich, Department of Mechanical and Process Engineering)
- Dr. Michael Pahle (Potsdam Institute for Climate Impact Research)
- Prof. Dr. Martin Patel (University of Geneva)

Table 2 List of interviewees (as of January 2024). More interviews on perceived uncertainty planned for Q1 2024

No.	Sector	Type of organization	Role of interviewee
Industry-focus			
1	Industry in general	Research group	Researcher
2	Chemicals	Research group	Researcher
3	Chemicals	Plant operator	Energy/environmental/sustainability manager
4	Chemicals	Sustainability Consultancy	Sustainability consultant
5	Chemicals	Plant operator	Site manager
6	Chemicals	Plant operator	Energy/environmental/sustainability manager
7	Chemicals	Plant operator	Energy/environmental/sustainability manager
8	Chemicals	Plant operator	Engineer
9	Chemicals	Technology provider	Project manager
10	Chemicals	Technology provider	Production engineer
11	Chemicals	Plant operator	Energy/environmental/sustainability manager
12	Chemicals	Plant operator	Energy/environmental/sustainability manager
13	Chemicals	Plant operator	Energy/environmental/sustainability manager
14	Chemicals	Consultancy	Energy consultant
15	Chemicals	Utility company	Manager
16	Chemicals	Plant operator	Site manager
17	Chemicals	Plant operator	Site manager
18	Chemicals	Plant operator	Site manager
19	Chemicals	Plant operator	Product manager
20	Food & Beverages	Research group	Researcher
21	Food & Beverages	Research group	Researcher
22	Food & Beverages	Plant operator	Energy/environmental/sustainability manager
23	Food & Beverages	Plant operator	Energy/environmental/sustainability manager
24	Food & Beverages	Plant operator	Managing director
25	Food & Beverages	Plant operator	Managing director
26	Metals	Industry association	Managing director
27	Metals	Utility	Energy/environmental/sustainability manager
28	Metals	Plant operator	Energy/environmental/sustainability manager
29	Minerals	Industry association	Head of communication and public affairs
30	Minerals	Industry association	Managing director
31	Minerals	Think-tank/Consultancy	Technology manager
32	Minerals	Plant operator	R&D program manager
33	Minerals	Plant operator	Director research centre
34	Minerals	Plant operator	(Deputy) plant manager
35	Minerals	Plant operator	Technology manager
36	Minerals	Plant operator	Technology manager
37	Minerals	Plant operator	(Deputy) plant manager
38	Minerals	Plant operator	Energy/environmental/sustainability manager
39	Minerals	Plant operator	Managing director
40	Minerals	Plant operator	Engineer
Policy-/uncertainty-focus			
41	Uncertainty around ETS	Bank	Head carbon markets
42	Uncertainty around ETS	Energy Utility	Head energy & climate policy
43	Uncertainty around ETS	Lobby organisation	Chairman
44	Uncertainty around ETS	Lobby organisation	Policy Director

2 Procedures and methodology

The project applied a mix of qualitative and quantitative research. While the sector-technology-matrix is the result of a qualitative analysis (cf. Section 2.1), the remainder is based on computational modelling: the dairy industry was studied using a simpler net present value (NPV) model (cf. Section 2.2), and the cement and chemical industries are analysed by means of a more elaborate model applying real option valuation (ROV) (cf. Section 2.3).

2.1 Sector-technology-matrix[1]

As part of WP 1 we developed a matrix of emitting industrial sectors and the decarbonization options most relevant for reaching net zero emissions in Switzerland (sector-technology matrix, cf. Figure 2). The matrix is a novel contribution for the Swiss context, and forms the basis for modelling and analysis in WPs 2 and 3.

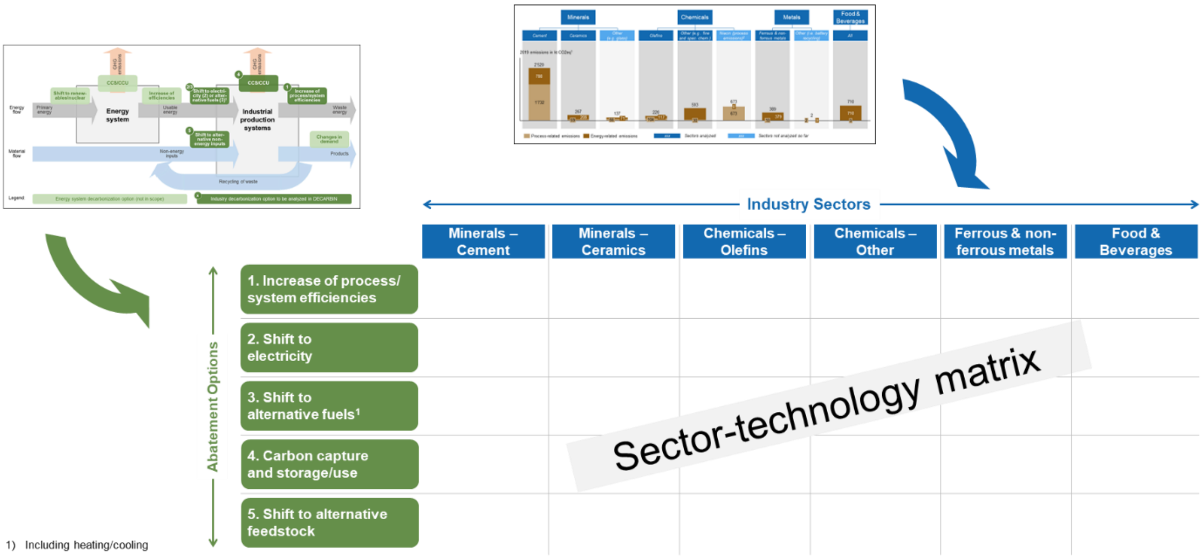


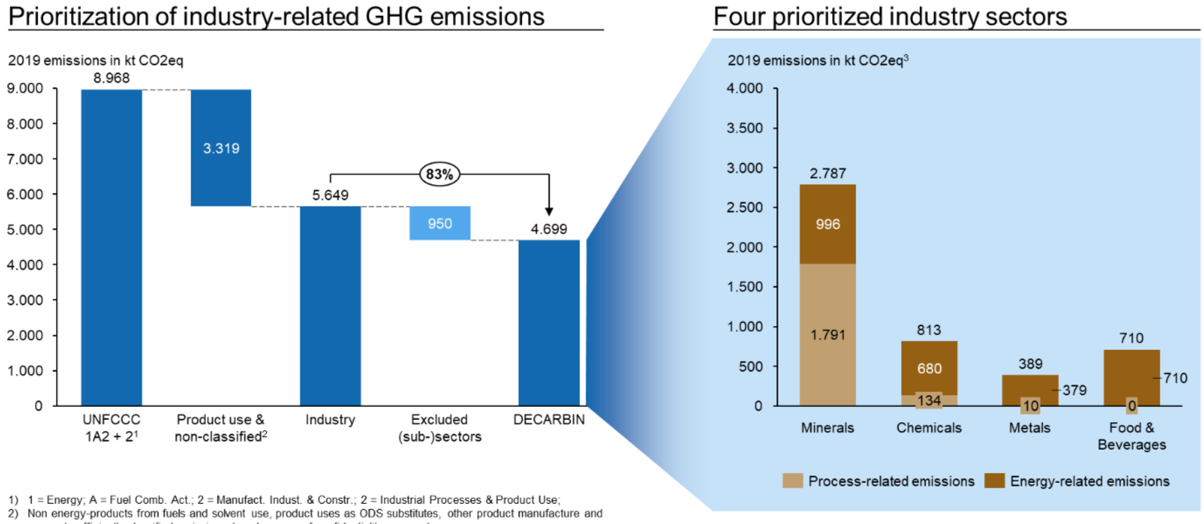
Figure 2 Matrix: Construction of sector-technology matrix based on DECARBIN framework and sector prioritization

First, using statistical data on emissions from the Swiss UNFCCC reporting tables for 2019 (UNFCCC, 2021) we prioritized subsectors with a major contribution to direct emission (i.e. scope 1 emissions) in Switzerland. Of all emissions reported as part of the relevant UNFCCC categories 1A2 (Energy > Fuel Combustion > Manufacturing Industry & Construction) and 2 (Industrial Processes and Product Use) we only considered sufficiently classified emissions that are emitted on site during the production process (cf. Figure 3). Furthermore, we de-prioritized subsectors if their yearly emissions did not exceed 100 kt CO2eq. We also explicitly de-prioritized process emissions associated with the production of the food supplement Niacin, as they will be largely mitigated by the installation of a catalyst in the near future (BAFU, 2020b). This left us with four prioritized industry sectors: (1) minerals (i.e., cement and ceramics), (2) chemicals (i.e., olefins and other chemicals and pharmaceuticals), (3) metals, and (4) food & beverages (cf. Figure 4). The indicated emissions, however, are subject to uncertainty as energy-related emissions (category 1A2) and process-related emissions (category 2) are reported in different

[1] This section largely overlaps with the separately published sector-technology-matrix report and is similar to previous annual DECARBIN reports.

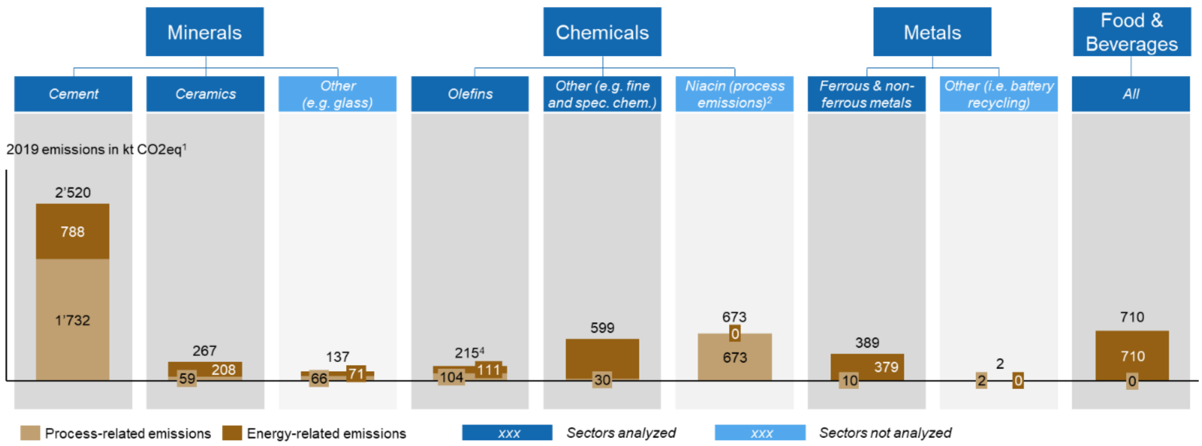
product/sector groups and energy related emissions thus had to be allocated to industry sectors based on assumptions.

At this point it must be highlighted that the matrix only considers scope 1 emissions from the industrial production system itself. I.e., it covers neither upstream emissions associated with the production of the usable energy or feedstock used by the industrial production system, nor downstream emissions associated with the use of manufactured products or their end of life. As a result, when evaluating the decarbonization potential of an option, neither the current nor the future footprint of any energy or feedstock inputs is considered.



1) 1 = Energy; A = Fuel Comb. Act.; 2 = Manufact. Indust. & Constr.; 2 = Industrial Processes & Product Use;
2) Non energy-products from fuels and solvent use, product uses as ODS substitutes, other product manufacture and use; not sufficiently classified emissions (e.g. because of confidentiality reasons)
3) Energy-related emissions (1A2) allocated to (sub-)industry sectors based on own estimations

Figure 3 Matrix: Prioritization of industry-related GHG emissions



1) Energy-related emissions (1A2) allocated to (sub-)industry sectors based on own estimations
2) Process-related emissions from Lonza's Niacin production will be reduced significantly through the installation of a catalyst in the coming years
3) Activity and emissions data, for instance, are often only documented in the confidential version of the NIR
4) Overestimates actual emissions as the process-related emissions reported to UNFCCC include emissions from the Swiss Ammonia production and as energy-related are allocated based on process-related emissions (see footnote 1)

Figure 4 Matrix: Breakdown of industry-related GHG emissions by sub-sector

To improve the understanding of industry-related GHG emissions in Switzerland, we further compared sectorial energy-related emissions to figures on industrial heat demand (cf. Figure 5). Industrial heat demand seems to be in line with reported emissions data.

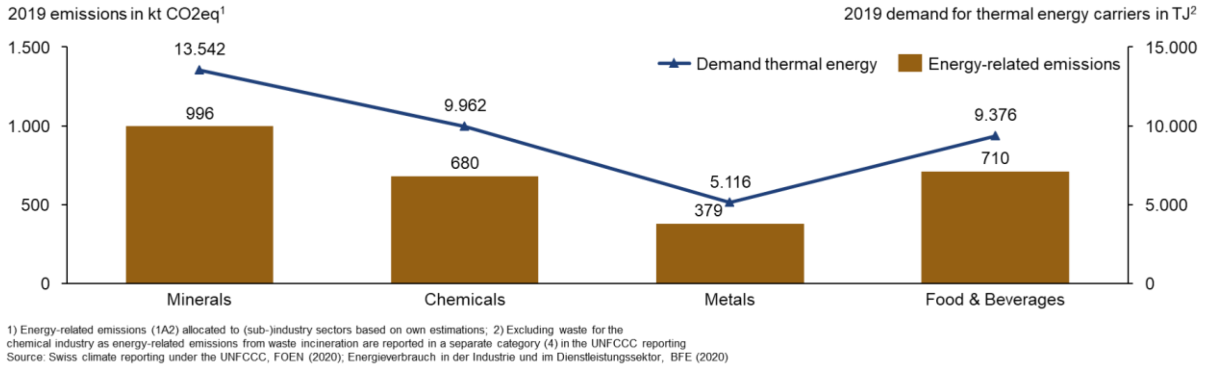


Figure 5 Matrix: Comparison of energy-related GHG emissions and demand for thermal energy carriers of selected industries

Second, by conducting a review of existing studies on industry decarbonization options and results of recent and ongoing projects in European countries (Agora Energiewende & Wuppertal Institut, 2019; Guidehouse, 2020; PBL Netherlands Environmental Assessment Agency, 2021), we created a synthesis of available abatement options for the decarbonization of the prioritized subsectors. As illustrated in the DECARBIN framework in Figure 6, we focused on technological options beyond those typically covered in energy system analysis, namely: (1) Increase of process/system efficiencies, (2) shift towards electricity-based processes (electrification), (3) shift towards alternative fuels, (4) carbon capture and storage (CCS) or use (CCU), and (5) shift to alternative feedstock. Breaking down each of these five options further by differentiating underlying technical approaches gave us a list of available sub-options (Figure 7).

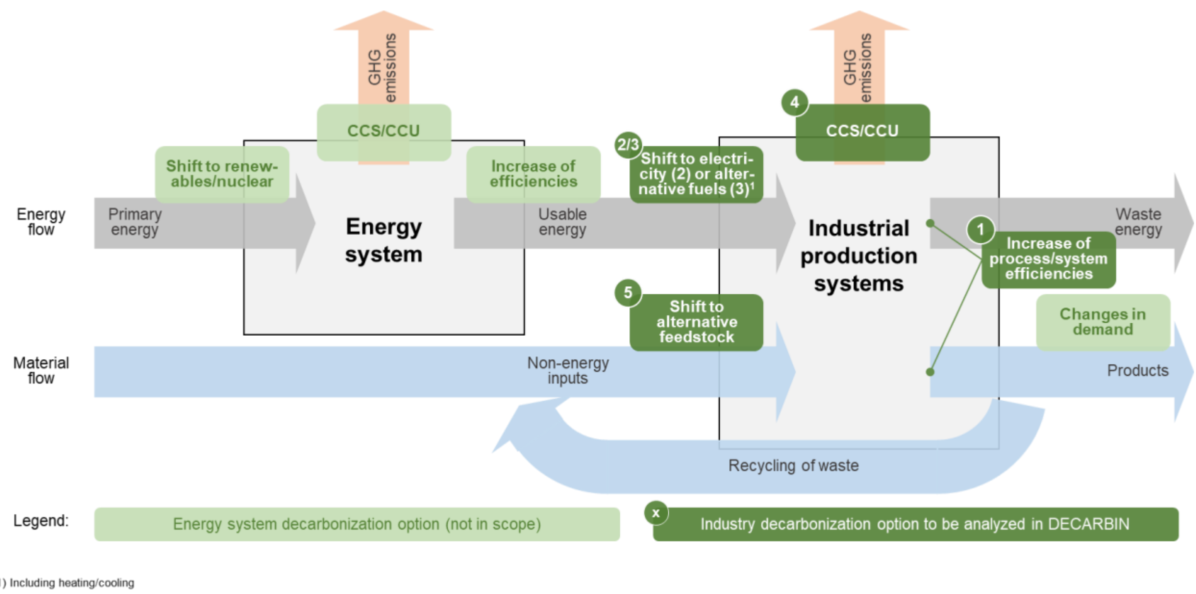


Figure 6 Matrix: Framework illustrating abatement options for the industrial production system

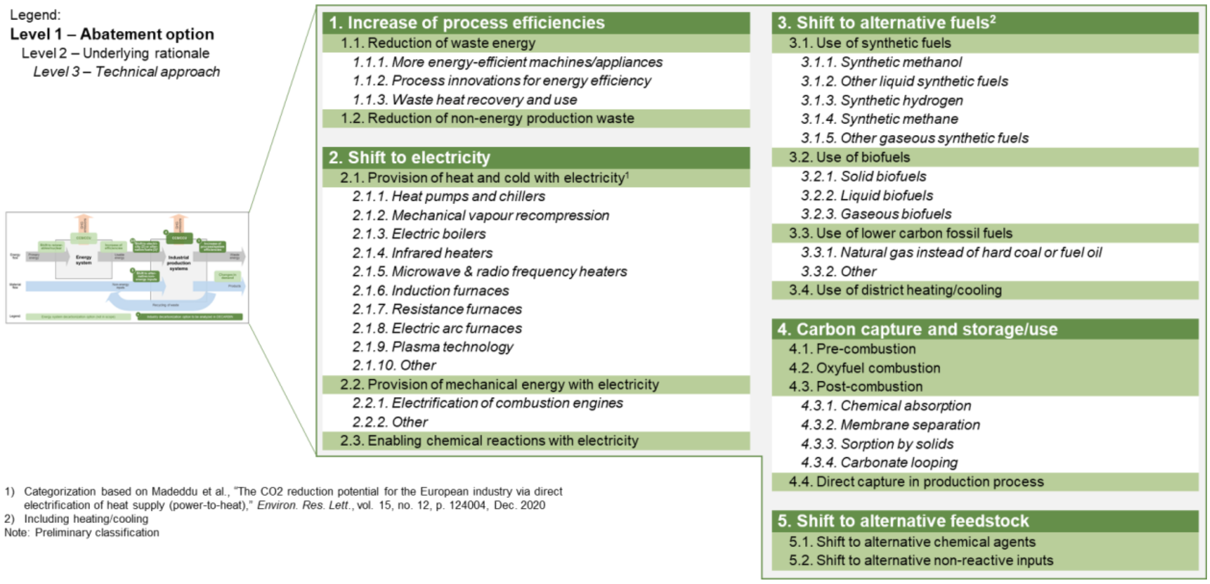


Figure 7 Matrix: Detailed list of technical approaches structured along abatement options

Per prioritized industry sector, we then evaluated each of the identified sub-options regarding their specific decarbonization potential, technology readiness, and the prospects for large-scale deployment by 2050 on a scale from 1 to 3 (cf. Figure 8). Based on the three scores and a defined procedure, the sub-options were then given an overall score indicating the relevance of a sub-option for a sector. This bottom-up derived score was in the following validated and adjusted based on expert interviews (cf. Table 2).

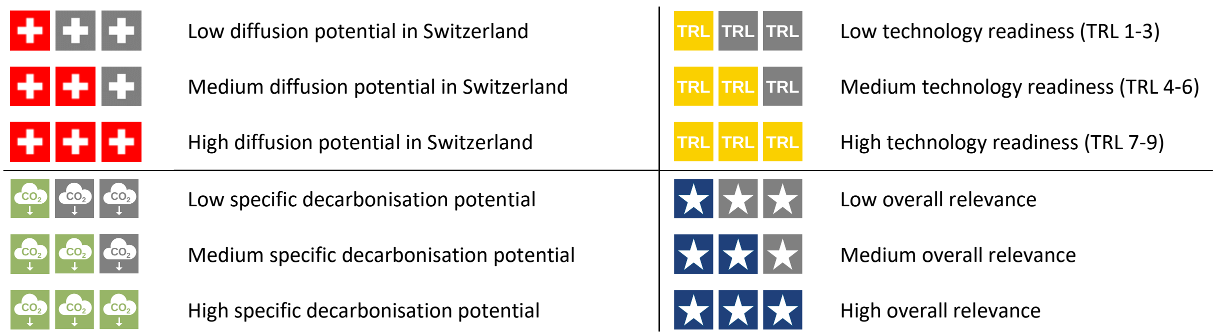


Figure 8 Matrix: Overview of the scores assigned to each sector-abatement option combination

In addition to expert interviews, we conducted a mapping of academic literature on industry decarbonization to test our WP 1 results for selected industries. In this context we developed an approach to automatically cluster large samples of academic literature based on their content using an unsupervised learning approach (i.e., topic modelling). The full approach can be found in Tautorat, Lalin, et al. (2023).

2.2 Net present value (NPV) model (applied for dairy sector)[2]

Switzerland aims at reaching net zero CO_2 emissions by 2050, but progress in the entire food sector has been limited to date—including in the dairy processing industry, despite comparatively low process temperatures and the absence of (difficult to abate) methane emissions (which occur upstream). Because many think the supply of cheap gas has come to an end in Europe (cf. Figure 31 in BloombergNEF's proprietary report on the German power market (2022), the section on natural gas in chapter 2.4.2 of IEA's World Energy Outlook (2022), and the supplemental information of this report), here we focus on whether it is economically feasible for producers of dairy products in Switzerland to switch to low-carbon alternatives, given the current energy and climate policy landscape in the country.

A techno-economic model was implemented to compare the costs of four heating technologies relevant for the Swiss dairy sector (cf. Figure 9): gas boilers, biomass boilers, electric boilers, and electric heat pumps. Other technological decarbonization options as, e.g., synthetic fuels, carbon capture and advanced electricity-based options (e.g., reverse osmosis) were not considered. Synthetic fuels were disregarded as biomass is assumed a cheaper substitute. Carbon capture was disregarded due to comparatively small installations in the dairy industry and the absence of process emissions – two factors negatively influencing the economics of carbon capture. Advanced electricity-based options were disregarded as their TRL is often still too low for them to be deployed in the near-term. Hybrid systems were neither considered for the sake of simplicity. Also, theoretically conceivable co-benefits from cooling were neglected for heat pumps.

[2] This section largely overlaps with Tautorat et al. (2023). Only minor things like cross-references were updated.

Case	(1)	(2)	(3)	(4)
Temperature level	< 100 °C (e.g., cheese, butter)	< 100 °C (e.g., cheese, butter)	< 150 °C (e.g., UHT milk)	> 200 °C (e.g., milk powder)
Thermal energy demand	~375 MWh/a (~0.6 MW, ~640 h/a)	~50,000 MWh/a (~5.7 MW, 8760 h/a)	~50,000 MWh/a (~5.7 MW, 8760 h/a)	~100,000 MWh/a (~11.4 MW, 8760 h/a)
Technology	Gas boiler Biomass boiler Electric boiler Electric heat pump	Gas boiler Biomass boiler Electric boiler Electric heat pump	Gas boiler Biomass boiler Electric boiler Electric heat pump	Gas boiler Biomass boiler Electric boiler
Use of heat (examples)	62 – 64 °C: Separation of fat from milk 72 – 75 °C: Pasteurization of milk 72 – 95 °C: Pasteurization generally 70 – 95 °C: Cleaning of equipment	*Same as for (1)*	135 – 150 °C: Ultra-high temperature treatment of milk	160 – 240 °C: Spray drying for dairy powder production

Legend:
Fossil fuel-based technology currently used and to be replaced in the future
Low-carbon technology currently used and potentially to be used in the future
Low-carbon technology not widely used but potentially to be used in the future

Figure 9 Dairy: Segmentation of the Swiss dairy sector and available technologies by case (examples based on Bylund (2015) and Liang et al. (2022))

Lifecycle costs were calculated for four cases representative of the Swiss dairy industry (cf. Figure 9), each being a combination of temperature level (determined by product type) and operation size (defined by the yearly demand for thermal energy). The categorization is based on expert interviews (cf. Table 24 in the supplemental information for details on the seven interviews with dairy producers and industry experts from Switzerland) and information provided by the association of Swiss cheese manufacturers FROMARTE (2022): (1) small producers consuming ~375 MWh/a of thermal heat at temperatures below 100°C to produce products like cheese, yoghurt or butter at varying temperatures; (2) large producers consuming ~50,000 MWh/a below 100°C to produce the same products, or (3) below 150°C to produce ultra-high temperature (UHT) milk; (4) very large producers consuming ~100,000 MWh/a above 200°C to produce dairy powder.

The calculated total discounted lifecycle costs are the sum of capital expenditures (CAPEX), energy expenditures, emissions expenditures, and operation and maintenance expenditures (O&M), with yearly costs being discounted to the base year 2023 assuming a uniform discount rate (r) of 7% based on the cost of capital/internal rate of return of three relevant food processing companies in Switzerland (confidentially obtained), and summed over a thirty years lifetime (2023-2052) assuming an investment (and immediate installation) in 2023 (cf. Equation 1). In line with current policies in Switzerland (and a low CO_2 footprint of the electricity mix), only gas boilers are penalized with direct emissions costs. Two different retail energy price scenarios were considered based on (1) low historic energy prices in Switzerland between 2012 and 2021 as well as (2) high forecasted energy prices (cf. Table 4 and Figure 26). Retail energy prices are differentiated according to yearly demand, with case (1) assuming higher prices than cases (2)-(4) (EAER, 2022; ElCom, 2022). An inflation of 2% is assumed in line with the upper ceiling targeted by the SNB (2023).

$$\text{Total discounted lifecycle costs}_{oper.\ size}^{tech} = \sum_{i=1}^{years} \frac{\text{CAPEX}_{oper.\ size_i}^{tech} + \text{ENERGY}_{oper.\ size_i}^{tech} + \text{EMISSIONS}_{oper.\ size_i}^{tech} + \text{O\&M}_{oper.\ size_i}^{tech}}{(1+r)^{i-1}} \quad (1)$$

The NPV model is designed to calculate and compare the NPVs of different investments today but does not allow for an inter-temporal optimization of investments under uncertainty, which is therefore analysed by means of a sensitivity analysis (cf. Figure 15).

Table 3 NPV model: Techno-economic assumptions used in the model.

Parameter	Unit	Technology			
		Gas boiler	Biomass boiler	Electric boiler	Electric heat pump
Lifetime	a	25	25	25	20
Efficiency	-	0.90	0.90	0.98	-
COP	MWh_{th}/MWh_{el}	-	-	-	2.1 (cases 1 & 2) 1.5 (case 3)
CO_2 intensity	t_{CO2}/MWh	0.20	0	0	0
Capital expenditures (CAPEX)	CHF/kW	55	620	210	345 (cases 2-4) 615 (case 1)
Fixed operation and maintenance expenditures	CHF/kW/a % of CAPEX/a	2.0	33.7	1.2	6.5 (cases 2-4) 1.5 (case 1)
Variable operation and maintenance expenditures	CHF/MWh	1.0	1.1	0.5	-
Auxiliary electricity consumption	MWh_{el}/MWh_{th}	0.001	0.023	0.005	-
Based on		Danish Energy Agency (2022), UNFCCC (2021)	Danish Energy Agency (2022)	Danish Energy Agency(2022)	Arpagaus (2019), Arpagaus & Bertsch (2020), Ayou et al. (2022)

Table 4 NPV model: Assumptions on retail energy prices and carbon prices (incl. VAT). Note: Both scenarios (i.e., historic and forecasted) use forecasted CO_2 prices and the techno-economic assumptions presented in Table 3

Parameter	Unit	Scenario					Based on
		Historic	Forecasted				
		Ø '12-'21	2023	2030	2040	2050	
Biomass *(assuming wood chips)*	CHF/MWh	50	53	61	74	90	Thees et al. (2017), interviews
Electricity	CHF/MWh						ElCom (2022), BloombergNEF (2022)
Case (1)		180	272	279	321	392	
Cases (2)-(4)		137	219	198	223	273	
Gas	CHF/MWh						EAER (2022), BloombergNEF (2022)
Case (1)		61	542	111	129	277	
Cases (2)-(4)		49	451	92	107	231	
CO_2	CHF/t_{CO2}		129	166	274	452	Hintermann & Zarkovic (2020), Pietzcker et al. (2021)

2.3 Real option valuation (ROV) model (applied for cement and chemical sectors)

A techno-economic model was developed to examine the influence of energy and climate policy on low-emissions investment decisions in the Swiss chemical and cement industries (cf. Figure 10 for an overview of the modelling framework). In particular the influence of industry characteristics as well as policy timing and stringency were analysed. Compared to the NPV model, the ROV model allows to analyse inter-temporal effects that take into account the perceived uncertainty of plant operators.

Based on a set of inputs (cf. Figure 10 a-f) the model determines those investment decisions that maximise the net present value (NPV) over the modelling period from a plant operator's perspective compared to the incumbent production setup. Inputs include general modelling parameters (cf. Section 2.3.1), characteristics of the plants modelled for the two industries (cf. Section 2.3.2), decarbonization options and related techno-economic data (cf. Section 2.3.3), prices for energy carriers and emissions costs (cf. Section 2.3.4), uncertainty assumptions (cf. Section 2.3.5), and policies modelled (cf. Section 2.3.6)

Per time step, the NPVs of investments into different technologies are calculated (cf. Figure 10 g) and compared (cf. Figure 10 h). To maximise the NPV over the modelling period rather than only per time step, NPVs are compared among all time steps (cf. Figure 10 h).

As the model assumes the type and quantity of goods produced by the chemical and cement plants to be independent of the decarbonization option, NPVs are calculated only based on the differences in costs between the incumbent production setup and the newly applied decarbonization option (denoted by Δ Equation 1). Accordingly, the NPV of an investment decision is the difference of lower emissions costs (EM) and potentially higher investment (I), operation and maintenance (O&M), fuel (FU), and CO_2 storage and transport (ST) costs. An option value accounting for potential future investment decisions complements this calculation (cf. Equation 1).

$$NPV = \Delta\ EM - \Delta\ (I + O\&M + FU + ST) + option\ value \quad (1)$$

When calculating NPVs the model takes into account that some input parameters are subject to technology, market and regulatory uncertainty (e.g., technology CAPEX, the price of emission certificates, or the electricity price). More precisely, all calculations weight two future states for selected input parameters – a reference (R) and an alternative state (A) – assuming that a transition from R to A can occur between every two decisions with a defined probability (cf. Figure 10 i).

In the actual Python model[3] this is done by first calculating the NPVs of all possible combinations of investments at the last possible time step, i.e., 2050, and considering them as an option value at the previous time steps.

For the chemical industry, three input parameters are assumed uncertain: (1) the CAPEX of a CCS installation (I in Equation 1), (2) the EU ETS price (EM in Equation 1), and (3) the electricity price (FU in Equation 1). Whereas for the cement industry, for which no electrification option is modelled, only (1) and (2) are considered. This results in 8 different combinations of states – in the following referred to as scenarios – for the chemical industry (three uncertainties à two states) and 4 scenarios for the cement industry (cf. Figure 10 j).

The model facilitates comparisons between NPVs of different decarbonization options (cf. Figure 10 k) per plant and scenario, to see which decisions maximize a plant's profits with different uncertainties being included (cf. Figure 10 l), similarly with various policies being included (cf. Figure 10 m), and how individual plant-level decisions aggregate to changes in demand for different energy carriers at the

[3] The model is implemented in Python and currently managed in a private github repository. Once the peer-reviewed articles are published, the code is going to be made available in the following public github repository: https://github.com/paultautorat/ROV4DECARBIN

industry level (cf. Figure 10 n). For a more detailed and formal description of the Real Options Valuation (ROV) model, refer to Section 9.2 in the appendix.

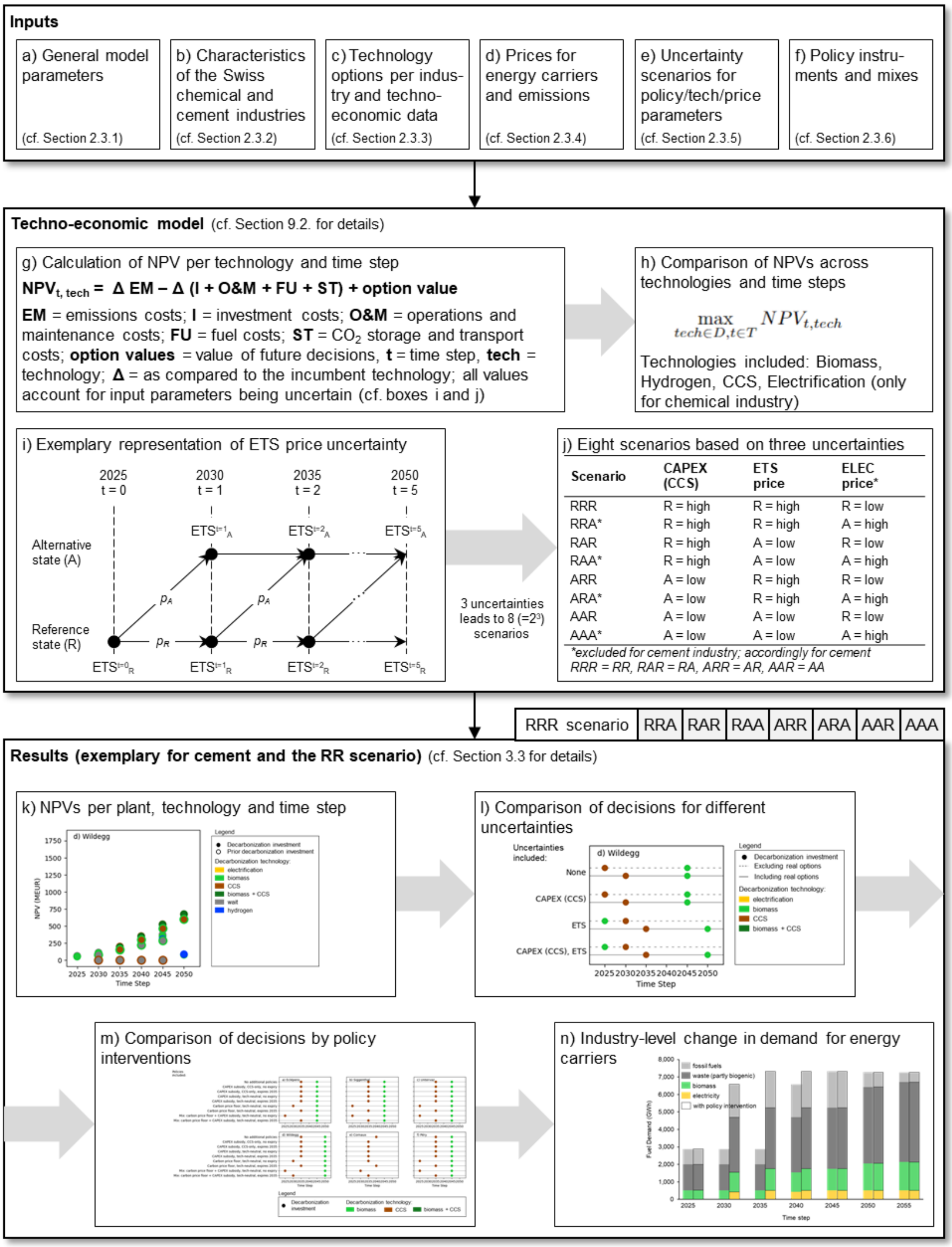


Figure 10 ROV model: Overview of the modelling approach. Notes: CCS = carbon capture and storage, NPV = net present value, ETS = emissions trading system, CAPEX = capital expenditures, O&M = operation and maintenance

2.3.1 General model parameters

The model is implemented as a tree model allowing for investments at six defined time steps, i.e., every five years from 2025 to 2050, and takes into account the option value of choosing to invest at a later point in time (option to wait) or taking a second investment in the future (option to expand). To account for option values of future investments the NPVs are calculated recursively starting in 2050. We model 2050 as the last possible time for investments to acknowledge Switzerland's goal to reach net zero emissions by then. Per plant investment decisions are modelled separately, i.e., feedbacks of investment decisions are not quantitatively modelled (e.g., demand for biomass or utilization of CO_2 infrastructure).

Table 5 ROV model: General information

General	
Programming language	Python
First year modelled	2025
Last year modelled	2079
First decision	2025
Last decision	2050
Years between two decisions	5
Number of decisions	6
Resolution of cash flow calculations	yearly
Inflation rate (assumed constant)	2%
Industry plants	
Chemical industry	9 exemplary plants (based on data of 68 Swiss plants)
Cement industry	6 Swiss plants
Uncertainty representation	
Number of uncertainties	
Chemical industry	3 (CCS CAPEX, ETS price, electricity price)
Cement industry	2 (CCS CAPEX, ETS price)
Number of states per uncertainty	2 (reference (R) and alternative (A))
Type of real options included	Option to wait, option to expand
Decarbonization options	
Chemical industry	4 (CCS, Biomass, Hydrogen, Electrification)
Cement industry	3 (CCS, Biomass, Hydrogen)

2.3.2 Plant selection and assumptions

<u>Cement industry</u>

The cement industry represents the biggest source of industrial CO2 emissions. The six cement plants located in Switzerland are modelled (cf. Table 6 for details). The plants are assumed to differ by three factors: First, their weighted average costs of capital (WACC, ranging between 5.6% and 11.1%). WACC values are the parent companies' average values between 2012 and 2021 from Bloomberg L.P. (2023). Second, plants differ by their clinker production capacity (ranging between ca. 200 and 670 kt_{cli}/a). Production capacities are assumed based on publications by Cemsuisse (2021) and swisstopo & BAFU (2020). Third, by their CO_2 transport and storage costs based on their locations. Costs are taken from Carbon Limits & CATF (2022). The costs and energy penalty of a CCS installation is assumed to scale with the plants' production capacity (cf. Table 12). CCS costs parameters are largely based on a report by ECRA (2017). Capacity-independent investment costs for a switch to more biomass account for additional storage requirements. Capacity-independent investment costs for a switch to hydrogen account for a new hydrogen burner and handling infrastructure. Industry-level results for the cement industry are aggregated based on the six modelled plants.

Although we refer to specific plant names (e.g. Eclépens), the results in Section 3.3 are to be understood less as exact results for these very plants, but rather as exemplary results for stylized plants with similar main characteristics. Exact modeling of the Swiss plants would only be possible with even more detailed information on the individual plants (e.g., kiln age), which are, however, not always publically availabel and were not disclosed to us by the plant owners.

Table 6 Cement: plant-specific data. Note: investment costs are assumed to decrease over time (cf. Table 12). The CATF ID is used to match plants with CO_2 transport and storage costs provided by Carbon Limits & CATF (2022). Bloomberg ID and name used to match plant owners' past WACCs (cf. Table 25 for details). Techno-economic data based on assumptions or calculated based on ECRA (2017).

Parameter	Unit	Eclépens	Siggenthal	Untervaz	Wildegg	Cornaux	Péry
CATF ID		85760	85761	85762	85763	85764	85765
Bloomberg ID		HOLN SW Equity	HOLN SW Equity	HOLN SW Equity	CRH ID Equity	CRH ID Equity	VCT FP Equity
Bloomberg name		Holcim AG	Holcim AG	Holcim AG	CRH PLC	CRH PLC	Vicat SA
Capacity	kt_{cli}/a	534	601	534	534	200	668
WACC	%	6.8	6.8	6.8	11.1	11.1	5.6
CCS costs							
Investment (in 2025)	MEUR	118	127	118	118	65	135
O&M	MEUR/a	26.2	29.5	26.2	26.2	9.8	32.7
Add. electricity demand	TJ/a	248	279	248	248	93	310
Add. heat demand	TJ/a	1,870	2,104	1,870	1,870	701	2,337
Investment Biomass	MEUR	5	5	5	5	5	5
Investment Hydrogen	MEUR	5	5	5	5	5	5

Chemical industry

The Swiss chemical and pharmaceutical industries constitute approximately 50% of Swiss exports and represent a substantial portion of industrial emissions. Our modelling approach is based on anonymized plant-level data obtained from BfE (2023), encompassing information from 111 plants within the industry. We concentrate on the subset of plants employing gas for heat generation, totalling 68 plants. It is essential to note that our analysis for the chemical industry – as opposed to the cement industry – specifically focuses on fuel-related emissions originating from heat generation at defined temperature levels.

Based on an analysis of the 68 plants, three representative plant sizes are modelled: 2, 22 and 48 GWh of yearly heat demand (cf. Figure 11). A second differentiator is the plants' required temperature level. Based on expert interviews, three plant types were modelled: below 160°C, between 160°C and 220°C, and more than 220°C. Based on these two critical dimensions, nine distinct plant archetypes are modelled. The temperature influences the heat pump efficiency and the yearly heat demand influences investment costs due to scale effects. Industry-level results for the chemical industry are derived from an extrapolation of the modelled nine plants.

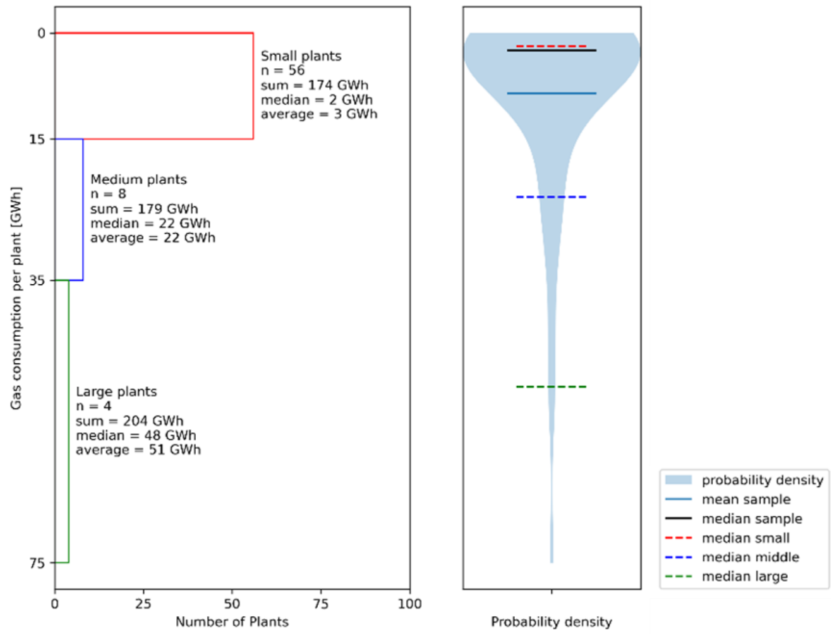


Figure 11 Chemical: Selection of representative plants

Table 7 Chemical: plant-specific data. Note: investment costs are assumed to decrease over time (cf. Table 9 and Table 10). Techno-economic data and calculations based on Arpagaus (2019), Arpagaus & Bertsch (2020), Ayou et al. (2022), BfE (2023), Danish Energy Agency (2022, 2023), den Ouden et al. (2017), and expert interviews.

Plant Name	**Unit**	**Plant**								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Capacity	GWh/a	2	2	2	8	8	8	13	13	13
	t_{CO2}/a	407	407	407	4,476	4,476	4,476	9,766	9,766	9,766
Temperature	°C	160	220	220<	160	220	220<	160	220	220<
WACC	%	8	8	8	8	8	8	8	8	8
CCS costs										
Investment (in 2025)	MEUR	2	2	2	8	8	8	13	13	13
O&M	MEUR/a	0.06	0.06	0.06	0.24	0.24	0.24	0.38	0.38	0.38
Add. electricity demand	GJ/a	44	44	44	483	483	483	1,055	1,055	1,055
Add. heat demand	TJ/a	1.2	1.2	1.2	13.4	13.4	13.4	29.3	29.3	29.3
Biomass										
Investment (in 2025)	MEUR	0.18	0.18	0.18	1.91	1.91	1.91	4.09	4.09	4.09
O&M	MEUR	0.01	0.01	0.01	0.15	0.15	0.15	0.32	0.32	0.32
Hydrogen										
Investment (in 2025)	MEUR	-	-	-	-	-	-	-	-	-
O&M	MEUR	-	-	-	-	-	-	-	-	-
Electrification										
Investment (in 2025)	MEUR	0.10	0.12	0.04	1.09	1.31	0.45	2.26	2.72	0.93
O&M	MEUR	0.01	0.01	0.00	0.08	0.08	0.02	0.16	0.16	0.05
COP	-	1.46	1.15	-	1.46	1.15	-	1.46	1.15	-

2.3.3 Technology selection and assumptions

Four different types of decarbonization options are modelled based on the analysis conducted for the sector-technology matrix and a series of interviews: Carbon capture and storage (CCS), a switch to biomass, a switch to hydrogen and electricity-based heat production, with the latter only included for the chemical industry (cf. Table 8).

Table 8 ROV model: Technologies included for the two modelled industries. Note: Oxyfuel CCS is implemented in the ROV model but in the presented report only parameters and results for amine CCS are presented.

Technology	Cement	Chemical
Incumbent		
Gas-based heat generation		Yes
Kiln fired by avg. fuel composition of Swiss cement plants	Yes	
CCS		
Amine	Yes	Yes
Oxyfuel	Yes	
Biomass		
95% biomass (wood chips)		Yes
Increase from 18 to 25%	Yes	
Hydrogen		
100% hydrogen	Yes	Yes
Electrification		
Heat pump		Yes
High temperature heat pump		Yes
Electrode boiler		Yes

The analysed decarbonization options are modelled to have different cost structures. For instance, the total cost of a solution based on electrifying industry processes is largely determined by the electricity cost. The most important assumptions are presented in the following in Table 9-Table 14.

Chemical industry

Table 9 Chemical industry: Electrification and fuel switch technologies. Based on Arpagaus (2019), Arpagaus & Bertsch (2020), Ayou et al. (2022), Danish Energy Agency (2022), den Ouden et al. (2017), and own assumptions.

Parameter	Unit	Heat Pump	High temperature heat pump	Electrode boiler	Biomass boiler
ΔT	K	150	210	-	-
COP	-	1.46	1.15	-	-
CAPEX Low	EUR/kW	450	540	186	770
CAPEX High	EUR/kW	250	300	96	618
O&M Fixed	EUR/MW/a	970	970	1,107	33,700
O&M Variable	EUR/MWh	3.3	3.3	0.88	2.78
Size Low	GWh/a	5	5	5	5
Size High	GWh/a	300	300	300	300
CAPEX scaling factor	-	0.6	0.6	0.6	0.6
CAPEX reduction	%/a	1	1	1	1

Table 10 Chemical industry: CCS technology parameter. Based on data from the Danish Energy Agency (2023) and own assumptions.

Parameter	Unit	CCS (amine scrubbing)
CAPEX low	MEUR/t_{CO2}/h	3.00
O&M fixed	MEUR/t_{CO2}/h	0.03
O&M variable	EUR/t_{CO2}	2.50
CAPEX reference plant	MEUR	96.00
Additional electricity	MWh/t_{CO2}	0.03
Additional heat	MWh/t_{CO2}	0.83
Size of reference plant	t_{CO2}/h	32.00
Scaling factor		0.60
CAPEX reduction	%/a	1

Cement industry

Table 11 Cement industry: Break down of industry's emissions based on Cemsuisse (2021) and swisstopo & BAFU (2020).

Emission Type	Clinker prod. [Mt_{cli}/a]	Cement prod. [Mt_{cem}/a]	Abs. emissions [tCO_2/a]	Spec. emissions [CO_2/t_{cli}]	Clinker ratio [t_{cli}/t_{cem}]
Total (from all plants)	3.07	4.15	2,410,000	0.78	0.74
Geogeneous			1,680,000	0.55	
Fuel Emission			730,000	0.24	
Fossil Fuels			330,000	0.11	
Alternative fuels			400,000	0.13	

Amine scrubbing was chosen due to its maturity. Future work could further study competing CCS sub-technologies, e.g., oxyfuel and direct capture. ECRA provides data for the former both sub-technologies.

Table 12 Cement industry: Assumptions CCS. Assumptions based on ECRA (2017).

Year	Unit	2020
Size of Reference Plant	tcli/a	2,190,000
Capture Rate High	%	95
CAPEX (reference plant)		
CAPEX New Low	MEUR	200
CAPEX New High	MEUR	275
CAPEX Retrofit Low	MEUR	200
CAPEX Retrofit Hight	MEUR	275
OPEX New High	EUR/t_{cli}	49
OPEX Retrofit High	EUR/t_{cli}	49
Additional Heat High	MJ/t_{cli}	3,500
Additional Electricity Low	kWh/t_{cli}	80
Additional Electricity High	kWh/t_{cli}	129
Scaling factor		0.60
CAPEX reduction	%/a	1

Table 13 ROV model: fuels considered in the calculations. Based on Cemsuisse (2021), FOEN (2021), and Obrist et al. (2021).

Input	Thermal efficiency	Biomass fraction	Emissions factor net [tCO2 /GJ]	Emissions factor gross [tCO2/GJ]	Specific energy [MJ/kg]
Electricity		0%	0	0	0
Coal	70%	0%	0.09	0.09	25
Fuel Oil	70%	0%	0.08	0.08	42
Natural Gas	90%	0%	0.06	0.06	0
Biomass	85%	100%	0	0.09	13.6
Waste	70%	7%	0.07	0.08	25.08
Hydrogen	90%	0%	0	0	0

Table 14 ROV model: fuel mixes. Natural gas is assumed the incumbent fuel for the chemical industry. Based on Obrist et al. (2021) and interviews.

Input	Cement: baseline	Cement: biomass	Chemical: baseline	Chemical: electricity	Chemical: biomass	Cement/ chemical: hydrogen
Electricity	0%	0%	0%	100%	0%	0%
Coal	31%	5%	0%	0%	0%	0%
Fuel Oil	0%	0%	0%	0%	0%	0%
Natural Gas	0%	0%	100%	0%	5%	0%
Biomass	18%	25%	0%	0%	95%	0%
Waste	52%	70%	0%	0%	0%	0%
Hydrogen	0%	0%	0%	0%	0%	100%

2.3.4 Price assumptions

Based on Equation 1 various price and costs assumptions are needed to calculate NPVs. Emissions costs (EM) are provided Table 17, CAPEX (I) and O&M costs are provided in Table 9, Table 10, and Table 12, fuel costs (FU) are provided in Table 16, and storage and transport costs in Table 15.

Table 15 ROV model: CO_2 transport and storage costs in EUR_{2022}/t_{CO2} based on Carbon Limits & CATF (2022). 2025 values based on the short-term scenario assuming few storage sites; 2050 values based on long-term scenario assuming various storage sites across Europe; values after 2050 were inflated. Refer to Table 26 and Table 27 in the appendix for yearly values based on linear interpolation.

Year	Chemicals	Cement					
	Swiss avg.	**Eclépens**	**Siggenthal**	**Untervaz**	**Wildegg**	**Cornaux**	**Péry**
No development of pipeline infrastructure possible							
2025	97.5	159.7	112.9	107.6	112.9	159.7	112.9
2030	90.0	144.2	103.3	99.1	103.3	144.2	103.3
2035	80.0	123.7	90.4	87.7	90.4	123.7	90.4
2040	66.8	97.3	73.7	72.9	73.7	97.3	73.7
2045	50.1	64.2	52.6	54.0	52.6	64.2	52.6
2050	34.4	32.6	32.6	36.3	32.6	32.6	32.6
2055	38.0	36.0	36.0	40.0	36.0	36.0	36.0
2060	42.0	39.7	39.7	44.2	39.7	39.7	39.7
2065	46.4	43.9	43.9	48.8	43.9	43.9	43.9
2070	51.2	48.4	48.4	53.9	48.4	48.4	48.4
2075	56.5	53.5	53.5	59.5	53.5	53.5	53.4
Development of pipeline infrastructure possible							
2025	59.7	98.5	83.0	76.8	83.0	98.5	83.0
2030	56.4	90.3	76.7	71.4	76.7	90.3	76.7
2035	51.8	79.4	68.3	64.1	68.3	79.4	68.3
2040	45.7	65.1	57.3	54.5	57.3	65.1	57.3
2045	37.7	47.1	43.2	42.3	43.2	47.1	43.2
2050	30.4	30.0	30.0	30.8	30.0	30.0	30.0
2055	33.6	33.2	33.2	34.0	33.2	33.2	33.2
2060	37.1	36.6	36.6	37.6	36.6	36.6	36.6
2065	41.0	40.4	40.4	41.5	40.4	40.4	40.4
2070	45.2	44.6	44.6	45.8	44.6	44.6	44.6
2075	49.9	49.3	49.3	50.5	49.3	49.3	49.3

Table 16 ROV model: Fuel costs in EUR/MJ. Refer to Table 28 in the appendix for yearly values based on linear interpolation or inflation adjustment. Based on BloombergNEF (2022), EAER (2022), ElCom (2022), Obrist et al. (2021), Pahle et al. (2023), Thees et al. (2017), interviews, and own assumptions.

Year	**Electricity** (reference scenario)	**Electricity** (alternative scenario)	**Hard coal**	**Fuel Oil**	**Natural Gas**	**Biomass**	**Waste**	**Hydrogen**
2025	0.036	0.053	0.007	0.009	0.020	0.015	0.006	0.029
2030	0.027	0.041	0.005	0.011	0.009	0.017	0.006	0.032
2035	0.027	0.041	0.005	0.012	0.008	0.019	0.007	0.036
2040	0.032	0.048	0.005	0.012	0.011	0.021	0.008	0.039
2045	0.035	0.052	0.006	0.013	0.016	0.023	0.009	0.043
2050	0.039	0.059	0.007	0.013	0.023	0.025	0.009	0.048
2055	0.043	0.065	0.008	0.014	0.026	0.028	0.010	0.053
2060	0.048	0.072	0.008	0.015	0.028	0.031	0.012	0.058
2065	0.053	0.079	0.009	0.017	0.031	0.034	0.013	0.065
2070	0.058	0.088	0.010	0.019	0.034	0.037	0.014	0.071
2075	0.064	0.097	0.011	0.021	0.038	0.041	0.016	0.079

Table 17 ROV model: EU ETS price assumptions in EUR_{2023}/t_{CO2} based on Pahle et al. (2023). Note that Pahle et al. refer to the alternative scenario as “reference scenario” and to the reference scenario as “reform scenario”. Refer to Table 29 in the appendix for yearly values based on linear interpolation.

Year	**ETS price [EUR_{2023}/t_{CO2}]** (reference scenario)	**ETS price [EUR_{2023}/t_{CO2}]** (alternative scenario)
2025	125	39
2030	160	50
2035	206	64
2040	265	82
2045	340	105
2050	436	135
2055	560	173
2060	574	626
2065	601	626
2070	664	637

2.3.5 Uncertainty selection and assumptions

Based on literature and the conducted interviews the following uncertainties are included in the model:

First, the chance of CCS CAPEX costs to decrease from ECRA's high to low scenario (cf. Table 12). CCS cost are primarily driven by adoption outside of Switzerland and even outside the sector; at the same time, the technology is CAPEX intensive. Hence foreign developments could result in major reduction (or not).

Second, the risk of the ETS to increase less quickly than anticipated due to changes in EU climate policy. The ETS price is the single most important instrument and the backbone of the Swiss and EU climate policy addressing industry. Given the coupling of the Swiss to the EU ETS, the carbon price is largely dependent on developments outside Switzerland.

Third, the risk of increasing electricity prices. Decarbonizing the economy will largely be enabled by shifting from molecules (fuels) to electrons (electricity), e.g., in transport. This additional electricity demand coupled with the transition of the power sector itself (from largely controllable fossil to more fluctuating renewable sources of power) bears major uncertainty regarding the fuel price. Especially as the wholesale power market was designed for high-OPEX controllable technologies.

In sum, all three uncertainties are (i) mainly driven by factors outside of the control of the sectors (they are price takers) and (ii) have major influence on the profitability of different decarbonization options. For the present report, a time-independent transition probability of 20% is assumed for all uncertainties. Future work will use time-dependent assumptions based on interviews in order implement option values more accurately.

Table 18 ROV model: Uncertainty assumptions assumed in the model. Note: Overnight transition at the end of the period.

Period	Uncertainty 1 CAPEX (CCS)	Uncertainty 2 ETS price	Uncertainty 3 ELEC price
2025-2029	20%	20%	20%
2030-2034	20%	20%	20%
2035-2039	20%	20%	20%
2040-2044	20%	20%	20%
2045-2049	20%	20%	20%
2050-2055	20%	20%	20%

Assuming uni-directional jumps, i.e., uncertain parameters can only transition from the reference to the alternative scenario and not vice versa, this leads to the state probabilities shown in Table 19. In 2025, when the first decision is taken, the model is by definition in the RRR scenario. In the following, the probability of being in the RRR scenario, however, reduces with every period. The last transition is assumed to occur after the last investment decision taken in 2050. Accordingly, the last decision is still made under uncertainty.

Table 19 ROV model: State probabilities per scenario and period in %. Note: * excluded for cement industry; accordingly for cement RRR = RR, RAR = RA, ARR = AR, AAR = AA

Scenario	2025 -2029	2030 -2034	2035 -2039	2040 -2044	2045 -2049	2050 -2054	2055 -2079
RRR	100	51.2	26.2	13.4	6.9	3.5	1.8
RRA*	0	12.8	14.7	12.8	9.9	7.2	5.1
RAR	0	12.8	14.7	12.8	9.9	7.2	5.1
RAA*	0	3.2	8.3	12.2	14.3	14.8	14.3
ARR	0	12.8	14.7	12.8	9.9	7.2	5.1
ARA*	0	3.2	8.3	12.2	14.3	14.8	14.3
AAR	0	3.2	8.3	12.2	14.3	14.8	14.3
AAA*	0	0.8	4.7	11.6	20.6	30.4	40.2

2.3.6 Selection of policy options and related assumptions

Given the multiple market failures related to the energy transition (pollution externalities, innovation and learning externalities, carbon leakage, etc.), reaching net zero in 2050 will require a policy mix, potentially adding industry-specific instruments to the current climate/energy policy regime. Table 20 describes relevant instruments, based on the economic literature and considerations in various countries, and which parts of the modelled *NPV* each instrument influences (cf. Equation 1).

We collaborated with Prof. Edenhofer and Dr. Pahle's group for Climate and Energy Policy at the Potsdam Institute for Climate Impact Research (PIK) in Germany, who conducted a major study comparing options to complement existing energy policies with further measures for decarbonization in other sectors, and specifically the role of carbon pricing therein (Edenhofer et al., 2019). In addition, we collected inputs from SFOE representatives in a joint workshop with PIK in Q2 2022 and agreed to link the policy mixes modelled in WP 2 to current and anticipated EU policies.

We derived eight policy interventions (cf. Table 21) to be applied in the ROV-model. Four interventions are assumed to expire by 2035, the other four are assumed to apply during the whole modelling period: (1)/(2) a 50% CAPEX subsidy for CCS with and without expiry; (3)/(4) a 50% CAPEX subsidy applied to all modelled technologies with and without expiry; (5)/(6) a 180 EUR/t_{CO2} carbon price floor with and without expiry; (7)/(8) a combination of a technology-neutral 50% CAPEX subsidy and a 180 EUR/t_{CO2} carbon price floor with and without expiry. The ROV model allowed us to assess how these eight policy mixes affect the timing of investments and the competitiveness among different decarbonization technologies.

Table 20 ROV model: Policy options for industry decarbonization (FU = fuel costs, I = investment costs, OM = Operation and maintenance costs, EM = Emissions costs, na = no direct influence on costs but discussed)

Policy options	Exemplary policy instruments	Total costs
A. Fuel/Electricity pricing	**A.1.** Lowering levies on electricity	FU
	A.2. Lowering petroleum tax for biofuels	FU
	A.3. Increasing petroleum tax	FU
B. Incentives for technology development & deployment	**B.1.** Investment subsidies (e.g., grants supporting pilots, first inst.)	I
	B.2. Instrument to lower financing cost (e.g., loan guarantees)	I
	B.3. Research and development support	na[1]
	B.4. "Voluntary" emissions reduction obligations (with threatened sticks)	EM
	B.5. Dynamics emissions standards	EM
C. Carbon pricing	**C.1.** Carbon taxes	EM
	C.2. Cap-and-trade system (targeting emitters and/or fuel importers, and including CDR off-setters)	EM
	C.3. EU-ETS collar/EU-ETS carbon price floor	EM
	C.4. Carbon contracts for differences (CCfDs)	EM
D. Provision of infrastructure	**D.1.** Provision of CO_2 transport infrastructure	EM
	D.2. Provision of H_2 transport infrastructure	FU
E. Instrument enhancing international competitiveness	**E.1.** Carbon border tax adjustments	na[2]
	E.2. Other compensation instruments	na
F. Other	e.g., instruments focusing demand side (i.e., sustainable public procurement, minimum content regulation, etc.)	na

[1] R&D support policies could be assumed to influence the availability of low-TRL technologies in the long-term; [2] On EU-level the Carbon Border Adjustment Mechanism (CBAM) could be assumed a prerequisite for phasing out free allowances in the EU ETS (i.e., C.2.).

Table 21 ROV model: Policy interventions modelled for cement and chemical

No.	B.1. CAPEX subsidy		C.3. Carbon price floor		Expiry
	Level	Technologies	Level	Technologies	
1	50%	CCS	-	-	No expiry
2	50%	CCS	-	-	2025-2035
3	50%	All	-	-	No expiry
4	50%	All	-	-	2025-2035
5	-	-	180 EUR/t_{CO2}	All	No expiry
6	-	-	180 EUR/t_{CO2}	All	2025-2035
7	50%	All	180 EUR/t_{CO2}	All	No expiry
8	50%	All	180 EUR/t_{CO2}	All	2025-2035

3 Results and discussion

3.1 Sector-technology-matrix[4]

The present analysis indicates that per sector a multitude of different abatement options and technical approaches could potentially contribute to the deep decarbonization (see Figure 13 for a version solely based on our bottom-up approach and Figure 13 for a version after an additional triangulation with experts). While from a technical perspective, increasing process/system efficiencies (option 1) and a shift to alternative fuels (option 3) could contribute significantly in all of the sectors, a shift in feedstock (option 5) is mainly applicable in the chemicals sector, a shift from fuel-based processes to electricity (option 2) in all but cement and minerals, and the capture and subsequent storage/use of carbon emissions (option 4) mainly in the cement industry. The economics as well as potential constraints of the analysed options (e.g., the availability of alternative fuels), however, were not analysed in the matrix. Accordingly, Only the modelling conducted as part of WP2 and WP3 allows for a concluding assessment of the options' potential. Refer to aramis for the detailed sector-technology matrix including the full assessment of each technical approach.

The results presented in the topic modelling paper support the past importance of efficiency-focused measures, but also show how the focus of academic research shifted towards decarbonization options that allow for a full decarbonization. The results can be found in Tautorat, Lalin, et al. (2023).

	Minerals – Cement	Minerals – Ceramics	Chemicals – Olefins	Chemicals – Other	Ferrous & non-ferrous metals	Food & Beverages
1. Increase of process/ system efficiencies	★★	★	★★	★★★	★★	★★
2. Shift to electricity	★★	★★	★★★	★★★	★★★	★★★
3. Shift to alternative fuels	★★	★★★	★★★	★★★	★★	★★
4. Carbon capture and storage/use	★★★	★★	★★★	★★★	★★	★★
5. Shift to alternative feedstock	★★	★	★★ [1]	Not applicable	Not applicable	Not applicable

1) Only relevant for scope 1 emissions if process is not fully electrified.

Figure 12 Matrix: Sector-technology-matrix before expert triangulation indicating the importance of abatement options per industry sector

[4] This section largely overlaps with the separately published sector-technology-matrix report and is similar to previous annual DECARBIN reports.

	Minerals – Cement	Minerals – Ceramics	Chemicals – Olefins	Chemicals – Other	Ferrous & non-ferrous metals	Food & Beverages
1. Increase of process/ system efficiencies	★★	★★	★★	★★	★★	★★
2. Shift to electricity	★	★	★★★	★★★	★★	★★★
3. Shift to alternative fuels	★★	★★★	★★★	★★	★★	★★★
4. Carbon capture and storage/use	★★★	★	★	★	★	★
5. Shift to alternative feedstock	★	★	★★ [1]	Not applicable	Not applicable	Not applicable

1) Only relevant for scope 1 emissions if process is not fully electrified

Figure 13 Matrix: Sector-technology-matrix after expert triangulation indicating the importance of abatement options per industry sector

3.2 Dairy industry[5]

Switzerland aims at reaching net zero CO_2 emissions by 2050, but progress in the entire food sector has been limited to date—including in the dairy processing industry, despite the absence of (difficult to abate) methane emissions and comparatively low process temperatures. Because many think the supply of cheap gas has come to an end in Europe (cf. Figure 31 in BloombergNEF's proprietary report on the German power market (2022), the section on natural gas in chapter 2.4.2 of IEA's World Energy Outlook (2022), and the supplemental information of this article), here we ask whether it is economically feasible for producers of dairy products in Switzerland to switch to low-carbon alternatives, given the current energy and climate policy landscape in the country.

Our findings suggest that changes in energy prices further improved the economic viability of low-carbon technologies in the Swiss dairy industry making either heat pumps (case 1) or biomass boilers (cases 2-4) the cheapest heating technology (cf. Figure 14).

For case (1), gas boilers are cheaper in the low energy price scenario, whereas for high energy prices heat pumps get most attractive, undercutting gas boilers by roughly 10%. Due to comparatively high capital expenditures and a low utilization, biomass boilers are more costly than gas boilers and heat pumps assuming low energy prices. Smaller anticipated price increases for biomass compared to gas, however, make biomass boilers slightly less costly for high energy prices.

For cases (2) and (3), biomass boilers are most economical in both energy price scenarios, followed by heat pumps. The latter are more costly for case (3) than for (2) as increasing temperatures lead to a lower coefficient of performance (COP), and consequently a higher electricity demand.

For case (4), biomass boilers are most economically viable in both energy price scenarios, followed by gas boilers. For high energy prices, electric boilers are only slightly more expensive than gas. Despite ongoing research, heat pumps are not commercially available yet for temperatures >200 °C (Liang et al., 2022).

For large producers (cases 2-4), the sum of energy and emissions expenditures contribute the largest share of total costs—more than 80% irrespective of the technology. For small producers (case 1), however, energy expenditures contribute considerably less for biomass boilers and heat pumps. Accordingly, the age of the current installations is much less important for investment considerations of large producers. Electric boilers are not competitive in any of the cases.

The presented findings hold true for changes in energy and emissions prices (cf. Figure 15): For gas boilers to become cheaper than heat pumps, electricity prices would need to increase substantially compared to forecasts for 2023-2052— by ca. 100 CHF/MWh for small and >100 CHF/MWh for large producers (cf. Figure 15 A.1-A.3). Similarly, for gas to become cheaper than biomass boilers for large producers, biomass prices would need to increase by >100 CHF/MWh (cf. Figure 15 C.1-C.4). CO_2 prices contribute a substantial share for low energy prices (32-41%) but a smaller share for high energy prices (17-21%). Accordingly, the findings for high energy prices are only marginally sensitive to falling CO_2 prices (cf. Figure 15 D.1-D.4).

While our results show that low gas prices can no longer impede the decarbonization of the Swiss dairy industry from an economic perspective, individual non-economic hurdles exist according to the interviews conducted: biomass is not always locally available and existing electricity distribution grids cannot always handle loads associated with electrification. Space needed for biomass and hot water storages as well as larger heat exchangers are often not available in historically developed dairy plants. The reliability and maintenance requirements of biomass boilers and heat pumps are also often considered inferior to that of gas boilers—a feature particularly important when handling perishable raw materials like milk. Given the promising economics of low-carbon technologies for dairy production, however, policy and industry effort to lower these non-economic hurdles would be desirable. Overall,

[5] This section largely overlaps with Tautorat et al. (2023). Only minor things like cross-references were updated.

the prospects for a decarbonization of Swiss dairy production have clearly improved, hopefully adding another piece to the food sector decarbonization puzzle.

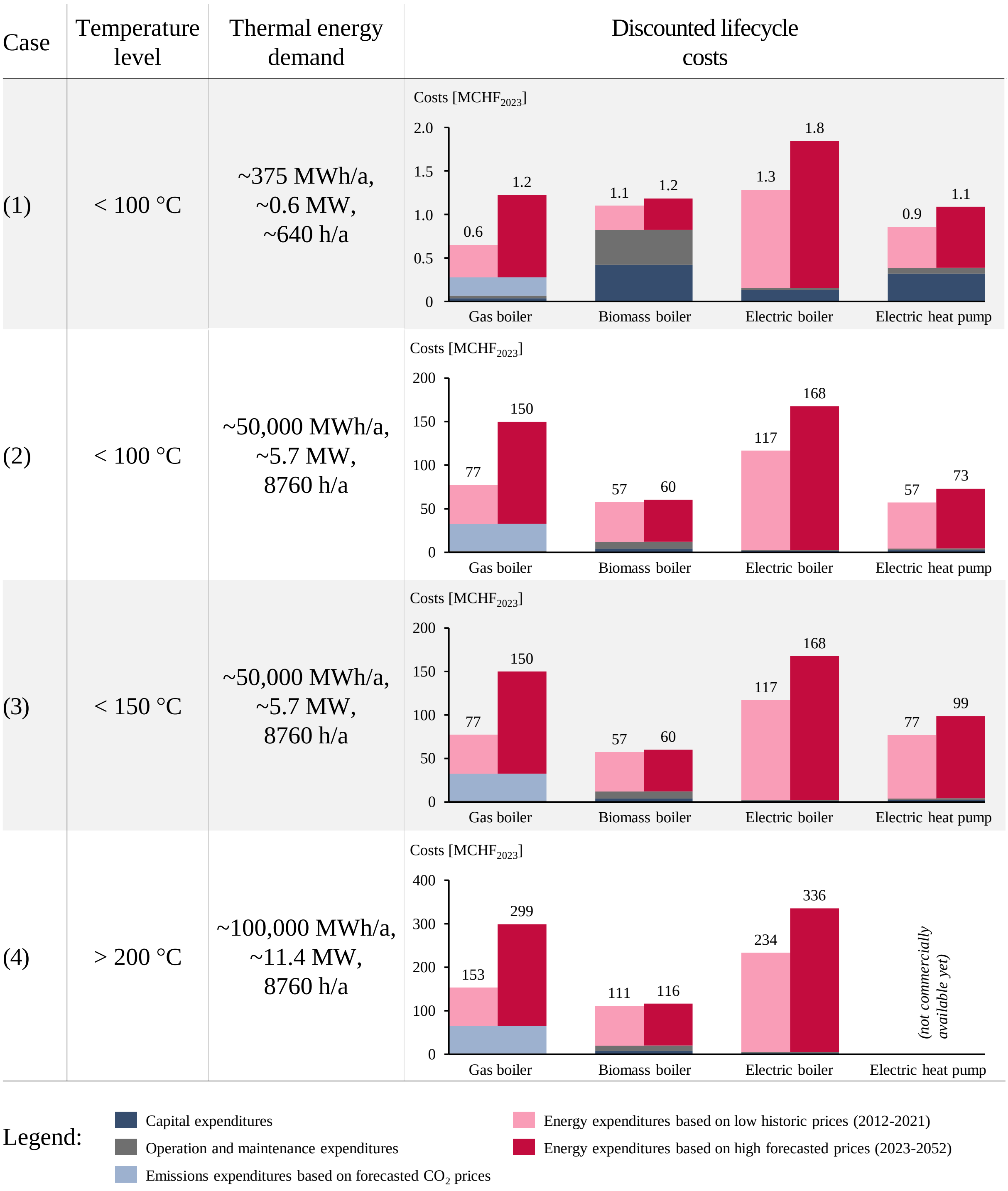


Figure 14 Dairy: Total discounted costs of the four technologies for low and high energy prices

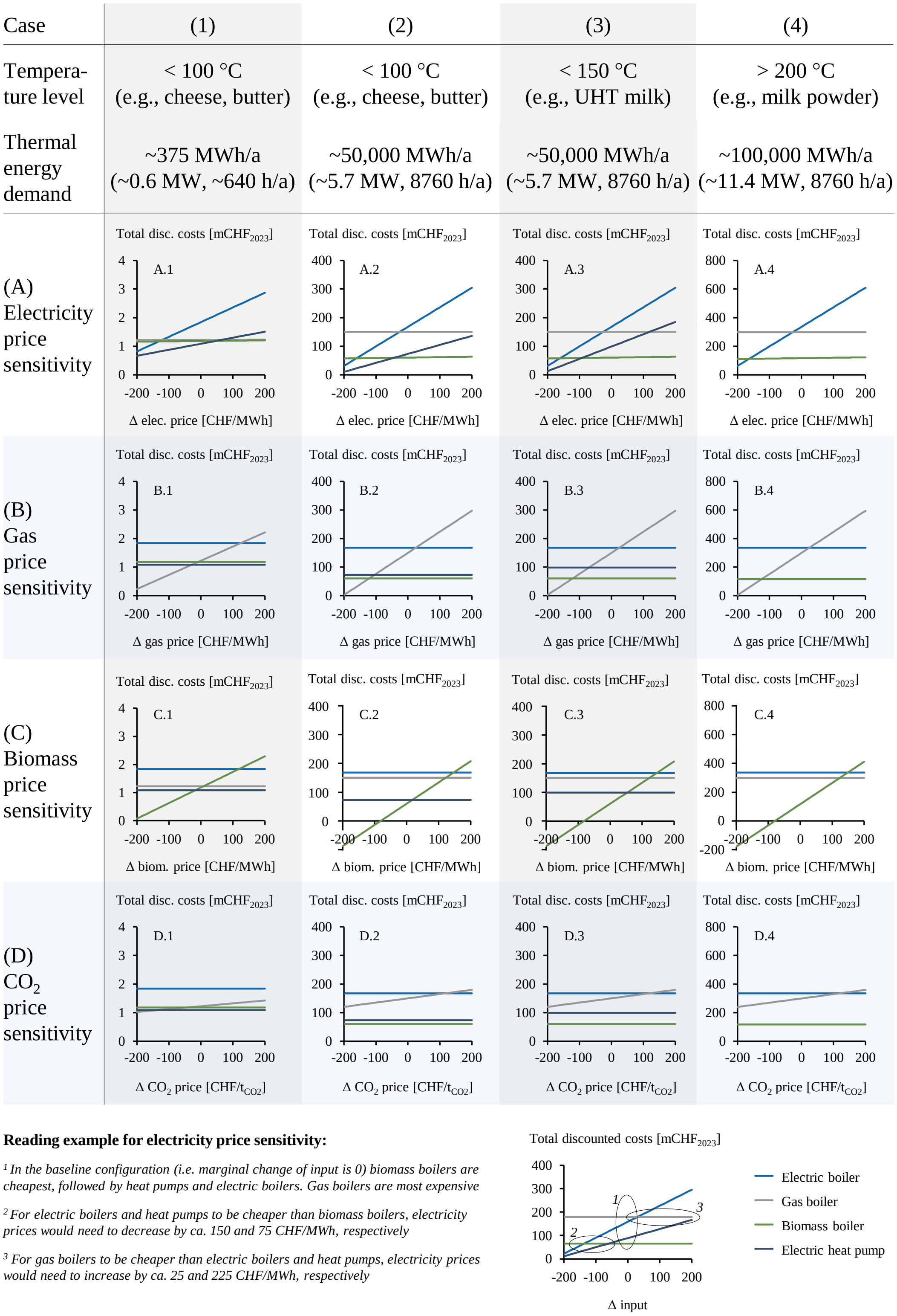


Figure 15 Dairy: Sensitivity analysis – total discounted costs of the four heat generating technologies for high energy prices (baseline) as a function of changes to energy and emissions expenditures

3.3 Cement industry

The following sub-sections present results for the Swiss cement industry based on the ROV model. Only results for the RR scenario are shown, i.e., a scenario in which the CCS CAPEX and the EU ETS price stay high. The risk (or chance) of diverting to a less (or more) favoriable scenario are, however, modelled implicitly through the inclusion of the uncertainties. Section 3.3.1 shows results for different uncertainty configurations and Section 3.3.2 for different policy configurations. Section 3.3.3 shows briefly how more favorable transport and storage costs of non-Swiss plants can influence the competitiveness within Europe over the next decades. Finally, Section 3.3.4 show how investment decisions translate in changes in fuel demand. As stated above, Although we refer to specific plant names (e.g. Eclépens), the results are to be understood less as exact results for these very plants, but rather as exemplary results for stylized plants with similar main characteristics. Exact modeling of the Swiss plants would only be possible after further consultation with the respective operators.

3.3.1 Influence of uncertainty

In the RR scenario, plants increase their biomass share over the modelling period, with the timing depending on the uncertainties included. Biomass investments are more sensitive to assumptions for the price spread between biogenic and fossil fuels than to comparatively small investment costs for additional storage required (the kiln and feeder system are assumed to stay unchanged). In the presented results, only the Cornaux plant does not increase its biomass share as it is the smallest plant and installation costs are assumed to be size-independent for the sake of simplicity.

In the absence of uncertainties (*"None"* line), all plants invest in CCS in 2025. This decision is driven by a high and certain EU ETS price, which offsets the high CCS CAPEX and OPEX.

Introducing CAPEX uncertainty, where CCS CAPEX could significantly decrease, leads some plants to delay CCS investments in anticipation of lower costs depending on their size and WACC. These delays occur only when option values are considered (solid line). When no option values are included (dashed line) plants optimize the NPV in a myopic fashion and continue with early CCS investments.

When ETS price uncertainty is considered, i.e. the risk of the EU ETS price to deviate from the high reference price and thereby to negatively influence decarbonization investments, CCS investments are deferred by 10-15 years. This delay is attributed to the fear of a drop in the EU ETS price, leading plants to wait for a time when even the less favorable scenario justifies CCS investment. Unlike CAPEX uncertainty, ETS uncertainty causes delays even when excluding option values, as plants anticipate future price slumps by weighing future reference and alternative scenarios.

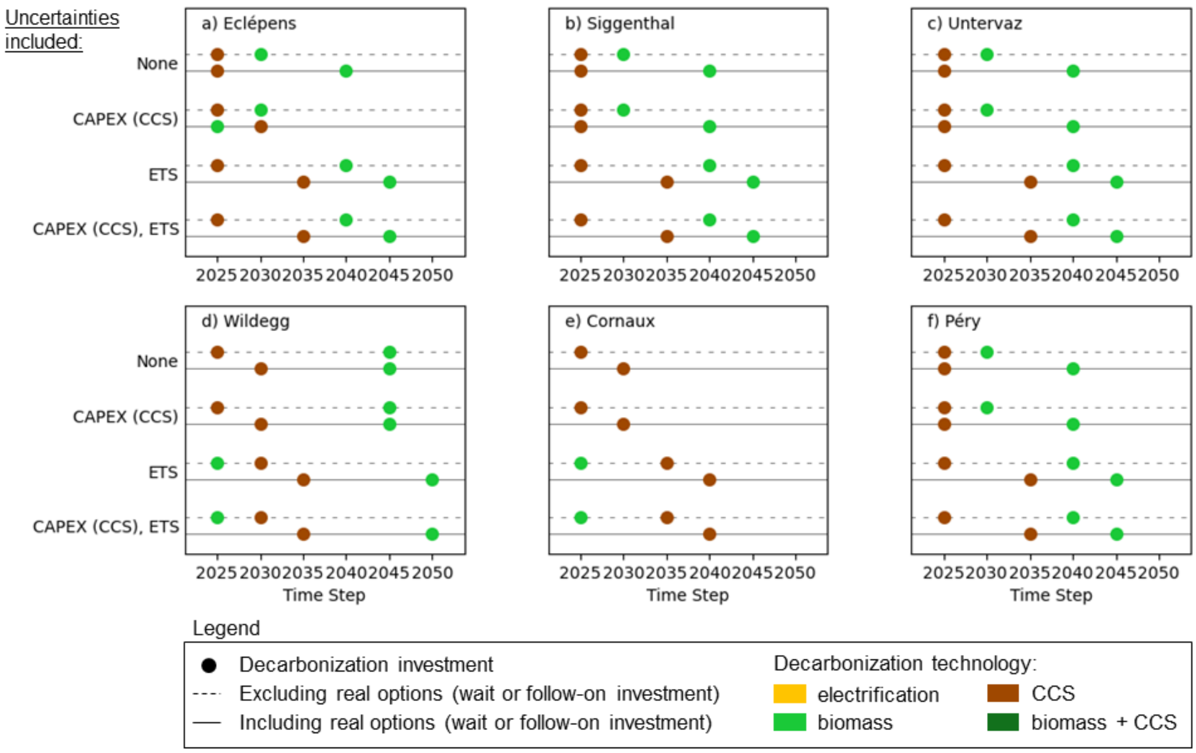


Figure 16 Cement: Investment decisions in RR scenario by plant depending on included uncertainty. Note: Assuming CO2 transport and storage infrastructure is developed.

When both CAPEX and ETS uncertainties are present, investment decisions largely mirror those under ETS uncertainty alone. The CAPEX uncertainty has a lesser impact on decisions, possibly because CAPEX contributes only partly to the total lifetime costs of CCS, whereas the ETS price is the sole "benefit" in the model.

Despite rather bullish price assumptions, hydrogen as an alternative fuel is not pursued in any scenario due to less favorable hydrogen prices compared to biomass and the complete elimination of fuel-related emissions, which reduces the economics of previous or subsequent CCS installations. Biomass combined with CCS, in contrary, is modeled to transform the cement plant into a Biomass Energy with Carbon Capture and Storage (BECCS) plant.

When comparing the results to a scenario without a developed CO_2 transport infrastructure (cf. Figure 17), plants tend to undertake investments five years later for some uncertainty configurations due to higher CO_2 costs. A more pronounced delay is not observable as the closer the model gets to 2050 the more onshore geological storage it assumes to be available in Europe making CO2 infrastructure increasingly less decisive for the investment decisions.

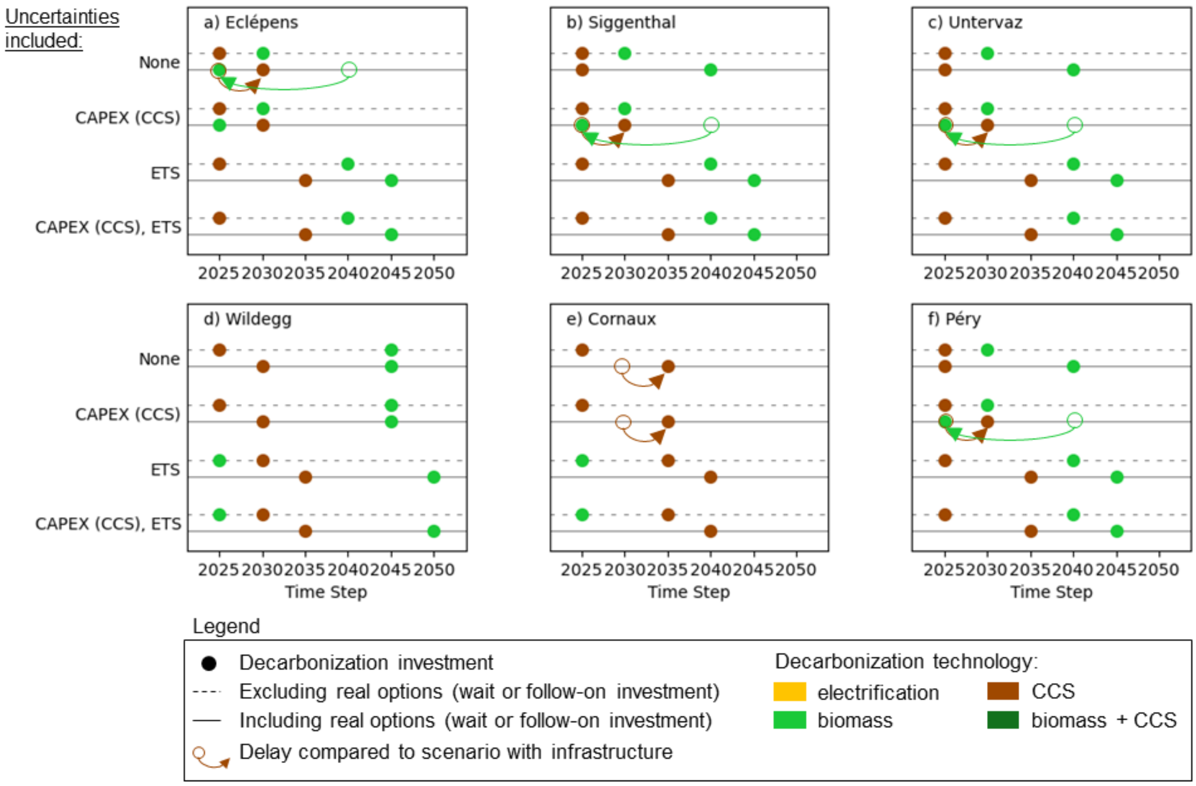


Figure 17 Cement: Investment decisions in RR scenario by plant depending on included uncertainty. Note: Assuming CO2 transport infrastructure is not developed.

Figure 18 complements the results in Figure 16 by showing NPVs for both uncertainties. Starting in 2025, each plant chooses the option with the highest NPV, favoring waiting in 2025 and 2030 for all six plants. CCS is only selected once its value (brown dot) surpasses the value of waiting (grey dot), i.e., in 2035 for all but the Cornaux plant, which invests not until 2040. The absolute NPVs presented in Figure 18 vary across plants due to different production capacities.

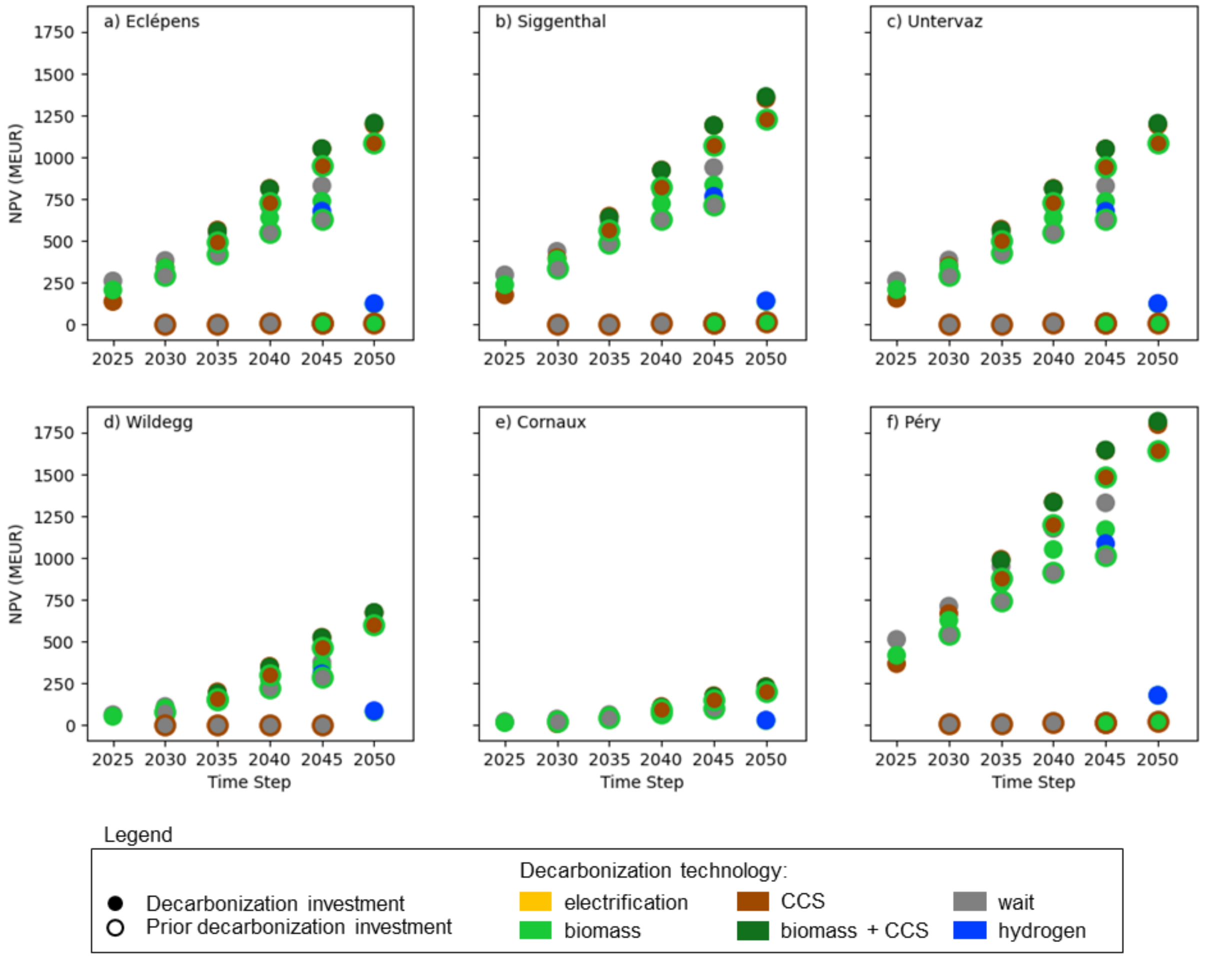


Figure 18 Cement: NPVs of decisions in RR scenario by plant with CAPEX (CCS) and ETS uncertainty included (bottom line in Figure 16)

3.3.2 Influence of policy

Based on the configuration that includes option values and both CAPEX and ETS uncertainties (most bottom line in Figure 16; top line in Figure 19) different policy interventions are evaluated for their influence on the plants’ investment decisions.

None of the tested policy interventions influence the timing of biomass investments. The underlying NPVs of investments into biomass, however, are positively influenced by technology-neutral CAPEX subsidies or price floors (not shown in Figure 19).

Specifically, CAPEX subsidies (lines 2-5) generally do not lead to earlier CCS investments; the only exception is the Cornaux plant, which, due to its smaller size and higher WACC, invests five years earlier under CAPEX subsidies. The impact of a time-limited (ending 2035) versus a non-expiring CAPEX subsidy is not evident.

CCS-specific (lines 2-3) and technology-neutral (lines 4-5) CAPEX subsidies have identical effects on technology choice and investment timing, as CCS and biomass technologies complement rather than compete with each other. This contrasts with the competitive relationship between hydrogen and CCS or electrification and CCS in the chemical industry (cf. Section 3.4).

A non-expiring carbon price floor (line 6) influences all plants to invest five to ten years earlier. In contrast, a carbon price floor expiring in 2035 alone (line 7) had no impact on any of the plants. This outcome suggests that the temporary certainty of a carbon price does not outweigh the risk of a potential decline in the ETS price post-2035. Considering the model assumes a five-year installation period for CCS, plants would need to invest in 2025 to benefit from an expiring limited price floor between 2030 to 2035.

When combining a CAPEX subsidy with a non-expiring price floor, plants are found to invest even earlier (second last line). This combination leads to all plants investing ten years earlier. Remarkably, this makes all but the Cornaux plant invest as early as 2025, the earliest period considered in the model.

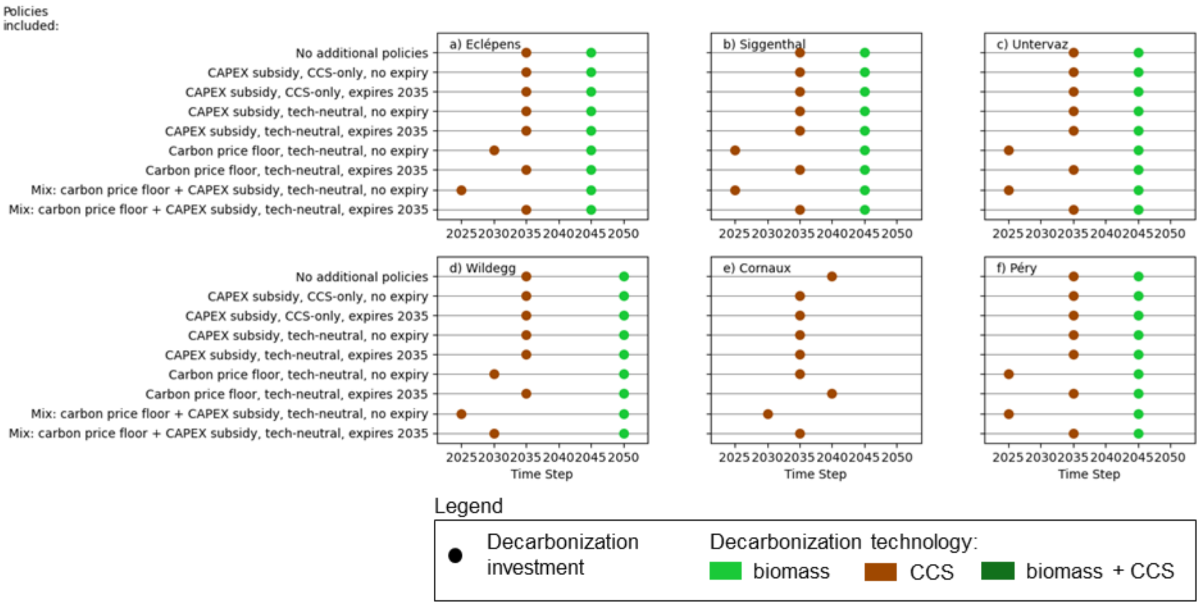


Figure 19 Cement: Investment decisions in RR scenario by plant for different policy interventions. Note: Assuming CO2 transport and storage infrastructure is developed. Assuming all uncertainties included.

3.3.3 Impact on energy vector

Figure 20 illustrates the impact of decarbonizing the cement sector on the energy system by comparing fuel demand scenarios. The first scenario shows the fuel demand without policy intervention (as depicted in the first line of Figure 19), while the second scenario presents the fuel demand for a mix of interventions (as shown in the second last line of Figure 19).

In both scenarios, in the long-term investments into biomass lead to a reduced share of fossil fuels and a higher share of biomass and waste. The waste is partially of biogenic nature.

The introduction of CCS increases the overall fuel demand in the industry. This is due to the electricity and heat penalties associated with CCS plants. Without policy interventions, fuel demand starts rising from 2040. However, with ambitious policy interventions, the rise in energy demand due to CCS begins as early as 2030. The delay between investment decisions shown in Figure 19 and the resulting changes in fuel demand shown in Figure 20 are due to an assumed lead time for CCS of five years.

The specific CCS sub-technology modelled, amine scrubbing, primarily raises the demand for thermal energy. In thermal power plants, this thermal energy can be met by abundant low-pressure steam, leading to comparatively small efficiency penalties. Due to the lack of steam in cement plants, the additional energy demand is assumed to be met using the cement plant's existing fuel mix. Other prominent CCS sub-technologies, such as oxyfuel, would have resulted in a less significant increase in absolute energy demand and a much higher proportion of electricity usage. Electricity-based kilns, like the LEILAC technology, would shift the demand towards more electricity.

Shifting the Swiss cement industry to amine CCS technology would significantly increase the demand for biomass and waste. This could lead to price increases for these energy carriers. Potential price changes have not been modelled yet. Interviewees from the European cement industry confirmed the challenge of procuring additional (biogenic) fuel, especially for the case of increasing demand due to CCS.

A potential relocation of clinker production within Europe (as discussed in Chapter 3.3.4) could on the contrary even lead to a reduction of energy demand by the Swiss cement industry. The resulting reduction of biomass demand could potentially even enable the full decarbonization of other sectors free of process-inherent emissions that produce less commoditized goods as, e.g., the specialty chemicals industry.

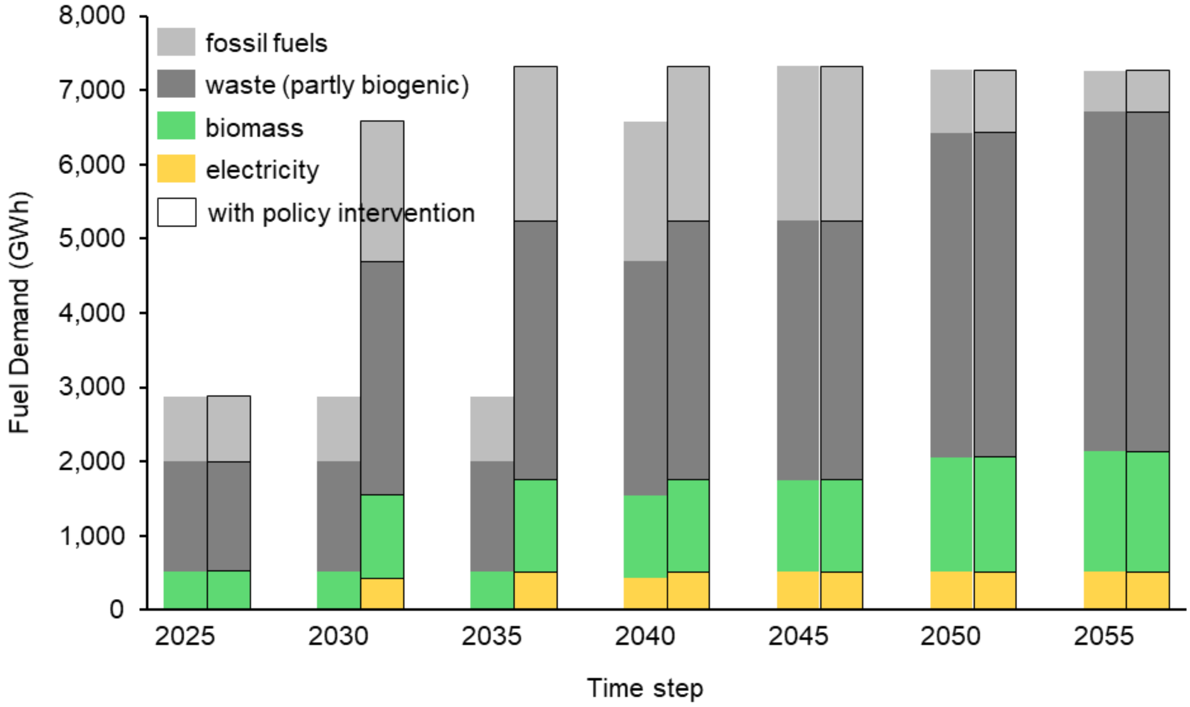


Figure 20 Cement: Industry-level fuel demand with and without policy intervention in GWh/a

Table 22 Cement: Industry-level fuel demand with and without policy intervention in GWh/a; percentage values indicate the increase compared to the scenario without policy intervention

	2025	2030	2035	2040	2045	2050	2055
Without policy intervention							
fossil fuels	884	884	884	1887	2087	851	553
waste	1476	1476	1476	3151	3486	4362	4572
biomass	523	523	523	1118	1236	1547	1622
electricity	0	0	0	431	517	517	517
With policy intervention							
fossil fuels	884 (0 %)	1887 (113 %)	2087 (136 %)	2087 (11 %)	2087 (0 %)	851 (0 %)	553 (0 %)
waste	1476 (0 %)	3151 (113 %)	3486 (136 %)	3486 (11 %)	3486 (0 %)	4362 (0 %)	4572 (0 %)
biomass	523 (0 %)	1118 (113 %)	1236 (136 %)	1236 (11 %)	1236 (0 %)	1547 (0 %)	1622 (0 %)
electricity	0 (-)	431 (-)	517 (-)	517 (20 %)	517 (0 %)	517 (0 %)	517 (0 %)

3.3.4 International competitiveness

The model allows to compare different plants in Europe and thereby to compare how uncertainty and policy intervention influence NPVs as well as investment decisions of Swiss plants vis à vis European plants. As a case in point, Figure 21 compares NPVs for the Péry plant assuming the Péry-specific CO_2 transport and storage costs (box a) to NPVs for the Péry plant applying the much lower transport and storage costs of the coastal Brevik plant in Norway (box b). When assuming the Brevik costs, the value of a CCS investment in 2025 increases by 15% from 322 to 371 MEUR.

Similarly, the model allows to compare the influence of other factors varying across plants in Europe, e.g., electricity costs, grid fees, fuel costs, country-specific carbon taxes, country-specific subsidies, and the willingness of the local market to pay a green premium for a less CO2-intense product.

High carbon prices increase the competition among the European plants as their decarbonization prospects vary heavily and clinker could theoretically be transported within Europe. Interviews with producers operating cement plants in Europe confirm that industry makes calculations similar to ours and optimizes NPVs of investments across their portfolio of plants. More concretely, the European cement industry might move to a situation where clinker is produced at sites close to carbon sinks (as depleted gas fields in the North Sea) and where energy is abundant. In the end, transporting clinker might be cheaper than transporting fuels and CO2 also in the long run. In this context, national policy allowing for onshore geological storage of CO2 close to industrial emitters could have a pivotal influence on intra-European competitiveness in CO2-intense industries like cement.

Clinker and cement (as opposed to dairy products and the majority of chemicals) are included in the goods to be protected from carbon leakage by the EU's carbon border adjustment mechanism (EU CBAM). The EU CBAM foresees that clinker and cement imported to the EU is taxed if produced at effective CO2 prices lower than those in the EU-ETS. Accordingly, clinker and cement could be traded tax-free between Switzerland and the EU if both trading systems remain coupled and effective CO2 prices on the same level. Without a similar instrument in Switzerland, however, carbon leakage from Switzerland to non-EU countries is conceivable, especially when considering the significant volumes of clinker and cement imported to the EU today. The introduction of an instrument in Switzerland similar to the EU CBAM could protect the cement industry from carbon leakage but could at the same time increase costs for imported goods processed in other industries. Clinker and cement exports from Switzerland to non-EU countries with lower effective CO2 prices are not protected by a CBAM but can be neglected given low export volumes.

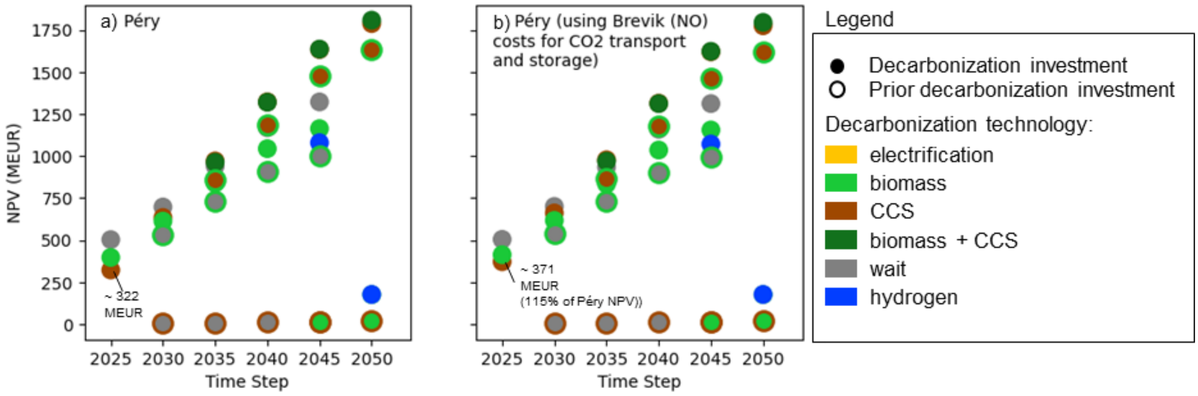


Figure 21 Cement: NPVs of Péry plant for different CO_2 transport and storage costs. Including CAPEX and ETS uncertainty. Excluding policy interventions. Assuming transport infrastructure is not developed.

3.4 Chemical industry

Building on the presented preliminary analysis, forthcoming detailed results are planned to be published in a journal article addressing the decarbonization of Switzerland's chemical industry.

3.4.1 Influence of uncertainty

The results paint a less heterogeneous picture of the Swiss chemical than the cement industry (cf. Figure 22). When including real options (solid lines) all plants in our model opt for electrification or biomass. Specifically, plants requiring heat below 160°C (plants 1, 4, 7) transition to electrified heat production by 2035. For plants operating between 160°C and 220°C (plants 2, 5, 8), biomass becomes the preferred choice by 2040 due to a conservative COP assumption of 1.15 for the electric alternative. The economic feasibility of switching to electricity or biomass in this temperature range is closely linked to COP values and the prices of biomass and electricity. Plants requiring temperatures above 220°C (plants 3, 6, 9) adopt biomass by 2040. Although technical solutions for electrification exist, economic factors favor biomass.

The inclusion of real options and electricity price uncertainties suggests a delayed shift to electricity by 2040 instead of 2035. CCS is not considered a viable option, regardless of the inclusion of CCS uncertainty and the availability of required infrastructure. This is due to the small scale of the installations and high CAPEX costs (the largest plant size modelled, 48 GWh/a, does not even consume a tenth of the energy of cement plant and on top is assumed to emit no additional process-related emissions). ETS uncertainty has no impact on decision-making when real options are considered. Without real options (dashed lines), larger plants prematurely invest into CCS early on in a myopic fashion despite very small associated NPVs. As plant operators can be expected to include option values in their considerations (be it fully through explicit calculations or implicitly through decision makers' gut feelings), these CCS investments are not realistic and cannot be expected to materialize in the real world.

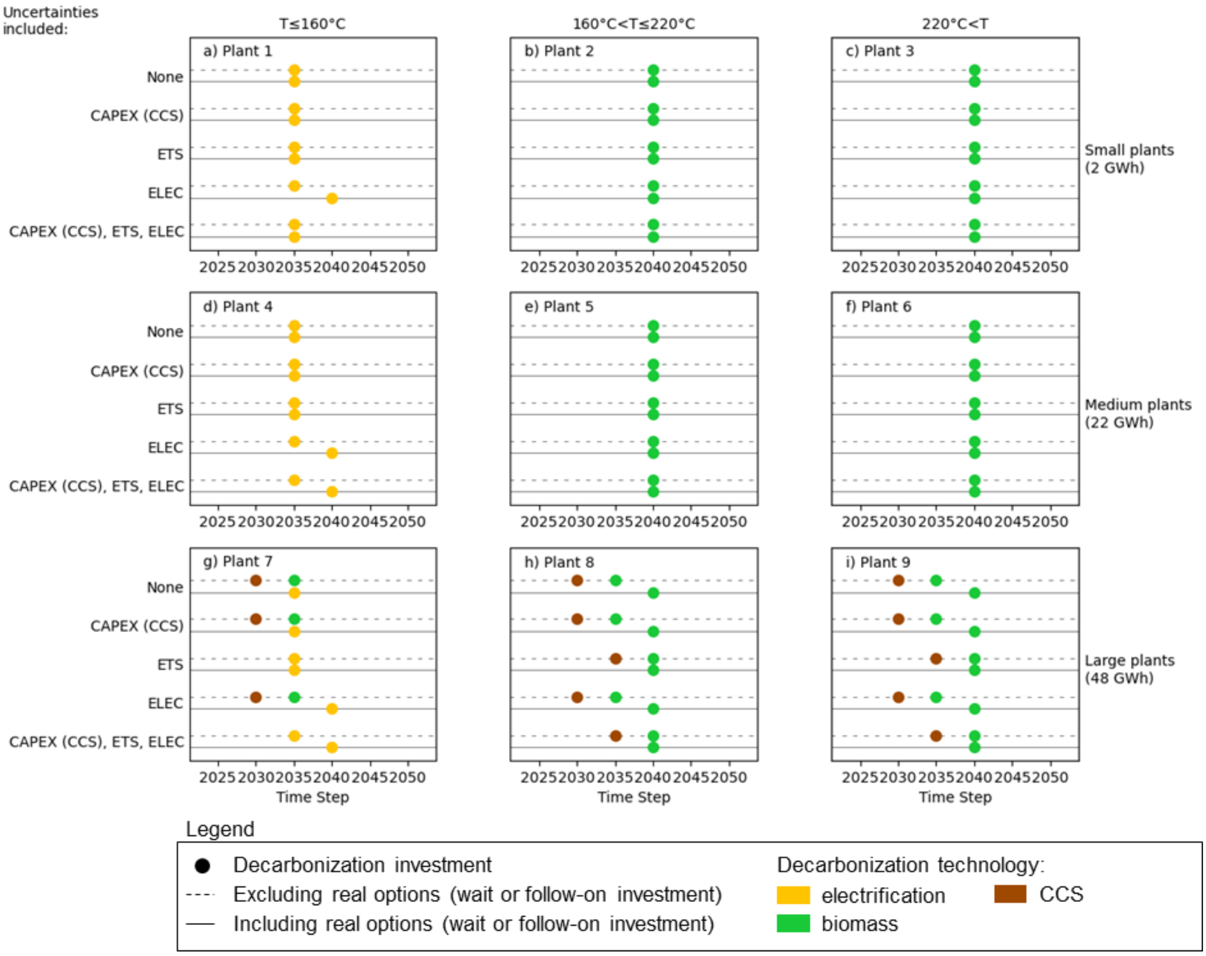


Figure 22 Chemical: Investment decisions in RRR scenario by plant depending on incl. uncertainty. Note: Assuming CO2 transport and storage infrastructure is developed.

Analysis of the underlying NPVs (Figure 23) considering CAPEX, ETS, and electricity uncertainties elucidates the decisions depicted in Figure 22. Particularly for seemingly undesirable decisions from an emissions or energy system perspective, such as delayed investments, in-depth analysis facilitates more effective policy interventions. For instance, the difference in the value of waiting versus investing in electrification for Plant 7 in 2035 is marginal (15.7 vs. 15.2 MEUR), suggesting that minor policy support could encourage earlier investments (although decision makers obviously do not think in 5-year periods but re-evaluate decisions continuously).

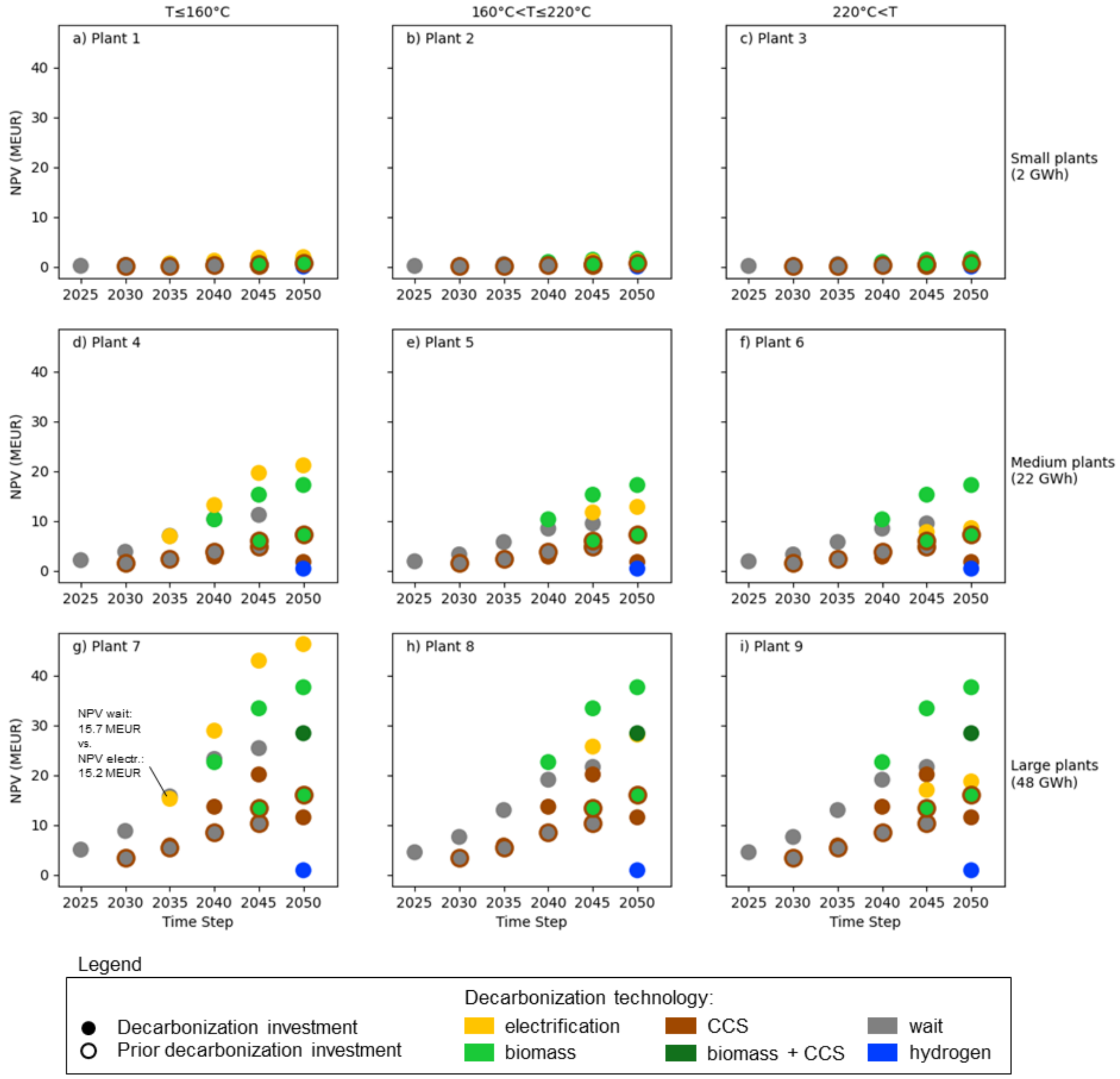


Figure 23 Chemical: NPVs of decisions in RRR scenario by plant with CAPEX (CCS), ETS, and ELEC uncertainty included (bottom line in Figure 22)

3.4.2 Influence of policy

In terms of policy influence, subsidies specific to CCS do not alter its adoption and the other analyzed policy instruments do not incentivize plants to switch from biomass to electricity in the mid-temperature range (160 to 220°C). Fundamental economic factors of different decarbonization strategies remain unchanged by policy interventions. Not even an electrification-specific 50% CAPEX subsidy (not shown in Figure 24) result in the model to choose electrifying this plant class. However, policies promoting lower electricity costs (e.g., participation in EU power market) or regulating biomass use could make electricity more competitive. Site-specific sources of waste heat can also give electrification an advantage over biomass. Plant 7 exemplifies the effectiveness of time-limited policies, where a non-expiring intervention leads to investment only in 2040 (cf. second line from the bottom) but a “take it or leave it” intervention (as currently seen for alpine PV subsidies) ending in 2035 can expedite investment decisions to 2035 (cf. bottom line).

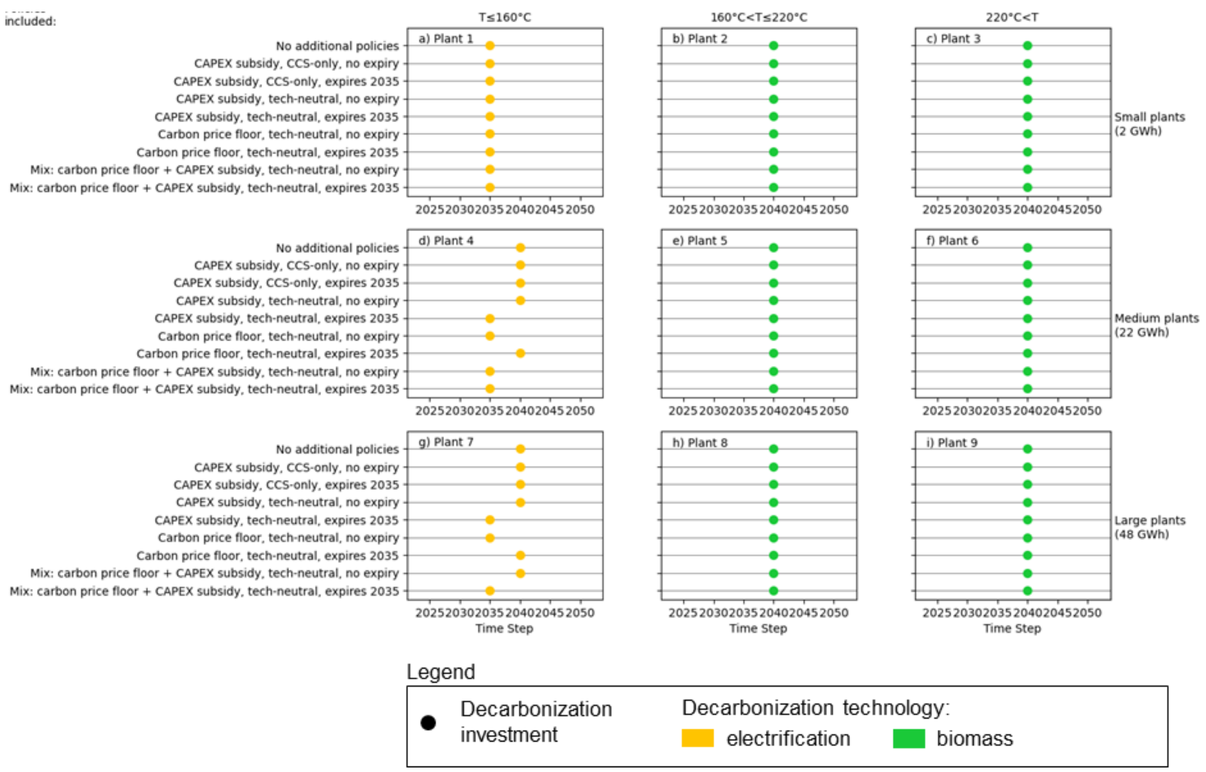


Figure 24 Chemical: Investment decisions in RRR scenario by plant for different policy interventions. Note: Assuming CO2 transport and storage infrastructure is developed. Assuming all uncertainties included.

3.4.3 Impact on energy vector

Finally, extrapolating from the decisions of Plants 1-9 to the sampled 68 plants, there is a noticeable shift in fuel demand within the chemical industry, as shown in Figure 25. Natural gas is largely replaced by electricity and biomass, and the adoption of heat pumps reduces overall energy requirements. This could counterbalance any potential rise in energy demand due to industry growth. Policy instruments do not significantly alter the energy carrier mix but do influence the timing of electricity demand increases. It is crucial to note that a consistent CO2 price in line with ETS assumptions will lead to a substantial reduction in gas demand by 2040, irrespective of it being replaced by electricity or biomass, which raises concerns about the potential obsolescence of gas transmission and distribution infrastructure. The relative use of electricity and biomass will depend on demand elasticity and policy directives guiding biomass utilization.

It is, however, difficult to extrapolate beyond the sampled 68 plants to the whole (specialty) chemicals industry in Switzerland as we limited our analysis to plants that primarily use gas for heat generation (cf. Chapter 2.3.2). The decarbonization of plants that rely on external heat generation, e.g., was not analyzed and could follow different dynamics. In addition, the thermal treatment of chemical waste (be it in waste incineration plants or in the chemical industry itself) could demand for some residual use of natural gas.

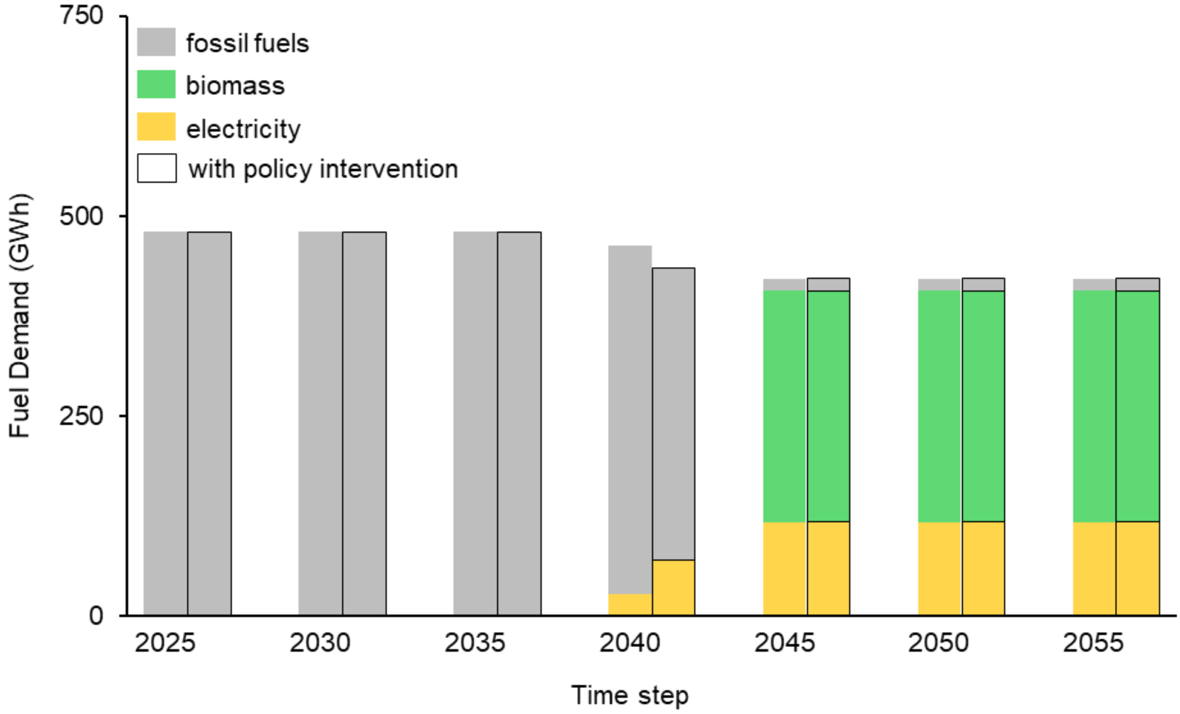


Figure 25 Chemical: Industry-level fuel demand with and without policy intervention in GWh/a

Table 23 Chemical: Industry-level (68 plants) fuel demand with and without policy intervention in GWh/a; percentage values indicate the increase compared to the scenario without policy intervention

	2025	2030	2035	2040	2045	2050	2055
Without policy intervention							
fossil fuels	480	480	480	435	15	15	15
biomass	0	0	0	0	289	289	289
electricity	0	0	0	28	118	118	118
With policy intervention							
fossil fuels	480(0 %)	480 (0 %)	480 (0 %)	365 (-16 %)	15 (0 %)	15 (0 %)	15 (0 %)
biomass	0 (0 %)	0 (0 %)	0 (0 %)	0 (0 %)	289 (0 %)	289 (0 %)	289 (0 %)
electricity	0 (0 %)	0 (0 %)	0 (0 %)	71 (157 %)	118 (0 %)	118 (0 %)	118 (0 %)

4 Conclusions

In conclusion, this report presents two comprehensive techno-economic models designed to assess the decarbonization pathways for the dairy processing, cement, and chemical sectors. The findings indicate that electrification and a shift to biomass are viable pathways for decarbonizing the chemical and dairy industries, while the cement industry employs a combination of CCS with biomass. Notably, hydrogen does not appear to play a significant role in any of the three industries despite bullish H2 costs assumptions.

From a policy perspective, several implications emerge. Firstly, the use of biomass in Switzerland should undergo critical evaluation due to potentially strong increases of demand. Using biomass in low-temperature applications (as widely observed today) seems unreasonable given the availability and economic efficiency of heat pumps coupled with the lack of clearly viable alternatives in high-temperature applications. Secondly, maintaining a stable and increasing CO2 price is identified as essential. Carbon contracts for difference, as experimented with in Germany, might be one option to guarantee these prices. Thirdly, the results emphasize the importance of low electricity costs, particularly in making electrification more economically viable than biomass for all but very high-temperature processes. Access of large industrial consumers to EU electricity markets could act as a potential lever. Fourth, further research and development in very high-temperature heat pumps is recommended. Finally, while CCS CAPEX subsidies can expedite investments in select cases, they are not deemed necessary. Regardless of policy interventions, there is a noteworthy risk of industry re-localization based on lower CO2 transport costs of non-Swiss plants (despite little changes in Figure 17).

Looking forward, the reduction of CO2 emissions in the chemical and cement industries is anticipated to happen only post-2030 due to high electricity and low ETS prices. In conclusion, the report underscores the multifaceted nature of the decarbonization landscape and emphasizes the importance of strategic policy measures.

5 National and international cooperation

To perform the research described in this report, we collaborated with Prof. Edenhofer's group at PIK in Potsdam. The PIK group has started a project on industry decarbonization focussing on Germany and the EU. Specifically, we met regularly in order to discuss the modelling approach and jointly develop policy portfolio scenarios. As a case in point, a joint workshop with PIK and the SFOE was conducted in Q2 2022.

Generally, our teams are well-connected with the Swiss energy research community (e.g., as part of the SWEET EDGE program), with established contacts to colleagues working on related topics. In the field of CCS, specifically, we benefitted from the SFOE-funded DemoUpCARMA project to incorporate latest insights on CCS, CO2 transport infrastructure and associated costs in the DECARBIN modelling (Prof. Schmidt and Prof. Steffen are part of the consortium). In addition, we exchanged with researchers from HSLU that are part of the DeCarbCH project as results from their tasks 4.1. (industrial energy demand profiles) and 4.3. (sectorial energy profiles) could be a valuable input to our modelling. Furthermore, we were in contact with Prof. Bardow's group at ETH, which conducts work on the Swiss chemicals industry. Where available we will also drew on results from industry specific research projects, as for instance this year's report on the Swiss cement industry published by the DecarbCem project (Nakhle et al., 2022).

6 Communication

The architecture of the ROV model used first results were presented and discussed at different occasions:

- October 17, 2024: “Real options analysis of decarbonization investments in the chemical industry”, SAEE 15th Student Chapter Workshop, ETH Zurich, Zurich/Switzerland (P. Tautorat, J. Iversen, T. S. Schmidt, B. Steffen)
- July 26, 2023: "The influence of uncertainty on the decarbonisation of the specialty chemicals industry", 18th IAEE European Conference, Milan, Italy (P. Tautorat, J. Iversen, T. S. Schmidt, B. Steffen)
- September 28, 2022: "De-risking the decarbonisation of the European cement industry", 11th International Ruhr Energy Conference (INREC), Essen, Germany (P. Tautorat, N. Ljubić, B. Steffen, T. S. Schmidt)
- September 23, 2022: "Policies for accelerating the decarbonisation of the European cement industry", 17th IAEE European Conference, Athens, Greece (P. Tautorat, N. Ljubić, B. Steffen, T. S. Schmidt)
- September 8, 2022: “Technologies and policies for the decarbonization of cement and steel production”, ISTP Summer School on Greening and Governing Global Supply Chains, Filzbach, Switzerland (P. Tautorat)

No additional communications efforts, yet. Dissemination of published peer-reviewed work is planned.

7 Publications

Until now, two articles were published in peer-reviewed scientific journals based on our DECARBIN research:

- Tautorat, P., Lalin, B., Schmidt, T. S., & Steffen, B. (2023). Directions of innovation for the decarbonization of cement and steel production – A topic modeling-based analysis. *Journal of Cleaner Production*, *407*, 137055. https://doi.org/10.1016/J.JCLEPRO.2023.137055
- Tautorat, P., Ramazanoğlu, T., Schmidt, T. S., & Steffen, B. (2023). Energy Transitions in the Food Sector: The Economic Viability of Low-carbon Technologies in the Swiss Dairy Industry. *Findings*. https://doi.org/10.32866/001c.75416

In addition, two further publications are planned that build on but go beyond the content presented in this report:

- Tautorat, P., Iversen, J., Schmidt, T.S., & Steffen, B. Real options analysis of decarbonization investments in the chemical industry. *Accepted for publication at Applied Energy.*
  - ➔ An analysis of the decarbonization of the Swiss chemical industry based on the presented ROV model: How does uncertainty influence plant operators’ decarbonization plans? How can policy interventions influence the industry’s decarbonization? What are the implications for the energy system?
- Tautorat, P., Sultani, D., Ljubic, N., Pahle, M., Steffen, B., & Schmidt, T. S. Green investment dynamics in the EU cement industry under technology and policy uncertainty. *in preparation.*
  - ➔ An analysis of decarbonization pathways for the European cement industry based on the presented ROV model: Which technologies will prevail? When can plants be expected to decarbonize? How does the decarbonization influence the competitiveness among the plants?

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9 Appendix

9.1 Supplementary information

NPV model[6]

The techno-economic model is provided in an Excel document together with the published article (cf. (Tautorat, Ramazanoğlu, et al., 2023)), which includes all assumptions and calculations needed to reproduce the results presented.

Table 24 Dairy: List of interviewees conducted for the dairy industry (Interviews were conducted between September and November 2022 by Taha Ramazanoğlu and/or Paul Tautorat. Interviews were conducted in person, via phone or online conferencing tools in either German or English and lasted between 15 and 180 minutes. Interviewees were sent an interview guide in advance, and in some cases answered follow up questions via e-mail following the interviews. The Chatham House rule applied for six out of the seven interviews.)

No.	Type of organization	Role of interviewee	Duration in min.	Age
1	Research group	Researcher	151 -165	60-70
2	Dairy producer	Energy/environm./sustain. manager	61 - 75	50-60
3	Dairy producer	Managing Director	31 - 45	30-40
4	Dairy producer	Managing Director	16 - 30	50-60
5	Industry association	Project manager	16 - 30	40-50
6	Research group	Researcher	46 - 60	30-40
7	Dairy producer	Energy/environm./sustain. manager	46 - 60	30-40

[6] This section largely overlaps with Tautorat et al. (2023). Only minor things like cross-references were updated.

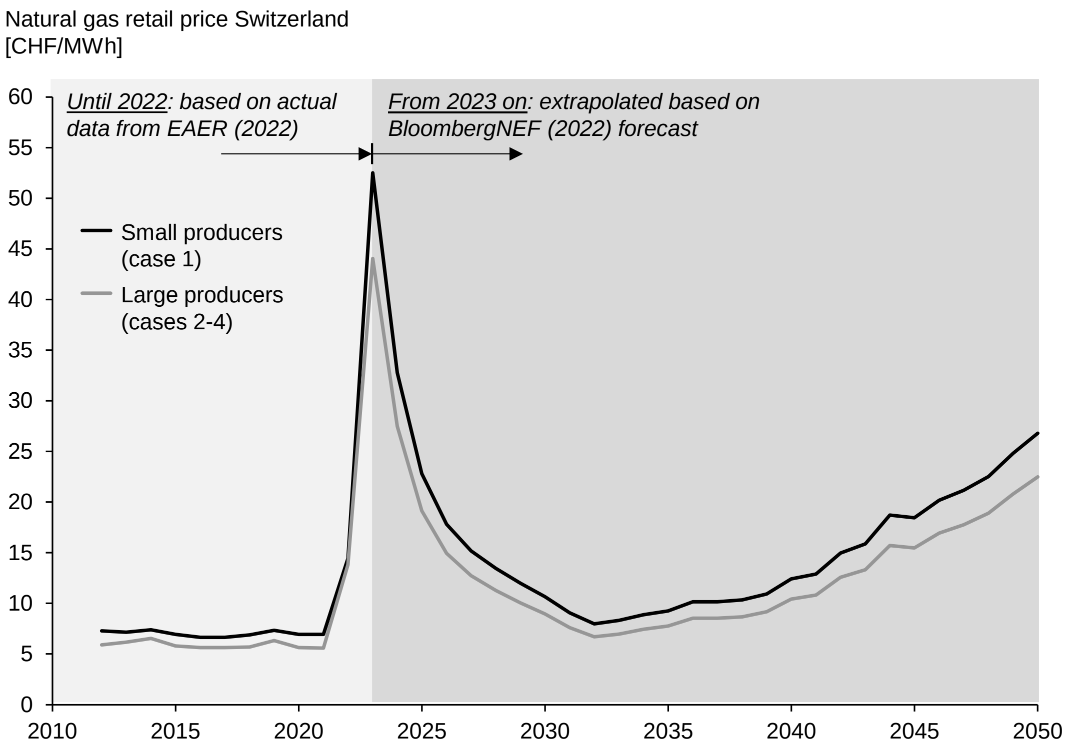

Figure 26 Dairy: Modelling assumptions for retail gas prices in Switzerland (Retail gas prices for the "high forecasted prices" case were extrapolated based on forecasts from BloombergNEF (2022) on the German market and the ratio of German and Swiss gas prices in the past. Plotted values are available in the provided Excel document)

ROV model

Table 25 Cement: WACCs of owners of Swiss cement plants in %. Based on information from Bloomberg L.P. (2023).

Bloomberg name	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Avg 2012-2021
CRH PLC	10.5	20.5	10.8	10.9	12.4	7.8	8.3	7.3	6.9	16.1	11.1
Holcim AG	7.8	7.0	7.0	6.5	6.6	7.1	6.8	6.5	6.3	6.6	6.8
Vicat SA	5.7	6.8	6.3	5.7	5.1	6.4	5.8	3.9	4.1	6.2	5.6

Table 26 ROV model: CO_2 transport and storage costs assuming no infrastructure in EUR_{2022}/t_{CO2} based on Carbon Limits & CATF (2022).

Year	Chemicals Avg. Swiss plants	Cement Eclépens	Siggenthal	Untervaz	Wildegg	Cornaux	Péry
2025	97.5	159.74	112.94	107.56	112.94	159.74	112.94
2026	96.2	156.99	111.24	106.08	111.24	156.99	111.24
2027	94.8	154.07	109.43	104.50	109.43	154.07	109.43
2028	93.3	150.97	107.51	102.81	107.51	150.97	107.51
2029	91.7	147.68	105.46	101.01	105.46	147.68	105.46
2030	90.0	144.20	103.29	99.10	103.29	144.20	103.29
2031	88.2	140.52	100.98	97.07	100.98	140.52	100.98
2032	86.3	136.63	98.55	94.92	98.55	136.63	98.55
2033	84.3	132.54	95.98	92.65	95.98	132.54	95.98
2034	82.2	128.22	93.26	90.25	93.26	128.22	93.26
2035	80.0	123.68	90.40	87.71	90.40	123.68	90.40
2036	77.6	118.91	87.39	85.04	87.39	118.91	87.39
2037	75.1	113.89	84.22	82.22	84.22	113.89	84.22
2038	72.5	108.63	80.88	79.26	80.88	108.63	80.88
2039	69.7	103.12	77.38	76.15	77.38	103.12	77.38
2040	66.8	97.33	73.71	72.88	73.71	97.33	73.71
2041	63.8	91.28	69.86	69.45	69.86	91.28	69.86
2042	60.6	84.94	65.83	65.85	65.83	84.94	65.83
2043	57.3	78.32	61.61	62.08	61.61	78.32	61.61
2044	53.8	71.40	57.19	58.14	57.19	71.40	57.19
2045	50.1	64.16	52.57	54.01	52.57	64.16	52.57
2046	46.3	56.61	47.75	49.69	47.75	56.61	47.75
2047	42.3	48.74	42.71	45.18	42.71	48.74	42.71
2048	38.1	40.52	37.44	40.47	37.44	40.52	37.44
2049	33.8	31.96	31.96	35.55	31.96	31.96	31.96
2050	34.4	32.60	32.60	36.26	32.60	32.60	32.60
2051	35.1	33.25	33.25	36.99	33.25	33.25	33.25
2052	35.8	33.91	33.91	37.73	33.91	33.91	33.91
2053	36.5	34.59	34.59	38.48	34.59	34.59	34.59
2054	37.3	35.28	35.28	39.25	35.28	35.28	35.28
2055	38.0	35.99	35.99	40.04	35.99	35.99	35.99
2056	38.8	36.71	36.71	40.84	36.71	36.71	36.71
2057	39.6	37.44	37.44	41.66	37.44	37.44	37.44
2058	40.4	38.19	38.19	42.49	38.19	38.19	38.19
2059	41.2	38.95	38.95	43.34	38.95	38.95	38.95
2060	42.0	39.73	39.73	44.21	39.73	39.73	39.73
2061	42.8	40.53	40.53	45.09	40.53	40.53	40.53
2062	43.7	41.34	41.34	45.99	41.34	41.34	41.34
2063	44.6	42.17	42.17	46.91	42.17	42.17	42.17
2064	45.4	43.01	43.01	47.85	43.01	43.01	43.01
2065	46.4	43.87	43.87	48.81	43.87	43.87	43.87
2066	47.3	44.75	44.75	49.78	44.75	44.75	44.75
2067	48.2	45.64	45.64	50.78	45.64	45.64	45.64
2068	49.2	46.55	46.55	51.79	46.55	46.55	46.55
2069	50.2	47.48	47.48	52.83	47.48	47.48	47.48
2070	51.2	48.43	48.43	53.89	48.43	48.43	48.43
2071	52.2	49.40	49.40	54.96	49.40	49.40	49.40
2072	53.2	50.39	50.39	56.06	50.39	50.39	50.39
2073	54.3	51.40	51.40	57.18	51.40	51.40	51.40
2074	55.4	52.43	52.43	58.33	52.43	52.43	52.43
2075	56.5	53.48	53.48	59.50	53.48	53.48	53.48
2076	57.6	54.55	54.55	60.68	54.55	54.55	54.55
2077	58.8	55.64	55.64	61.90	55.64	55.64	55.64
2078	60.0	56.75	56.75	63.14	56.75	56.75	56.75
2079	61.2	57.88	57.88	64.40	57.88	57.88	57.88

Table 27 ROV model: CO_2 transport and storage costs assuming infrastructure EUR_{2022}/t_{CO2} based on Carbon Limits & CATF (2022).

Year	Chemicals Avg. Swiss plants	Cement					
		Eclépens	Siggenthal	Untervaz	Wildegg	Cornaux	Péry
2025	59.7	98.52	82.97	76.76	82.97	98.52	82.97
2026	59.1	97.08	81.89	75.83	81.89	97.08	81.89
2027	58.5	95.54	80.72	74.83	80.72	95.54	80.72
2028	57.9	93.91	79.48	73.76	79.48	93.91	79.48
2029	57.2	92.17	78.15	72.63	78.15	92.17	78.15
2030	56.4	90.32	76.74	71.41	76.74	90.32	76.74
2031	55.6	88.36	75.24	70.12	75.24	88.36	75.24
2032	54.8	86.29	73.65	68.75	73.65	86.29	73.65
2033	53.9	84.10	71.96	67.29	71.96	84.10	71.96
2034	52.9	81.79	70.18	65.75	70.18	81.79	70.18
2035	51.8	79.35	68.30	64.12	68.30	79.35	68.30
2036	50.8	76.78	66.32	62.40	66.32	76.78	66.32
2037	49.6	74.08	64.23	60.58	64.23	74.08	64.23
2038	48.4	71.24	62.03	58.67	62.03	71.24	62.03
2039	47.1	68.26	59.71	56.65	59.71	68.26	59.71
2040	45.7	65.12	57.28	54.53	57.28	65.12	57.28
2041	44.3	61.84	54.73	52.31	54.73	61.84	54.73
2042	42.8	58.40	52.05	49.97	52.05	58.40	52.05
2043	41.2	54.79	49.24	47.52	49.24	54.79	49.24
2044	39.5	51.02	46.30	44.95	46.30	51.02	46.30
2045	37.7	47.07	43.22	42.26	43.22	47.07	43.22
2046	35.9	42.95	40.00	39.44	40.00	42.95	40.00
2047	34.0	38.64	36.64	36.50	36.64	38.64	36.64
2048	31.9	34.14	33.12	33.42	33.12	34.14	33.12
2049	29.8	29.45	29.45	30.20	29.45	29.45	29.45

Year	Chemicals Avg. Swiss plants	Eclépens	Siggenthal	Untervaz	Wildegg	Cornaux	Péry
2050	30.4	30.04	30.04	30.81	30.04	30.04	30.04
2051	31.0	30.64	30.64	31.42	30.64	30.64	30.64
2052	31.7	31.25	31.25	32.05	31.25	31.25	31.25
2053	32.3	31.88	31.88	32.69	31.88	31.88	31.88
2054	32.9	32.52	32.52	33.35	32.52	32.52	32.52
2055	33.6	33.17	33.17	34.01	33.17	33.17	33.17
2056	34.3	33.83	33.83	34.69	33.83	33.83	33.83
2057	35.0	34.51	34.51	35.39	34.51	34.51	34.51
2058	35.7	35.20	35.20	36.09	35.20	35.20	35.20
2059	36.4	35.90	35.90	36.82	35.90	35.90	35.90
2060	37.1	36.62	36.62	37.55	36.62	36.62	36.62
2061	37.8	37.35	37.35	38.30	37.35	37.35	37.35
2062	38.6	38.10	38.10	39.07	38.10	38.10	38.10
2063	39.4	38.86	38.86	39.85	38.86	38.86	38.86
2064	40.1	39.64	39.64	40.65	39.64	39.64	39.64
2065	41.0	40.43	40.43	41.46	40.43	40.43	40.43
2066	41.8	41.24	41.24	42.29	41.24	41.24	41.24
2067	42.6	42.06	42.06	43.14	42.06	42.06	42.06
2068	43.5	42.91	42.91	44.00	42.91	42.91	42.91
2069	44.3	43.76	43.76	44.88	43.76	43.76	43.76
2070	45.2	44.64	44.64	45.78	44.64	44.64	44.64
2071	46.1	45.53	45.53	46.69	45.53	45.53	45.53
2072	47.0	46.44	46.44	47.63	46.44	46.44	46.44
2073	48.0	47.37	47.37	48.58	47.37	47.37	47.37
2074	48.9	48.32	48.32	49.55	48.32	48.32	48.32
2075	49.9	49.29	49.29	50.54	49.29	49.29	49.29
2076	50.9	50.27	50.27	51.55	50.27	50.27	50.27
2077	51.9	51.28	51.28	52.58	51.28	51.28	51.28
2078	53.0	52.30	52.30	53.63	52.30	52.30	52.30
2079	54.0	53.35	53.35	54.71	53.35	53.35	53.35

Table 28 ROV model: Fuel costs in EUR/MJ. Based on BloombergNEF (2022), EAER (2022), ElCom (2022), Pahle et al. (2023), Thees et al. (2017), interviews, and own assumptions.

Year	**Electricity** (reference scenario)	**Electricity** (alternative scenario)	**Hard coal**	**Fuel Oil**	**Natural Gas**	**Biomass**	**Waste**	**Hydrogen**
2025	0.036	0.053	0.007	0.009	0.020	0.015	0.006	0.029
2026	0.035	0.053	0.006	0.009	0.015	0.016	0.006	0.030
2027	0.033	0.049	0.004	0.010	0.013	0.016	0.006	0.030
2028	0.030	0.044	0.004	0.010	0.012	0.016	0.006	0.031
2029	0.027	0.041	0.005	0.011	0.010	0.017	0.006	0.032
2030	0.027	0.041	0.005	0.011	0.009	0.017	0.006	0.032
2031	0.026	0.039	0.005	0.011	0.008	0.017	0.007	0.033
2032	0.027	0.040	0.005	0.011	0.007	0.018	0.007	0.034
2033	0.027	0.041	0.005	0.012	0.007	0.018	0.007	0.034
2034	0.027	0.041	0.005	0.012	0.008	0.018	0.007	0.035
2035	0.027	0.041	0.005	0.012	0.008	0.019	0.007	0.036
2036	0.029	0.043	0.005	0.012	0.009	0.019	0.007	0.036
2037	0.030	0.044	0.005	0.012	0.009	0.019	0.007	0.037
2038	0.030	0.045	0.005	0.012	0.009	0.020	0.007	0.038
2039	0.031	0.046	0.005	0.012	0.009	0.020	0.008	0.039
2040	0.032	0.048	0.005	0.012	0.011	0.021	0.008	0.039
2041	0.032	0.049	0.006	0.012	0.011	0.021	0.008	0.040
2042	0.034	0.051	0.006	0.012	0.013	0.021	0.008	0.041
2043	0.034	0.051	0.006	0.012	0.014	0.022	0.008	0.042
2044	0.034	0.052	0.006	0.012	0.016	0.022	0.008	0.043
2045	0.035	0.052	0.006	0.013	0.016	0.023	0.009	0.043
2046	0.036	0.054	0.006	0.013	0.017	0.023	0.009	0.044
2047	0.037	0.055	0.006	0.013	0.018	0.024	0.009	0.045
2048	0.037	0.055	0.007	0.013	0.019	0.024	0.009	0.046
2049	0.038	0.057	0.007	0.013	0.021	0.025	0.009	0.047
2050	0.039	0.059	0.007	0.013	0.023	0.025	0.009	0.048
2051	0.040	0.060	0.007	0.013	0.024	0.026	0.010	0.049
2052	0.041	0.061	0.007	0.013	0.024	0.026	0.010	0.050
2053	0.042	0.063	0.007	0.013	0.025	0.027	0.010	0.051
2054	0.043	0.064	0.008	0.014	0.025	0.027	0.010	0.052
2055	0.043	0.065	0.008	0.014	0.026	0.028	0.010	0.053
2056	0.044	0.066	0.008	0.014	0.026	0.028	0.011	0.054
2057	0.045	0.068	0.008	0.015	0.027	0.029	0.011	0.055
2058	0.046	0.069	0.008	0.015	0.027	0.029	0.011	0.056
2059	0.047	0.070	0.008	0.015	0.028	0.030	0.011	0.057
2060	0.048	0.072	0.008	0.015	0.028	0.031	0.012	0.058
2061	0.049	0.073	0.009	0.016	0.029	0.031	0.012	0.060
2062	0.050	0.075	0.009	0.016	0.029	0.032	0.012	0.061
2063	0.051	0.076	0.009	0.016	0.030	0.033	0.012	0.062
2064	0.052	0.078	0.009	0.017	0.031	0.033	0.013	0.063
2065	0.053	0.079	0.009	0.017	0.031	0.034	0.013	0.065
2066	0.054	0.081	0.010	0.017	0.032	0.034	0.013	0.066
2067	0.055	0.082	0.010	0.018	0.032	0.035	0.013	0.067
2068	0.056	0.084	0.010	0.018	0.033	0.036	0.014	0.069
2069	0.057	0.086	0.010	0.018	0.034	0.037	0.014	0.070
2070	0.058	0.088	0.010	0.019	0.034	0.037	0.014	0.071
2071	0.060	0.089	0.011	0.019	0.035	0.038	0.014	0.073
2072	0.061	0.091	0.011	0.020	0.036	0.039	0.015	0.074
2073	0.062	0.093	0.011	0.020	0.036	0.040	0.015	0.076
2074	0.063	0.095	0.011	0.020	0.037	0.040	0.015	0.077
2075	0.064	0.097	0.011	0.021	0.038	0.041	0.016	0.079
2076	0.066	0.099	0.012	0.021	0.039	0.042	0.016	0.080
2077	0.067	0.101	0.012	0.022	0.039	0.043	0.016	0.082
2078	0.068	0.103	0.012	0.022	0.040	0.044	0.017	0.084
2079	0.070	0.105	0.012	0.023	0.041	0.045	0.017	0.085

Table 29 ROV model: EU ETS price assumptions in EUR_{2023}/t_{CO2}. Five-year values between 2025 and 2070 based on Pahle et al. (2023). Yearly values were linearly interpolated and values after 2070 inflated. Note that Pahle et al. refer to the alternative scenario as "reference scenario" and to the reference scenario as "reform scenario" as their work was published before the reform was passed.

Year	ETS price [EUR_{2023}/t_{CO2}] (reference scenario)	ETS Price [EUR_{2023}/t_{CO2}] (alternative scenario)	Year	ETS price [EUR_{2023}/t_{CO2}] (reference scenario)	ETS Price [EUR_{2023}/t_{CO2}] (alternative scenario)
2025	125	39	2053	511	158
2026	132	41	2054	535	166
2027	139	43	2055	560	173
2028	146	45	2056	563	264
2029	153	47	2057	566	354
2030	160	50	2058	568	445
2031	170	52	2059	571	536
2032	179	55	2060	574	626
2033	188	58	2061	579	626
2034	197	61	2062	585	626
2035	206	64	2063	590	626
2036	218	67	2064	596	626
2037	229	71	2065	601	626
2038	241	75	2066	614	628
2039	253	78	2067	626	630
2040	265	82	2068	639	633
2041	280	87	2069	652	635
2042	295	91	2070	664	637
2043	310	96	2071	678	650
2044	325	101	2072	691	663
2045	340	105	2073	705	676
2046	359	111	2074	719	689
2047	378	117	2075	734	703
2048	398	123	2076	748	717
2049	417	129	2077	763	732
2050	436	135	2078	778	746
2051	461	143	2079	794	761
2052	486	150			

9.2 Detailed ROV model

9.2 Detailed ROV model

Contents

1 ROV model

1.1 Modelling framework

A model is developed and implemented in Python, which calculates if and when in the future different plants were to pursue decarbonization measures. Compared to a regular net present value (NPV) approach, it performs real options valuation (ROV).

In each scenario $sc \in SC$ and period $t \in T$ of length l_t each plant $p \in P$ takes the irreversible decision $d \in D_p$[1] that maximizes its expected profits over all modelled years $y \in Y$ by either reducing its emissions and associated emissions costs through one or a combination of decarbonization measures, or by waiting and emitting as before (cf. Section 1.6). Each plant's decisions are, however, completely independent of the decisions of other plants. For a decision to be taken it has to meet two necessary conditions, referred to as the *payback criterion* and the *NPV criterion* (cf. Sections 1.2 and 1.3, respectively). The models ROV-logic takes into account the value of the option to wait (cf. Section 1.4), which goes back to the model's logic that, starting from a *reference* scenario in the first period, the scenario (i.e., the investment environment) can transition between two subsequent periods (cf. Section 1.5). Scenario transitions are modelled to influence the cash flows resulting from each decarbonization measure (cf. Section 1.7. In addition, also policy instruments and mixes are modelled to influence cash flows (cf. Section 1.8).

1.2 Payback criterion

First, any decision is only considered if its payback time meets a defined, plant-specific threshold c_p as specified in Eq 1 (*payback criterion*)

$$NPV^{sc}_{t,p,d} = \begin{cases} NPV^{sc}_{t,p,d} & \text{if } NPV'^{sc}_{t,p,d}(c_p) \geq 0 \\ 0 & otherwise \end{cases} \tag{1}$$

where the net present value $NPV^{sc}_{t,p,d}$ is defined as the sum of discounted future cash flows CF until the end of the modelling horizon, which are weighted for all future scenarios as specified in Eq 2. $NPV^{sc}_{t,p,d}$ structurally differs for different t. For $t = |T|$, which represents the ultimate period to invest in, CF is certain as no further scenario transitions are assumed to occur. For $t = |T| - 1$, the penultimate period, CF is the sum of certain CF until and uncertain CF after the unknown ultimate scenario transition. Analogously, for $t < |T| - 1$, CF are a sum of certain and uncertain CF.

[1] D differs by plant p due to plant-specific restrictions. In the case of the Swiss chemical and pharmaceutical industry, e.g., some plants are limited to applying CCS as they are incinerating chemical waste and therefore cannot easily switch fuels or electrify heat generation.

$$NPV^{sc}_{t,p,d} = \begin{cases} \sum_{j=t+1}^{|T|-1} \rho_{p,(j-t)l} \sum_{sc' \in SC} (g'^{t,sc}_{j,sc'} \sum_{y=0}^{l-1} \rho_{p,y} CF^{i}_{y+jl,p,d}) & \\ \quad + \rho_{p,l'} \sum_{sc' \in SC} (g'^{t,sc}_{|T|,sc'} \sum_{y=0}^{l''-1} \rho_{p,y} CF^{i}_{y+l',p,d}) & \\ \quad + \sum_{y=0}^{l-1} \rho_{p,y} CF^{sc}_{y,p,d} & \text{if } t < |T|-1 \\ \rho_{p,(|T|-t)l} \sum_{sc' \in SC} (g'^{t,sc}_{|T|,sc'} \sum_{y=0}^{l''-1} \rho_{p,y} CF^{i}_{y+l,p,d}) & \\ \quad + \sum_{y=0}^{l-1} \rho_{p,y} CF^{sc}_{y,p,d} & \text{if } t = |T|-1 \\ \sum_{y=0}^{l''-1} \rho_{p,y} CF^{sc}_{y,p,d}) & \text{if } t = |T| \end{cases} \tag{2}$$

l' is defined in Eq 3 as the time between t and the ultimate decisions. l'' is defined in Eq 4 as the time between between the ultimate decision an the end of the modelling horizon. $NPV'^{sc}_{t,p,d}$ is defined in Eq 5 as the sum of discounted cash flows over c_p years. $g'^{t,sc}_{j,sc'}$ is defined in Eq 6 as the probability of a transition from scenario sc in period t to scenario sc' in a future period j (cf. Section 1.5 for details).

$$l' = (|T| - t)l \tag{3}$$

$$l'' = |Y| - |T|l \tag{4}$$

$$NPV'^{sc}_{t,p,d}(c_p) = \sum_{y=1}^{c_p} \rho_{p,y} CF^{sc}_{y,p,d} \tag{5}$$

$$g'^{t,sc}_{j,sc'} = \begin{cases} g^{sc}_{t,sc'} & \text{if } j = t+1 \\ \sum_{sc_1=1}^{SC} g^{sc}_{t,sc_1} \, g^{sc_1}_{t+1,sc'} & \text{if } j = t+2 \\ \sum_{sc_2=1}^{SC} \sum_{sc_1=1}^{SC} g^{sc}_{t,sc_1} \, g^{sc_1}_{t+1,sc_2} \, g^{sc_2}_{t+2,sc'} & \text{if } j = t+3 \\ \sum_{sc_3=1}^{SC} \sum_{sc_2=1}^{SC} \sum_{sc_1=1}^{SC} g^{sc}_{t,sc_1} \, g^{sc_1}_{t+1,sc_2} \, g^{sc_2}_{t+2,sc_3} \, g^{sc_3}_{t+3,sc'} & \text{if } j = t+4 \\ \sum_{sc_4=1}^{SC} \sum_{sc_3=1}^{SC} \sum_{sc_2=1}^{SC} \sum_{sc_1=1}^{SC} g^{sc}_{t,sc_1} \, g^{sc_1}_{t+1,sc_2} \, g^{sc_2}_{t+2,sc_3} \, g^{sc_3}_{t+3,sc_4} \, g^{sc_4}_{t+4,sc'} & \text{if } j = t+5 \end{cases} \tag{6}$$

The discount factor $\rho_{p,y}$ is defined based on the plant-specific discount rate r_p and the number of years y to discount for as specified in Eq 7

$$\rho_{p,y} = \frac{1}{(1+r_p)^y} \tag{7}$$

and $|Y|$ being defined as the total number of years modelled, which is the number of years between start and end of the modelling horizon, as specified in Eq 8

$$|Y| = Y_{end} - Y_{start} \tag{8}$$

In comparison to the NPV described in Eq 2 $NPV^{'}$, which is used to test the payback criterion, is assumed not to be a function of future uncertainties for the sake of simplicity.

1.3 NPV criterion

As plants are assumed to maximize their profits, the decision taken per period and plant has the highest net present value $\overline{NPV}$ of all decisions $D_{t,p}$ as specified in Eq 10 (*NPV criterion*)

$$\overline{NPV}^{sc}_{t,p} = \max_{d \in D_{t,p}} \overline{NPV}^{sc}_{t,p,d} \tag{9}$$

$$NPV_{t,tech} = \max_{tech \in D, t \in T} NPV_{t,tech} \tag{10}$$

where the $\overline{NPV}$ is defined as the NPV including the option value $V^{sc}_{t,p,d}$ of taking decisions in the next period $t+1$ after having taken decision d in t as specified in Eq 11

$$\overline{NPV}^{sc}_{t,p,d} = NPV^{sc}_{t,p,d} + V^{sc}_{t,p,d} \tag{11}$$

1.4 Option values

The option value $V^{sc}_{t,p,d}$ is defined as zero for the last period in which plants take decisions ($t = |T|$). For all $t < |T|$ it is defined as the scenario-weighted maximum of all $\overline{NPV}$ of decisions D in $t+1$ corrected for $NPV^{''sc}_{t,p}$ and discounted by the discount factor $\rho_{p,l}$ as specified in Eq 12

$$V^{sc}_{t,p,d} = \begin{cases} \rho_{p,l} \sum\limits_{sc' \in SC} g^{sc}_{t,sc'} \max\limits_{\bar{d} \in D(d)} (\overline{NPV}^{sc'}_{t+1,p}(\bar{d}) - NPV^{''sc}_{t,p}(d)) & \textbf{if } t < |T| \\ 0 & \textbf{if } t = |T| \end{cases} \tag{12}$$

with the $NPV^{''sc}_{t,p}(d))$ being a term that corrects for double counting in case of interdependent, staggered investments (cf. Section 1.6 and Eq 15).

1.5 Scenarios, uncertainties and transition probabilities

Each scenario is defined by a combination of three uncertainties with two binary states each: reference or ref and alternative or alt (cf. Table 2). The three uncertainties are: Reductions in capital expenditures, as modelled through uncertainty 1, change the specific capital expenditures as shown in Eq 31. A slump in the applied carbon price, as modelled through uncertainty 2, change the specific cost associated with emitting a ton of CO_2 as shown in Eq 29. Changes in the availability of the CO_2 transport infrastructure and increases in the electricity price, as modelled through uncertainty 3, change the specific transport and storage costs or specific electricity costs as shown in Eq 35 and 33, respectively.

Scenario sc	Uncertainty n		
	First	Second	Third
1	alt	alt	alt
2	alt	alt	ref
3	alt	ref	alt
4	alt	ref	ref
5	ref	alt	alt
6	ref	alt	ref
7	ref	ref	alt
8	ref	ref	ref

Table 1: Definition of scenarios

In Eq 12 the maximum in each scenario is weighted by the probability $g^{sc}_{t,sc'}$ of a transition from scenario sc in t to scenario sc' in period $t+1$ as the underlying scenario can change between the two periods. $g^{sc}_{t,sc'}$ is defined as the product of individual transition probabilities $\bar{g}^{sc}_{n,t,sc'}$ $n \in N$ that describe the probability for one of the defined $|N|$ states each as specified in Eq 13 and visualized in Table 2

$$g^{sc}_{t,sc'} = \prod_{n \in N} \bar{g}^{sc}_{n,t,sc'} \tag{13}$$

Transition from scenario sc...	Transition to scenario sc' ...							
	1	2	3	4	5	6	7	8
1	1	0	0	0	0	0	0	0
2	γ_t	$\tilde{\gamma}_t$	0	0	0	0	0	0
3	β_t	0	$\tilde{\beta}_t$	0	0	0	0	0
4	$\beta_t\gamma_t$	$\beta_t\tilde{\gamma}_t$	$\tilde{\beta}_t\gamma_t$	$\tilde{\beta}_t\tilde{\gamma}_t$	0	0	0	0
5	α_t	0	0	0	$\tilde{\alpha}_t$	0	0	0
6	$\alpha_t \quad \gamma_t$	$\alpha_t \quad \tilde{\gamma}_t$	0	0	$\tilde{\alpha}_t \quad \gamma_t$	$\tilde{\alpha}_t \quad \tilde{\gamma}_t$	0	0
7	$\alpha_t\beta_t$	$\alpha_t\beta_t$	$\alpha_t\tilde{\beta}_t$	0	$\tilde{\alpha}_t\beta_t$	0	$\tilde{\alpha}_t\tilde{\beta}_t$	0
8	$\alpha_t\beta_t\gamma_t$	$\alpha_t\beta_t\tilde{\gamma}_t$	$\alpha_t\tilde{\beta}_t\gamma_t$	$\alpha_t\tilde{\beta}_t\tilde{\gamma}_t$	$\tilde{\alpha}_t\beta_t\gamma_t$	$\tilde{\alpha}_t\beta_t\tilde{\gamma}_t$	$\tilde{\alpha}_t\tilde{\beta}_t\gamma_t$	$\tilde{\alpha}_t\tilde{\beta}_t\tilde{\gamma}_t$

Table 2: Combined transition probabilities for time step t

The individual transition probabilities $\bar{g}^{sc}_{n,t,sc'}$ for each state $n \in N$ are defined in Eq 14a, 14b and 14c

$$\bar{g}^{sc}_{1,t,sc'} = \begin{cases} 0 & \text{if } sc \in \{1,2,3,4\} \wedge \; sc' \in \{5,6,7,8\} \\ 1 & \text{if } sc \in \{1,2,3,4\} \wedge \; sc' \in \{1,2,3,4\} \\ \alpha_t & \text{if } sc \in \{5,6,7,8\} \wedge \; sc' \in \{1,2,3,4\} \\ \tilde{\alpha}_t & \text{if } sc \in \{5,6,7,8\} \wedge \; sc' \in \{5,6,7,8\} \end{cases} \tag{14a}$$

$$\bar{g}^{sc}_{2,t,sc'} = \begin{cases} 0 & \text{if } sc \in \{1,2,5,6\} \wedge \; sc' \in \{3,4,7,8\} \\ 1 & \text{if } sc \in \{1,2,5,6\} \wedge \; sc' \in \{1,2,5,6\} \\ \beta_t & \text{if } sc \in \{3,4,7,8\} \wedge \; sc' \in \{1,2,5,6\} \\ \tilde{\beta}_t & \text{if } sc \in \{3,4,7,8\} \wedge \; sc' \in \{3,4,7,8\} \end{cases} \tag{14b}$$

$$\bar{g}^{sc}_{3,t,sc'} = \begin{cases} 0 & \text{if } sc \in \{1,3,5,7\} \wedge \ sc' \in \{2,4,6,8\} \\ 1 & \text{if } sc \in \{1,3,5,7\} \wedge \ sc' \in \{1,3,5,7\} \\ \gamma_t & \text{if } sc \in \{2,4,6,8\} \wedge \ sc' \in \{1,3,5,7\} \\ \tilde{\gamma}_t & \text{if } sc \in \{2,4,6,8\} \wedge \ sc' \in \{2,4,6,8\} \end{cases} \tag{14c}$$

with α_t, β_t and γ_t being defined as the probability to transition from a *reference* to an *alternative* state between period t and period $t+1$ for uncertainty 1, 2 and 3, respectively. Accordingly, the probabilities of staying at the reference state, i.e., $\tilde{\alpha}_t$, $\tilde{\beta}_t$ and $\tilde{\gamma}_t$, are defined as $1-\alpha$, $1-\beta$ and $1-\gamma$, respectively. Only uni-directional changes are assumed, i.e., the probability of a transition from the alternative to the reference state is always zero and as a consequence that of staying at the alternative state always one. Transitions are assumed uni-directional as (i) once improved, technologies will not do a step back, as (ii) once loosened, EU climate policy regaining trust is difficult to imagine and as (iii) once built, CO_2 infrastructure is assumed to stay operational.

1.6 Decarbonization measures, decisions and staggered measures

The decarbonization measures modelled are: (1) Carbon capture and storage (CCS), (2) a switch to biomass (BIO), (3) a switch to hydrogen (H2) and (4) an electrification (EL). Heat generation from gas is assumed the incumbent technology.

With those four different individual decarbonization measures available there are theoretically 16 possible combinations (2^4), of which, however, only six are practical: The four individual solutions as well as the combination of CCS with BIO or H2, respectively. In addition to those six, staggered investments are modelled, i.e., after a plant invested in CCS it can still invest in BIO or H2 afterwards. Vice versa, after a BIO or H2 investments, plants can still add CCS resulting in 14 conceivable decisions as shown in 3 and 1.

Decisions D	Decarbonization measure			
	CCS	BIO	H2	EL
1	0	0	0	0
2	1	0	0	0
3	0	1	0	0
4	0	0	1	0
5	0	0	0	1
6	1	1	0	0
7	1	0	1	0
8	1	x	0	0
9	1	0	x	0
10	x	1	0	0
11	x	0	1	0
12	x	0	0	0
13	0	x	0	0
14	0	0	x	0

Table 3: Definition of decisions. 0 indicates a particular measure is not part of the decision, 1 indicates it is part of a decision, and an x indicates it was pursued in a period before.

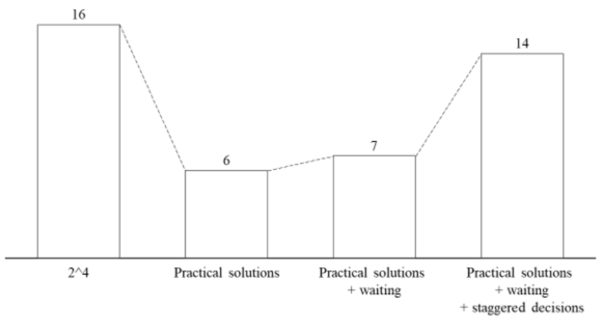

Figure 1: 14 different decision are modelled

The correction term NPV'' is subtracted from each $\overline{NPV}$ as the measure taken in period $t+1$ effects that of a decision taken in period t

$$NPV''^{sc}_{t,p,d} = NPV^{sc}_{t,p,d} \text{ substituting } y = y + 5 \tag{15}$$

In Eq 12 $D_t(d)$ denotes the available decisions in period $t+1$ if decision d was taken in period t. Table 3 includes a list of all 14 decisions with a 0 indicating that a particular measure is not part of the decision, a 1 indicating it is part of a decision, and an x indicating that it was pursued in a period before t. If a plant waited ($d = 1$) in period t it can still pursue decisions 1-7 in period $t+1$. If a plant pursed the decision CCS in period t ($d = 2$) or any period before ($d = 12$), it can still do BIO ($d = 10$), H2 ($d = 11$) or wait ($d = 12$) in period $t+1$. Whereas if a plant took the decision BIO in period t ($d = 3$) or any period before ($d = 13$), it can still do CCS ($d = 8$) or wait ($d = 13$) in period $t+1$. Similarly, if a plant took decision H2 in period t ($d = 4$) or any period before ($d = 14$), it can still do CCS ($d = 9$) or wait ($d = 14$) in period $t+1$. After pursuing either the decision EL ($d = 5$) or a combination of two decisions ($d = [6, 11]$), however, no additional decisions are assumed to be available. Eq 16 summarizes possible staggered investments.

$$D(d) = \begin{cases} [1,7] & \text{if } d = 1 \\ [10,12] & \text{if } d \in \{2,12\} \\ \{8,13\} & \text{if } d \in \{3,13\} \\ \{9,14\} & \text{if } d \in \{4,14\} \\ \{\} & \text{if } d \in [5,11] \end{cases} \tag{16}$$

1.7 Cash flow and cost components

The cash flow $CF^{sc}_{y,p,d}$ per year is defined in Eq 17 as the difference between relative savings $\Delta S^{sc}_{y,p,d}$ and relative costs $\Delta C^{sc}_{y,p,d}$ with savings and costs being defined relative to a business as usual case that assumes heat generation based on natural gas prior to any decarbonization measure

$$CF^{sc}_{y,p,d} = \Delta S^{sc}_{y,p,d} - \Delta C^{sc}_{y,p,d} \tag{17}$$

1.7.1 Savings

The relative savings per year are defined in Eq 18 as the product of the difference in absolute emissions $\Delta E_{y,p,d}$ and the applied carbon price $b^{sc,\phi}_{y,p,d}$

$$\Delta S^{sc}_{y,p,d} = \Delta E_{y,p,d}\, b^{sc,\phi}_{y,p,d} \tag{18}$$

with the difference in absolute emissions being defined in Eq 19 as the product of the difference in specific emissions $\Delta e_{y,p,d}$ and the plant size (represented by the yearly heat demand h_p)

$$\Delta E_{y,p,d} = h_p\, \Delta e_{y,p,d} \tag{19}$$

where $\Delta e_{y,p,d}$ is defined in Eq 20 as the sum of process- and fuel-related emissions[2] and $\Delta e^{fuel}_{y,p,d}$ is defined in Eq 21 as the sum of all fuels constituents' $f \in F_d$ emission factors ef_f weighted by their shares per decision $\Delta s_{f,d}$ (relative to the incumbent technology, i.e., gas) and corrected for the efficiencies of the constituents and decisions $\eta_{f,d}$.

$$\Delta e_{y,p,d} = \Delta e^{proc}_{y,p,d} + \Delta e^{fuel}_{y,p,d} \tag{20}$$

$$\Delta e^{fuel}_{y,p,d} = \sum_{f \in F_d} \frac{ef_f}{\eta_f}\, \Delta s_{f,y,p,d} \tag{21}$$

1.7.2 Costs

Relative yearly costs are defined in Eq 22

$$\Delta c^{sc}_{y,po} = \Delta I^{sc}_{y,p,d} + \Delta FU^{sc}_{y,p,d} + \Delta OM^{sc}_{y,p,d} + \Delta ST^{sc}_{y,p,d} \tag{22}$$

where ΔI, ΔFU, ΔOM, and ΔST represent the investment, fuel, operations & maintenance, and CO_2 storage & transport costs relative to business as usual, respectively. It can be broken down further using Eq 23-26

$$\Delta I^{sc}_{y,p,d} = H_p\, \Delta i^{sc}_{y,p,d} \tag{23}$$

$$\Delta FU^{sc}_{y,p,d} = \frac{h_p}{\eta_o} \Delta fu^{sc}_{y,p,d} \tag{24}$$

$$\Delta OM_{y,p,d} = H_p\, \Delta om_{y,p,d} \tag{25}$$

$$\Delta ST_{y,p,d} = e_{capt_{y,p,d}} \Delta st^{sc}_{y,p,d} \tag{26}$$

leading to

$$\Delta c^{sc}_{y,p,d} = H_p\, \Delta i^{sc,\chi}_{y,p,d} + \frac{h_p}{\eta_o} \Delta fu^{sc,chi}_{y,p,d} + H_p\, \Delta om_{y,p,d} + e_{capt_{y,p,d}} \Delta st^{sc}_{y,p,d} \tag{27}$$

$$H_p = \frac{h_p}{FL_p} \tag{28}$$

[2] For the Swiss chemical and pharmaceutical industry we limit the analysis to fuel-related emissions from heat generation. Accordingly, $\Delta e^{proc}_{y,p,d}$ is assumed to be zero.

1.8 Policy interventions

Four different policy interventions could be modelled. For each policy a set of parameters have to be defined, among others, the time frame it is applied, the level of CCfD/subsidy/tax exemption, decarbonization measures it applies to, and whether/how it interacts with the uncertainties (e.g., is a CAPEX subsidy always applied, or only if CAPEX do not see cost declines). The interventions are operationalized as follows.

1.8.1 Carbon Contract for Difference

$$b_{y,p,d}^{sc,\phi} = \begin{cases} b_{y,p} & \text{if } \phi_y = 0 \wedge sc \in \{3,4,7,8\} \\ b_{y,p} & \text{if } \phi_y = 1 \wedge sc \in \{3,4,7,8\} \wedge d \notin D_\phi \\ b_{y,p}^{*} & \text{if } \phi_y = 0 \wedge sc \in \{1,2,5,6\} \\ b_{y,p}^{*} & \text{if } \phi_y = 1 \wedge sc \in \{1,2,5,6\} \wedge d \notin D_\phi \\ b_{y,p}^{**} & \text{if } \phi_y = 1 \wedge d \in D_\phi \end{cases} \tag{29}$$

$$D_\phi = \{2\} \cup [6, 12] \tag{30}$$

with $b_{y,p}$ being defined as the reference price that applies in scenarios 3, 4, 7 and 8 if no carbon price support policy applies ($\phi_y = 0$), or if a carbon price support policy applies but the decision d is not eligible for the policy ($d \notin D_\phi$). b_y^* is defined analogously as the alternative price that applies in scenarios 1, 2, 5 and 6 if no carbon price support policy applies ($\phi_y = 0$) or if a carbon price support policy applies ($\phi_y = 1$) but decision d is not eligible for the policy ($d \notin D_\phi$). In the presented results all decisions involving CCS are assumed eligible (cf. Eq 30). On the contrary, $b_{y,p}^{**}$ is a defined price, which applies if a carbon price support policy applies ($\phi_y = 1$) and d is eligible for support ($d \in D_\phi$).

1.8.2 Investment subsidy

tbd, defined analogously to the CCfD one.

$$i_{y,d}^{sc,\chi} = \begin{cases} i_y & \text{if } \chi_y = 0 \wedge sc \in \{5,6,7,8\} \\ i_y & \text{if } \chi_y = 1 \wedge sc \in \{5,6,7,8\} \wedge d \notin D_\chi \\ i_y^{*} & \text{if } \chi_y = 0 \wedge sc \in \{1,2,3,4\} \\ i_y^{*} & \text{if } \chi_y = 1 \wedge sc \in \{1,2,3,4\} \wedge d \notin D_\chi \\ i_y^{**} & \text{if } \chi_y = 1 \wedge d \in D_\chi \end{cases} \tag{31}$$

$$D_\chi = \{2, 5, 6, 7, 8, 9\} \tag{32}$$

1.8.3 Fuel tax

tbd, defined analogously to the CCfD one.

$$fu_{y,p,d}^{sc,\psi} = \begin{cases} fu_{elec} & \text{if } \psi_y = 0,\ sc \in \{2,4,6,8\} \vee \upsilon = 1 \\ fu_{elec}^{*} & \text{if } \psi_y = 0,\ sc \in \{1,3,5,7\} \wedge \upsilon = 0 \\ fu_{elec}^{**} & \text{if } \psi_y = 1,\ \forall\, sc,\ \forall\, \upsilon \end{cases} \tag{33}$$

$$D_\psi = D \tag{34}$$

with υ being zero in case the third uncertainty is assumed to be a change in electricity price and υ being 1 in case the it is assumed to be a change in CO_2 transport infrastructure.

1.8.4 CO_2 transport infrastructure

tbd, defined analogously to the CCfD one.

$$st_{y,p}^{sc,\omega} = \begin{cases} st_{y,p} & \text{if } \omega_y = 0,\ sc \in \{2,4,6,8\} \vee \upsilon = 0 \\ st_{y,p}^{*} & \text{if } \omega_y = 0,\ sc \in \{1,3,5,7\} \wedge \upsilon = 1 \\ st_{y,p}^{**} & \text{if } \omega_y = 1,\ \forall\ sc,\ \forall\ \upsilon \end{cases} \tag{35}$$

$$D_\omega = D \tag{36}$$