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CCUS Study: State of the Art and Pre-Feasibility at Alperia SpA

Analisi delle Tecnologie di Cattura e Utilizzo della CO_2 e applicazione in Alperia SpA

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Porque caminante no hay camino, se hace camino al andar; el camino que hasta aquí he recorrido me ha formado gracias a con quien lo he compartido.

A la Ma y el Pa por el apoyo incondicional; a mis hermanos; a la Cerda por los esenciales, siempre auténticos, consejos; a mis amigos de la facu de Córdoba que me afirmaron que los ingenieros ambientales somos particulares, por no decir especiales; y a la Miche, que hasta con 40°C a la sombra nos apoyamos mateando el arduo estudio de estos años.

Y aunque nadie leerá esta dedicatoria, a esta senda recorrida le pongo un punto final.

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Abstract

The global rise in atmospheric CO_2 levels and the increasing pressure from international agencies and local communities are compelling governments and companies to take action.

Alperia SpA positions itself as a pioneer for the Alto Adige region of Italy, with ambitious and challenging objectives and a clear sustainable strategy aimed at reducing both direct and indirect emissions. Given the nature of some of the plants comprising Alperia's infrastructure (natural gas power plants), Carbon Capture and Storage (CCS) emerges as a viable solution. This technology represents a rapid method for decarbonizing hard-to-abate industries.

This study aims to analyse the available technologies, alongside current European and Italian regulations, to determine the most suitable and cost-effective solution for mitigating the impact of Alperia's direct and indirect greenhouse gas emissions.

The input data for this study includes various directives and regulations pertinent to the topic; reports from IPCC, Global CCS Institute, and IEA, among others; data provided by Alperia SpA; and information from external technology providers. Subsequently, through analysis and numerical application, results were obtained based on both the current and projected future scenario of the Group.

Findings indicate that CCUS technologies are not feasible for all of Alperia's plants. The facilities with potential for such a project were identified based on their emission levels, operating hours, location, between others; Bolzano and Merano emerged as potential sites for project development. Furthermore, CO_2 storage in the Alto Adige appears unfeasible, and many proposed utilizations of the captured carbon are not attractive for the Group, mainly due to associated costs and the divergent nature of its activities. The most suitable option appears to be the sale/purchase of CO_2 to Eni-Snam for storage in their depleted gas field in the Adriatic, as part of the Ravenna CCS project. This approach could effectively address Alperia's impact due to its direct Scope 1 emissions.

Additionally, it was concluded that the Group could reduce its Scope 3 emissions (indirect emissions) by implementing an innovative business model ("carbon performance contracts") with its gas clients, wherein the CO_2 produced by these third parties would be managed by Alperia.

Abstract (Italian)

L’aumento dei livelli di CO_2 nell'atmosfera e della temperatura globale, nonché la crescente pressione da parte delle agenzie internazionali e delle comunità locali stanno spingendo governi e aziende ad agire.

Alperia S.p.A. si posiziona come pioniera nel territorio dell'Alto Adige, con obiettivi ambiziosi e sfidanti e un chiaro percorso sostenibile che mira a ridurre le proprie emissioni dirette e indirette. Data la natura di alcuni degli impianti che compongono l'infrastruttura di Alperia (quali centrali cogenerative alimentate a gas naturale), la Cattura e lo Stoccaggio dell’Anidride Carbonica (CCS) sembrano una soluzione praticabile per la riduzione delle emissioni di CO_2 in atmosfera. Questa tecnologia rappresenta un metodo rapido per decarbonizzare industrie del settore hard-to-abate.

Questo studio ha l’obbiettivo di analizzare le tecnologie disponibili, insieme alla regolamentazione europea e italiana, al fine di determinare la soluzione più adatta a livello di costo efficacia per mitigare l’impatto delle emissioni dirette e indirette di gas serra di Alperia.

I dati di input dello studio comprendono diverse direttive e regolamenti pertinenti all’argomento; rapporti dell’IPCC, del Global CCS Institute, dell’IEA, tra gli altri; dati forniti da Alperia S.p.A.; e informazioni provenienti da aziende esterne fornitrici di tecnologia. Successivamente, attraverso analisi specifiche e applicazioni numeriche, e sulla base della situazione attuale e futura del Gruppo, sono stati ottenuti i risultati.

I risultati indicano che le tecnologie di CCUS non sono fattibili per tutti gli impianti di Alperia. Gli impianti con potenzialità maggiori per un progetto di questo tipo sono stati individuati in base a emissioni, ore di funzionamento e ubicazione; gli impianti di teleriscaldamento di Bolzano e Merano sono stati identificati come siti potenziali per lo sviluppo del progetto. Inoltre, lo stoccaggio in Alto Adige non sembra possibile, e molte delle opzioni di utilizzo della CO_2 catturata non risultano attrattive per il Gruppo, principalmente a causa dei costi associati e della natura divergente delle attività. L’opzione più adatta sembra essere la compra/vendita della CO_2 da Eni-Snam per lo stoccaggio nel loro giacimento di gas esaurito nell’Adriatico (nell'ambito del progetto CCS di Ravenna). Questo approccio potrebbe ridurre l’impatto delle emissioni dirette di Scopo 1 generate da Alperia.

Inoltre, è stata anche analizzata la possibilità per il Gruppo di ridurre le proprie emissioni indirette di Scopo 3 attraverso un modello di business innovativo, “carbon performance contact”, da implementare con i propri clienti del gas, in cui la cattura e lo stoccaggio della CO_2 prodotta verrebbero gestiti da Alperia.

Climate Change

2023 was the warmest year ever registered. According to data from Copernicus Climate Change Service, the global mean temperature went over the 1.5ºC limit respect to pre-industrial levels for approximately 86 days. Also, the CO_2 global emissions from fossil fuels reach a new maximum peak (1.1% higher than 2022).

The effects of this increment can already be seen in day-by-day activities around the whole globe, making governments, enterprises and society start moving and coming together for limiting the impact global warming is generating. It is important to continue moving in this direction to limit the increment of the global mean temperature and ideally under the 2°C. Doing the best effort for not going over the threshold of 1.5°C, settled by the 2015 Paris Agreement. This objective was reiterated by the COP 28 (UNFCCC, United Nations Framework Convention on Climate Change), where, for the first time, the states have assumed the commitment of transition and progressive abandonment of fossil fuels.

The global power sector is in front of a challenge, it must meet the rising electricity demand while providing a low-carbon supply. Despite the rapid expansion of renewable energy generation, the vital role of electrification and the magnitude of the power sector emissions led to the necessity that countries reduce their emissions from power to meet these global climate goals.

It is relevant to highlight that the climate crisis is a global concern that requires the participation of all actors; a challenge to which also companies should take part, analysing their own environmental impacts, and the risks that climate change has over them. Without proper climate change mitigation and adaptation measurements, the companies will be exposed to financial, operative and legal risks as well as patrimonial damages.

In addition, power plants fuelled by coal and gas are still dominating the electricity market globally. They account for almost 2/3 of the world power generation a share that has remained relatively constant since 2000, reflecting the steady rise in global demand for power. While for the European Union the electricity production from fossil fuels in 2022 was of 39.2% and for Italy of 64.2% (Ember, 2024), tendencies that don't seem to decrease. Power is the largest carbon emitter in the energy sector, creating almost 40% of global energy-related emissions; emissions in 2019 from the power sector were only slightly below their 2018, all time high at 13.6 $GtCO_2$ (International Energy Agency [IEA], 2019).

European Energy Transition Strategy

The European Union in order to counteract the effects of climate change, made in 1990 the first step towards the reduction of GHG emissions by taking membership to the Kyoto Protocol. Later, in 2015, the Paris Agreement was signed, where participating States took the responsibility of limiting the temperature incrementation under 2°C respect to pre-industrial levels, with efforts to remain under the 1.5°C, aiming to reach the emissions peak as soon as possible and the Net Zero in the second half of the century. The Paris Agreement came into force in 2016, it is applied since 2021, and it integrates the 2030 Agenda for Sustainable Development (plan of action adopted at the United Nations Sustainable Development Summit in September 2015).

In this context, the European countries have taken compromise to reach the scope of climate neutrality by 2050 defining the European Green Deal strategy. The Green Deal puts into evidence the necessity of a holistic and transversal approach, where all the strategic sectors contribute to the final objective in climate matter. The package contains policy initiatives regarding climate, environment, energy, transport, industry, agriculture and sustainable finance. It contains the so called “The Fit for 55 package”, a set of proposals to revise and update EU legislation with the aim of ensuring that EU policies are into line with the climate goals. The main actions look to reduce the net GHG emissions at least at 55% by 2030, through the following measurements:

- A better gathering and sharing of data,
- Nature based solutions for creating resilience to climate change and protecting the ecosystems,
- Integration in the adaptation in the macro-fiscal politics.

For supporting a fare transition Europe has introduced a Found for a fare transition where support will be given to the regions that are more vulnerable to the transition towards a CO_2 low emission economy.

Also, a social Found for the climate has been created in 2022. Moreover, it has been achieved a provisory agreement about the Carbon Border Adjustment Mechanism (CBAM) that seeks to guarantee that the EU efforts on the emissions reduction don’t get compensated with an incrementation of the emissions outside its frontiers; through delocalization of industry in developing countries or through importing products with high carbon footprint.

Furthermore, different objectives have been adopted aiming to be reached by 2030; in 2023, the Counsil adopted new annual objectives regarding the GHG emissions at EU level; from 29% up to 40% respect to 2005 in the sectors involved. In the same year the Counsil adopted a revision of the directive regarding the promotion of renewable energies, with which intends to increase the actual scope of the EU until at least 32% of renewable energy sources in the energetic mix, taking it up to 40%. In the same way, the Energy Efficiency European Directive was review, raising the energy efficiency target to 11.7% compared to the projections of the EU reference scenario 2020. The Counsil and the Parliament settled a common normative for the internal market of renewable gas, natural gas and hydrogen with the aim to move from natural gas towards renewable and low carbon emission gas and to promote its diffusion in the EU also by 2030.

From September 2024 it has come into force the Directive number 2022/2464 Corporate Sustainability Reporting Directive under the European Green Deal, that settles the obligation of communicating the non-financial information for some organizations, specifically Environmental, Social and corporate Governance (ESG) factors for improving the monitoring of the business activities in an objective and shared way.

On February 26, 2025, the European Commission launched a legislative proposal to amend the above-mentioned Directive, introducing a "Simplified Omnibus Package." This initiative aims to simplify the regulatory framework for businesses and reduce reporting requirements, with the objective of decreasing administrative burdens by 25% for EU companies and by 35% for SMEs, thereby enhancing competitiveness and economic growth.

The proposal suggests extending the deadlines and implementation dates for the Corporate Sustainability Reporting Directive (CSRD), significantly reducing the number of companies subject to its requirements, though Alperia would still be included. Additionally, amendments are suggested to the Taxonomy Delegated Acts that would exempt certain companies from specific evaluations, potentially allowing Alperia to benefit from some of these simplifications.

Italy's Piano Nazionale Integrato per l'Energia e il Clima (PNIEC)

The PNIEC is the national plan that settles the politics and measures that Italy seeks to adopt for achieving the 2030 objectives in order to reduce emissions and achieve the climate neutrality by 2050 as foresee by the Paris Agreement. It has five intervention dimensions: decarbonization, energetic efficiency, energetic security, internal market of energy and research, innovation and competitiveness.

According to the national inventory on GHG emissions, the emissions relative to the energetic uses represent 81% of the total Italian emissions, equal to, in 2016, approximately 428 Mt CO_2eq. Because of this the PNIEC fixes a renewable capacity objective of 131 GW by 2030. Further on, foresees to go over the "FitFor55" objective for the industrial plants framed under ETS normative, arriving to a 66% reduction respect to 2005 levels (while EU has a 62% objective). A decrease in foreign energy dependence is observed, thanks to the diversification of the supply sources and the new infrastructure planification.

Piano Clima Alto Adige

Like many other cities and members of the EU, also the Alto Adige Italian Region, has recognized the need to implement the climate objectives settled by the COP 21, but in a faster way, fixing them for 2040 rather than 2050. For achieving so the Alto Adige climate plan aims to:

- reduce CO_2 emissions a 55% by 2030 and 70% by 2037 respect to 2019 levels. Achieving climate neutrality (achievement of net zero greenhouse gas emissions) by 2040;
- increase the renewable energy quote from 67% to 75% by 2030 and to 85% by 2037, arriving to 100% climate neutrality by 2040;
- reduce emissions from agriculture activity (CO_2, CH4, N2O), a 10% by 2030 and a 40% by the 2040 respect to 2019 levels;
- reduce the population poverty risk quote by 2030 a 5% respect to 2019 levels;
- increment over proportionally the Alto Adige economical quote in the climate transition emerging markets.

The Alto Adige wants to take the lead regarding the climate neutrality, nonetheless this transformation will require important investments from enterprises, public and private sector.

Alperia S.p.A. is a corporation that settles itself as the main provider of energy in the Alto Adige and the second hydroelectric energy producer in Italy. It provides 100% sustainable energetic services, producing clean energy from renewable sources (mainly hydroelectric, with the objective of increasing in the future the quote of photovoltaic, biomethane and hydrogen). Given the nature of its own business, pays attention to climate change and applies measures to make efficient consumption, reducing the emissions and increase the energy provision by renewable sources, orienting every time more the business towards sustainable services and products.

This way, Alperia intends to take part in the Alto Adige challenge by giving its own contributes through direct and indirect actions.

Alperia

Alperia manages 35 hydroelectric plants, 7 photovoltaic facilities and 7 direct heating facilities. It owns an electricity network of 9.348 kilometres that delivers energy to 400.000 clients. Furthermore, it participates in the RECs (Renewable Energy Communities), the smart mobility, the advisement to enterprises in decarbonization matters and the energetic transition.

The main goal of the Group is to give a sustainable shape to the energy of the future. For doing so it promotes an energetic development model that is respectful with the environment and takes a socially responsible position. The mission is to be part of the energetic transition, urgent theme no longer postponable.

For consenting the Climate Plan, Alperia verifies its greenhouse gas emissions and the relative compensation measurements in accordance with the GHG Protocol Corporate Standard. This Protocol settles the accounting principles intended to guide GHG accounting and reporting to ensure that reported information represents a faithful, true and fair account of the company's emissions.
The protocol defines three scopes for properly delineating direct and indirect emission sources as well as for improving transparency and ensuring that two or more companies won't make double accounting.

- Scope 1: direct ghg emissions generated by the installations located inside the confines of the organization and resulting from the usage of fossil fuels and other atmosphere emissions from other greenhouse gasses (CO_2 emissions generated from fuels burned in the plant for energetic production and originated from the company-owned fleet/vehicles).
- Scope 2: indirect ghg emissions resulting from the indirect usage (for example emissions generated by the acquisition of electrical energy from third-party supplier(s) but consumed in the Group facilities or locations).
- Scope 3: includes the emission sources that are not under the direct corporate control, but which emissions are indirectly result of the corporate's activities. This includes the upstream emissions like those generated by purchased goods and services or generated from the transportation of materials and people; but also, the downstream emissions like those generated from the usage of Alperia's products and services.

Alperia has a **sustainable vision**; it seeks to contribute with its activity and the proper solutions and measurements to the Sustainable Development Goals (SDGs) fixed by the United Nations. Further it has integrated the principles of the sustainable development into the business strategy, in detail, since 2022 three new main documents are part of the business strategies:

I. Vision 2031: It contains the objectives that Alperia intends to achieve in a mid-long term period from the analysis of the main trends in progress (scarcity of natural resources, digitalization and innovation acceleration, smart mobility development, increment in the geopolitical tension, climate change impact, etc.), the market evolution and the main risks for the business. The keystones of this vision are the sustainability and the integrated allocation in the energy value chain.

II. Piano Industriale 2023-2027: It indicates the path that Alperia must follow until 2027 where are detailed the objectives that it sees to achieve. Up to 2027 it intends to invest in the hydroelectric generation, distribution and direct heating, 560 million of euro. These investments should lead Alperia to the reduction of the 46% of the emissions by 2027 and the 70% by 2031 respect to 2021 levels, including emissions compensation in the cases of being inevitable and achieving the Net Zero by the year 2040.
These objectives are intended to be achieved by the following measures:

Scope 1:

- increment of the energy production from renewable sources
- moving to direct heating facilities fed with biomass or other sources with low carbon emissions or more efficient technologies
- implementation of efficiency measures inside the activities

Scope 2:

- full transition towards energy consumption from renewable sources
- reduction on the network losses

Scope 3:

- increase the sales of electricity from renewable sources
- Increase biomethane sales or of other green gasses.

III. Piano di Sostenibilità 2022-2027: Its objective is to evaluate, improve and implement all the corporate activities into a sustainable politic, strengthening the green development of the Group with clear key performance indicators for each strategic action area. These areas are: (1) Governance and resilience, (2) Clients, (3) Green Mission, (4) Territory and (5) People.

Adding to the mentioned strategies, Alperia, during 2023 improved monitoring and sent to validation the short and long term decarbonization targets to the Science Based Targets Initiative (SBTi), in order to align the climate strategy of the Group with the objectives of the Paris Agreement; since the SBTi is, by today, the only international standard for verifying that a company's decarbonization objectives are aligned with the mentioned Agreement. And, in addition, respecting the European Green Deal and the rectifying laws from the member states (Corporate Social Responsibility Directive, Piano Clima Alto Adige).
The SBTi targets for Alperia have as baseline the year 2022 and include the near-term objectives, to achieve by 2032:

I. Reduce scope 1 and 2 emissions from electricity and heat generation by a 76,7% per MWh.

II. Reduce scope 1 and 3 emissions from the electric energy production and sell by a 77,9% per MWh.
III. Reduce absolute scope 3 emissions from the use of fossil fuel sold products by a 50%.

While to achieve by 2040:

I. Reduce scope 1 and 2 emissions from electricity and heat generation by 93,96% per MWh.
II. Reduce scope 1 and 3 emissions related to electric energy production and sell by 94,4% per MWh.
III. Reduce absolute scope 3 emissions from the use of fossil fuel sold products by a 90%.

Under this situation Alperia defined a focus for the next years (2025-2032) where the Carbon Capture and Storage is intended to be applied from 2030, between other measures.

The compromise Alperia is taking is in continuous progress; only in 2023, approximately 1.7 million tCO_2 emissions were avoided and it intends to avoid, by 2027, 1.38 million tCO_2 emissions and, by 2031, 2.0 million tCO_2 emissions. All these goals are being achieved by the societies integrating Alperia.

The mentioned measures also contribute to the realization of the "Piano Clima-Energia Alto Adige" since Alperia is 46,38% owned by the Alto Adige region. Furthermore, the quote of the sales figures done with sustainable products and services increased from 31% in 2017 up to 71% in 2023.

Alperia's Emissions

The direct impacts Alperia accounts are given by the exercise of the hydroelectric plants, the direct heating and the electric energy distribution infrastructure.

For the emissions reduction, Alperia has been adopting a strategy that consists of:

- Monitoring: accurate and punctual calculations on the emissions production. The Group reports its emissions since 2016.
- Emissions reduction: develop and adopt new technologies that lead to emissions reduction; for example, converting the existing plants into biomass, developing projects of energetic efficiency.
- Compensation: take part into specific programs of climate protection for compensating the remaining emissions (Scope 1 and 2) and carry forward an initiative for developing an own compensation project. Since 2020 Alperia compensates the operative emissions with compensations activated through VCS and Gold Standard certificates.

For a better understanding of Alperia's current situation and where it is located respect to its scopes, the numbers in tonnes CO_2 equivalent (tCO_2e) for the different Scopes of the Industrial Plan are presented, recalling:

→ reduction of the 46% of the total emissions by 2027 with respect to 2021 levels,

→ reduction of the 70% of the total emissions by 2031 with respect to 2021 levels.

Emissions	2021	2022	2023	2024	2027	2031	2031 with CCS
SCOPE 1 (non biogenic+ biogenic)	61742,28	61726,25	92879,72	76705,25	90471,68	70829,56	70829,56
SCOPE 2 - location based	25474,31	1631,65	2435,28	4041,08	3850,37	3690,91	
SCOPE 2 - market based	21840,92	611,81	669,82	943,27	889,75	863,25	863,25
SCOPE 3	2871885,14	2390798,41	1622914,72	1781668,73	1547401,80	1214455,97	814947,69
Total emissions - market-based	2955468,34	2453136,47	1716464,26	1859317,25	1638763,24	1286148,79	886640,50

Variation respect to 2021 - without CCS	2021	2022	2023	2024	2027	2031	2031 with CCS
% variation SCOPO 1		-0,03%	50,43%	24,23%	46,53%	14,72%	14,72%
% variation SCOPO 2 (Market)		-97,20%	-96,93%	-95,68%	-95,93%	-96,05%	-96,05%
% variation SCOPO 3		-16,75%	-43,49%	-37,96%	-46,12%	-57,71%	-71,62%
% TOTAL variation		-17,00%	-41,92%	-37,09%	-44,55%	-56,48%	-70,00%
Total reduction tCO2e		502331,87	1239004,08	1096151,09	1316705,10	1669319,55	2068827,84

target	-46%	-70%
emissions reduction required tCO2e	-42810,33	-399508,29

Table 1: Environmental balance of Alperia with emissions category details, registered and predicted. For 2031, two scenarios are presented: one with and one without Carbon Capture and Storage (CCS)

Regarding emissions of Scope 1, an increment can be seen from year 2022 to year 2023, resulting from the incorporated cogeneration plants of the business units. After, a decrease can be seen due to reduction of fuel oil consumption and transition from natural gas to biofuels and electrification, and increased production efficiency. From year 2024 to 2027 emissions estimations increase because the Group has already signed the inclusion of a gas turbine in the Bolzano Hospital that will start working in 2026. Followed by a predicted decrease by 2031 because of the construction of a new biomass power plant in Merano.

The Scope 2 emission values remain approximately constant after the remarked decrease from 2021 to 2022 that results from a modification in the accounting methodology.

Over time, Scope 3 emissions have decreased, primarily due to the transition to exclusively selling renewable electricity and the decline in natural gas sales. This reduction is driven by electrification efforts and the shift towards alternative energy sources such as biomethane and hydrogen.

With the current plan in motion, emissions predictions show a total reduction of carbon dioxide of 44.5% by 2027 which is very close to the 46% fixed. While for the year 2031 the current strategies may not be sufficient, since the percentage calculated is of 56.5%, 13,5% away from the expected 70%.

In order to address this difference and reach the Industrial Plan objective for 2031, Carbon Capture Utilization and Storage (CCUS) is proposed as a potential strategy for reducing Alperia CO_2 emissions. For achieving the 70% by 2031, the Group should reduce its total emissions approximately a 400.000 tCO_2e over the already predicted reduction values for 2031.

The calculated reduction value has been applied to Scope 3 emissions, since is the category with the largest impact for Alperia. However, the reduction can be achieved through actions across different categories. Indeed, initially, this study will analyse the achievement of the decrease through the implementation of CCUS on the direct heating systems owned by Alperia, as these are the plants with direct GHG emissions and so corresponding to Scope 1 emissions. Afterwards, an alternative solution will be proposed where the accounting should be allocated under Scope 3 emissions, as it will represent the reduction of indirect emissions.
Nonetheless these allocations are hypothesis that depend on the forthcoming publications by the GHG Protocol regarding CCUS accounting.
Subsequently, the GHG Protocol will be analysed to better understand where the reductions can be allocated, without passing over that the 400 $ktCO_2eq$ include all types of GHG emissions.

Carbon Capture, Utilization and Storage (CCUS)

According to the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA), CCS plays a crucial role in facilitating the global transition to the net-zero emissions economy. It is a technically mature option for the sustainable use of fossil energy resources.

Despite the negative environmental impact, carbon dioxide gas is a valuable substance with diverse applications in different industries.

Carbon capture, utilization and storage (CCUS) covers a broad range of technologies that capture the carbon dioxide (CO_2) present in the flue gas and separate it from other gases that may compose it, rather than being emitted to the atmosphere. The flue gas may come for example from large point sources like power generation or industrial facilities that use either fossil fuels or biomass. If not being used on-site, the carbon dioxide will be compressed and transported by pipeline, ship, rail or truck to be used in a range of applications or injected into a storage site to be safely and permanently stored.

CCS includes both capturing CO_2 from large emission sources (point-source capture), directly from the atmosphere (DAC, Direct Air Capture) or bioenergy used with capture and storage (BECCS), (Möllersten, Yan and Moreira, 2003). This last one can yield net removal of CO_2 from the atmosphere because the CO_2 put into storage comes from biomass (burned for energy conversion) which has absorbed CO_2 from the atmosphere as it grew. Furthermore, CCU refers to the utilization of the captured CO_2 as raw material for manufacturing applications, methanol production or other types of applications.

CCUS has achieved remarkable development in the recent years, to mention, there are more than 30 CCUS programs in operation around the world. Among them, North America is dominated by CO_2 flooding, while in Europe, ocean storage of CO_2 is the main focus (Liu, Lu and Wang, 2023).
By 2040, 315 GW of electricity generation capacity is expected to be equipped with carbon capture, utilisation and storage; equivalent of adding about 15 GW CCUS capacity per year on average over the next two decades (IEA, 2019). In 2040, CCUS-equipped plants will generate 1900 TWh (5% of global power) up from approximately 470 TWh (1.5%) in 2030.

According to the CO_2RE Global CCS Institute facilities database, currently (2024) there are 60 operating commercial CCS facilities; includes, activities that capture CO_2 and transport it for permanent storage as part of an ongoing commercial operation; they generally have economic lives similar to the host facility whose CO_2 they capture; they must support a commercial return while operating and meet a regulatory requirement. Operational in 2024, 45 pilot/demonstration facilities. Deeper, these facilities capture CO_2 for testing, developing or demonstrating CCS technologies or processes; captured CO_2 may or may not be permanently stored; compared to commercial facilities these are short life in terms of the time required to complete test and development processes and they are not expected to have a commercial return during their operation.

Importance of CCUS technologies

CCUS has been taking wider attention in the last decades because of its large advantages.
It takes a key role in the clean energy transition through addressing the emissions from already existing fossil-fuel power plants; helping power networks to achieve electricity security goals and flexibility in the power systems and reducing the cost of energy sector decarbonisation in the hard-to-abate sectors through enabling negative emissions from power generation when combined with bioenergy (delivering near zero emissions heat and power generation from fossil fuels).

Carbon capture has consistently been identified as an integral part of a least-cost portfolio of technologies needed to support the transformation of power systems globally (Pratama and Mac Dowell, 2019). Because there are some countries where fossil fuel is likely to remain as the main power generation source, CCUS may be key to transform this generation into a low-carbon one. Also, renewable energies may not be an available option for certain sites due to different limitations like its larger requirement of land compared to CCUS-equipped power stations, leading to a different approach for pursuing the Net Zero objective.

Meeting long-term climate goals without applying carbon capture, utilisation and storage technologies in the power sector would require the virtual elimination of coal-fired power generation and, eventually, that of gas-fired generation as well.

Regarding the cost, even though CCUS technologies have major expenses to consider, renewable energies can be combined with energy storage technologies for achieving a cost-effectively displacement of the fossil energy.

CCS technology is technically mature and commercially available today. All elements of the CCS value chain have been demonstrated around the world for decades. The core technologies for the capture step were developed in the early part of the 20th century and are in regular commercial use today. Importantly, geologically sequestered CO_2 is, today, considered to be secure (Mac Dowell, Fennell, Shah and Maitland, 2017).

The International Energy Agency (IEA) Sustainable Development Scenario gives carbon capture technologies an important role for the transformation of the global energy system. Under the Energy Technology Perspectives 2012 (ETP 2012) 2 °C Scenario (2DS), CCS contributes one-sixth of CO_2 emission reductions required in 2050, and 14% of the cumulative emissions reductions between 2015 and 2050 compared to a business-as-usual approach, which would correspond to a 6 °C rise in average global temperature (IEA, 2013).

Technologies

In order to mitigate climate change there is a combination of known and emerging technologies that aim to capture and use or store carbon dioxide. In particular, it is the only technology available to mitigate the emissions from large-scale fossil fuel usage in fuel transformation, industry and power generation.

In 2009 the IEA presented a roadmap that details the scenario for the CCS technology's development with an update published in 2013. It aims at assisting governments and industries when integrating CCS as an emissions reduction strategy. Seven key actions are highlighted to be applied each year from 2020 in order to create a solid foundation for the deployment of CCS.

The individual component technologies required for capture, transport and storage are generally well understood and, in some cases, technologically mature. For example, capture of CO_2 from natural gas sweetening and hydrogen production is technically mature and commercially practiced, as is transport of CO_2 by pipelines. While safe and effective storage of CO_2 has been demonstrated, there is still much to learn from large-scale projects. However, the largest challenge for CCS deployment is the integration of component technologies into large-scale demonstration projects. Lack of understanding and acceptance of the technology by the public, as well as some energy and climate stakeholders, also contributes to delays and difficulties in deployment (IEA, 2013).

Capture Technologies

Regarding capture of carbon dioxide several solutions are currently being developed. The applicable CO_2 capture technique will depend on the combustion approach taken; post-combustion for the cases the CO_2 is captured from flue gasses after fuel combustion with air, oxy-fuel combustion when the flue gasses generate CO_2 after fuel combustion with oxygen or pre-combustion for the capture of CO_2 from a synthesis gas before fuel combustion. The technique chosen will be also a function of the required CO_2 purity level. The level and nature of impurities in the CO_2 stream can affect some capture processes that are sensitive to pollutants and can also be important for the further carbon dioxide transport and storage.

There is no consensus on which option will be the least costly in the future; each has pros and cons, and the costs appear to be comparable (Lecomte et al, 2017).

Post-combustion

This capture system can be applied to, in principle, flue gases produced from the combustion of any type of fuel (coal, natural gas, oil or biomass) in air. Consist of extracting the CO_2 that is diluted in the combustion flue gas, which is then fed to a storage reservoir and the remaining gas is discharged into the atmosphere. The solvents for CO_2 post-combustion capture can be physical, chemical, or intermediate. Chemical solvents, such as amines, are most likely to be used.

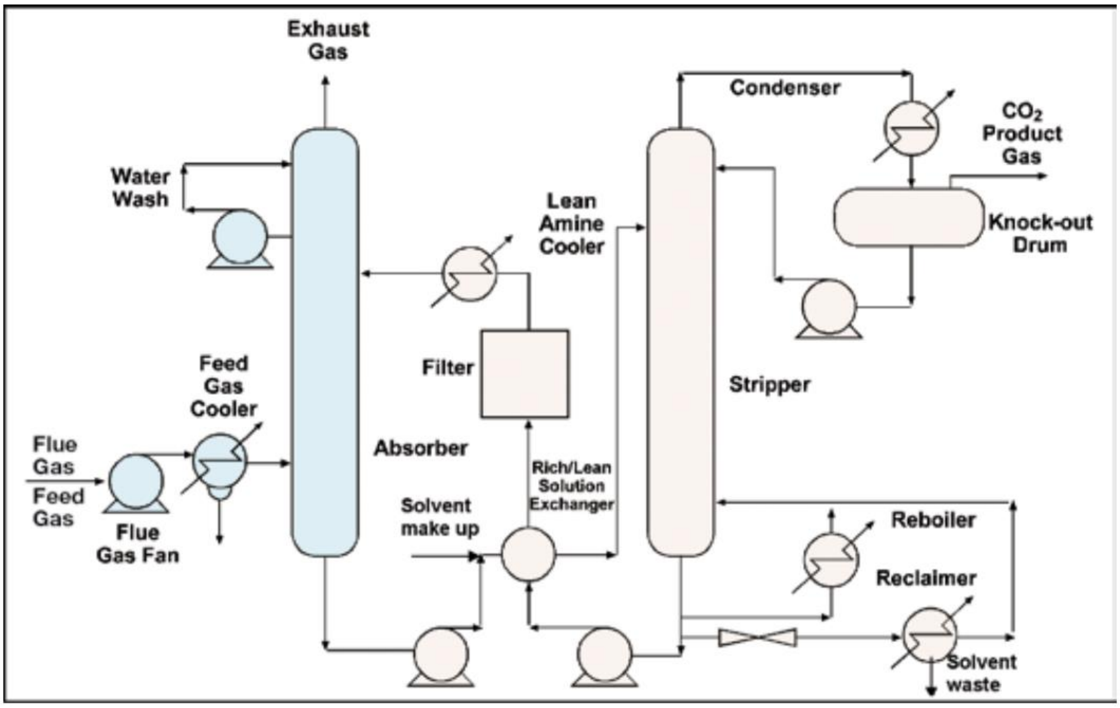

Figure 1: Process flow diagram for CO_2 recovery from flue gas by chemical absorption. Source: IPCC report on CCS

I) Absorption processes: it makes use of the reversible nature of the chemical reaction of an aqueous alkaline solvent with an acid or sour gas. The flue gas is cooled and then brought into contact with a solvent in the absorber, CO_2 is bound by the chemical solvent in the absorber. The flue gas then undergoes a water wash and the solvent containing the CO_2 is pumped to the top of a stripper, via a heat exchanger for separating the CO_2.

- Amine Process:

The flue gas is treated with an aqueous amine solution, which reacts with CO_2. Raising the temperature reverses the reaction and CO_2 is released. The solution is recycled for reuse.

The Amine Process is based on the chemistry of the amine-CO_2-H_2 O system and the ability of the amine solution to absorb CO_2 at low temperatures and to release the CO_2 at moderately elevated temperatures. CO_2 and water produce carbonic acid to react with amine solution in the absorption column, forming chemical compound and resulting in the removal of CO_2 from the gaseous stream.

The typical target CO_2 removal efficiency is 90% though 99% efficiencies could be achieved in well-designed absorbers.

A key feature of amine systems is the large amount of heat required to regenerate the solvent. This heat is typically drawn from the steam cycle reducing the net efficiency of the power plant.

- Chilled Ammonia Process:

The flue-gas leaving the WFGD (Wet Flue Gas Desulphurization) system is cooled and sent to the CO_2 absorber, where the CO_2 in the flue-gas reacts with ammonium carbonate to form ammonium bicarbonate (ABC). The flue-gas stream, with most of the CO_2 removed, returns to the existing stack for discharge, and the remaining is sent to the wastewater treatment plant for processing. The rich ammonium bicarbonate (ABC) solution is sent to a regenerator column under pressure. Heat is added in the regenerator to separate the CO_2 and return the ammonium carbonate (AC) solution to the CO_2 absorber for reuse. The CO_2 stream is scrubbed to remove excess ammonia, then compressed and transported to the storage system.

Gaseous ammonia (NH3) is released from the ammoniated solution during absorption of CO_2. To minimize gaseous NH3 emissions, CO_2 absorption is carried out at lower flue-gas temperatures. Generally, a lower absorption temperature results in lower ammonia emissions from the CAP absorber and higher power consumption for the cooling process equipment.

- Biocatalysis Techniques:

The remotion of CO_2 from the flue-gases is done by enzymes which accelerate CO_2 separation by promoting its hydration to bicarbonate at a rate substantially higher than amines.

The enzyme is embedded in a thin polymer film in the immediate vicinity of the gas-liquid interface in order to address the problem of low enzyme stability under high pH, temperature and shear forces.

The benefits under this technique include low investment cost due to elimination of auxiliary component, reduced system footprint, avoidance of solvent emissions, minimal solution replacement requirements and reduced maintenance requirements.

The amine process, chilled ammonia process and the biocatalysis techniques are detailed as Best Available Technologies (BAT) for Large Combustion Plants under section 11.2.4.1.1, 11.2.4.1.2 and 11.2.4.1.3 respectively.

Emerging techniques:

II) Adsorption process: In the adsorption process for flue gas CO_2 recovery, molecular sieves or activated carbons are used in adsorbing CO_2. Desorbing CO_2 is then done by a pressure swing operation (PSA) or temperature swing operation (TSA).

III) Membranes: CO_2 removal is performed at high pressure and at high CO_2 concentration. In the case of commercially available polymeric gas separation membranes the energy required to perform the CO_2 removal is higher than in standard chemical absorption process and the removed percentage is lower. Improvements can be made with membranes under current development.

IV) Cryogenic: The gaseous CO_2 can be separated from other components in the flue gas due to their different condensation and desublimation temperatures. Still in early developing stages.

V) Solid sorbents.

<u>Oxy-fuel combustion</u>

These systems are characterized by the burning of coal with relatively pure O_2, diluted with treated or untreated recycled flue-gas. Under these conditions, the primary products of the combustion are water (H_2O) and a high concentration of CO_2. The CO_2 is separated by condensation of the H_2O. Firing with pure oxygen would result in too high a flame temperature, so the mixture is diluted with recycled flue-gas. The recycled flue-gas can also be used to carry fuel into the boiler. Oxy-fuel combustion produces approximately 75 % less flue-gas than air-fired combustion and produces exhaust gas consisting primarily of CO_2 and H_2O. After condensation of the H_2O, the highly concentrated CO_2 is purified and compressed to a liquid or supercritical state, depending on the means of transportation.

An additional purification stage for the flue-gas may be necessary to remove other minor gas constituents such as N2, O_2 and argon, in order to produce a CO_2 stream that meets pipeline and storage requirements.

In an oxy-fuel combustion process, almost all of the N2 is removed from the air, there resulting in a stream that is approximately 95-97.5 % O_2. This leads to the production of approximately 75 % less combustion product volume than air-fired combustion. The lower gas volume also allows for flue-gas contaminants (SOX, NOX, mercury, particulates) to be more easily removed and at a lower cost.

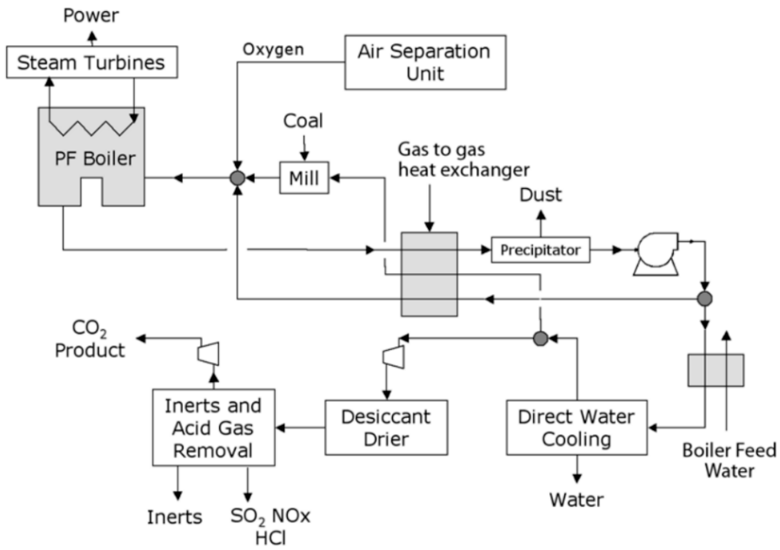

Figure 2: Schematic of an oxy-fuel, pulverized coal fired power plant. Source: IPCC report on CCS

I) Oxy-fuel indirect heating - steam cycle: provides heat to a separate fluid by heat transfer through a surface.

II) Oxy-fuel direct heating - gas turbine cycle: natural gas, light hydrocarbons and syngas (CO + H_2) can be used as fuel. Takes place in a pressurized CO_2-rich recirculating stream in a modified gas turbine. The hot gas is expanded in the turbine producing power. The turbine exhaust provides the heat for a steam cycle and water vapour is condensed by further cooling. The CO_2-rich gas is compressed in the compressor section. The net CO_2-rich combustion product is removed from the system.

III) Oxy-fuel direct heating - steam turbine cycle: water is pressurized as a liquid and is then evaporated, heated by the direct injection and combustion of a fuel with pure oxygen and expanded in a turbine. Most of the water in the low-pressure turbine exhaust gas is cooled and condensed, prior to pumping back to a high pressure while the CO_2 produced from combustion is removed and compressed for pipeline transport.

Pre-combustion

Pre-combustion process involves conversion (gasification or partial oxidation) of fuel into a synthesis gas (carbon monoxide and hydrogen) which is then reacted with steam in a shift reactor to convert CO into CO_2 or another organic substance. The process produces highly concentrated CO_2 that is readily removable by physical absorbents. H_2 can then be burnt in a gas turbine. There are two possible applications, to produce a carbon-free fuel (Hydrogen) or to reduce the carbon content on a fuel for storing it. For the moment, none of the existing coal-fired IGCC plants includes shift conversion with CO_2 capture.

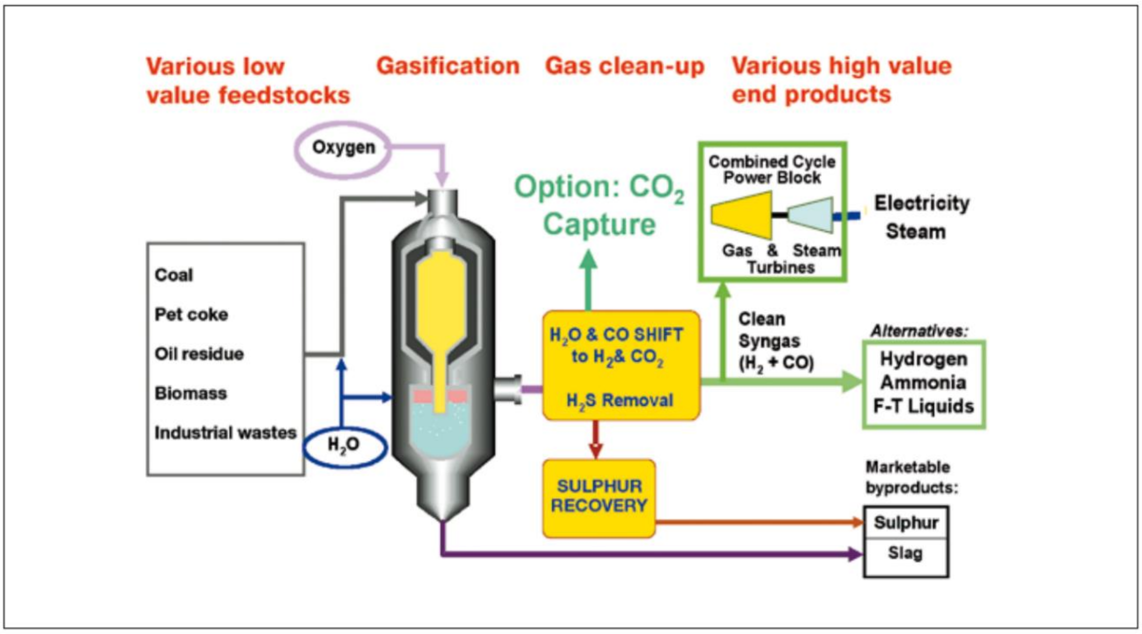

Figure 3: Simplified schematic of a gasification process showing options with CO_2 capture and electricity, hydrogen or chemical production. Source: IPCC report on CCS

I) Steam reforming (SMR): The process begins with the removal of sulphur compounds from the feed. The reforming reaction, which is endothermic, takes place over a catalyst at high temperature (800 °C-900 °C). Heat is supplied to the reactor tubes by burning part of the fuel (secondary fuel). The reformed gas is cooled in a waste heat boiler which generates the steam needed for the reactions and passed into the CO shift system where the CO in the syngas will be converted to CO_2.

II) Partial oxidation (POX): the fuel reacts with pure oxygen at high pressure. The process is exothermic and occurs at high temperatures. All the heat required for the syngas reaction is supplied by the partial combustion of the fuel, so no external heat is required. The syngas will be cooled, shifted and the CO_2 removed from the mixture.

III) Auto-thermal reforming: It is a combination of the two processes mentioned above. The heat required in the SMR reactor is generated by the partial oxidation reaction using air or oxygen, but because steam is supplied to the reactor as well as excess natural gas, the endothermic reforming reaction occurs in a catalytic section of the reactor downstream of the POX burner. The feed gas must be sulphur free.

IV) Gasification of biomass: Gasification is basically a partial oxidation, although steam is also supplied to the reactor in most processes. Fixed bed, fluidized bed or entrained flow gasifiers can be used. Gasification is generally considered to be suitable only for large plants.

Utilisation

After capturing the CO_2, it can be destinated to utilisation for a range of applications; a direct use, without chemical alteration, or an indirect use, through transformation into different products.

It offers a wide range of opportunities. In an environmental perspective reduces the amount of emitted CO_2 and in an economical perspective, it can be used as feedstock for sustainable aviation fuels, fuels used for the maritime and trucking industries, chemical manufacturing and even sustainable materials such as concrete.

Mineral Carbonation

CO_2 is brought into contact with metal oxide bearing materials with the purpose of fixing CO_2 as carbonates.

The energy required to drive the mineral carbonation process will depend on the energy that is needed for: (a) the preparation of the solid reactants, including mining, transport, grinding and activation when necessary; (b) the processing, including the equivalent energy associated with the use, recycling and possible losses of additives and catalysts; (c) the disposal of carbonates and byproducts.

Suitable materials for being used as metal oxides may be:

I) Materials that contain alkaline earth metals because their corresponding carbonates are very soluble in water. One example are silicate rocks; mafic and ultramafic rocks that contain high amounts of magnesium, calcium and iron and have a low content of sodium and potassium. Some of their main mineral constituents are olivine, serpentine, wollastonite, between others. Rocks containing magnesium silicate exhibit a higher MgO concentration (up to 50% by weight) than rocks containing calcium silicates, corresponding to a theoretical CO_2 storage capacity of 0.55 kg CO_2/kg rock. Carbonation can be carried out in-situ by injecting CO_2 in silicate rich geological formations or ex-situ, in a processing plant after mining and pre-treating the silicates (additional energy required).

II) Industrial wastes and mining tailings provide sources of alkalinity that are readily available and reactive; nonetheless their total amounts are too small to substantially reduce CO_2 emissions. Waste streams of calcium silicate materials from municipal solid waste incinerators, bottom ash (with a calcium oxide content about 20% by weight CaO) and fly ash (about 35% by weight CaO) can be considered as suitable materials. It is an ex-situ carbonation.

The potential of mineral carbonation depends on the trade-off between costs associated with the energy consuming steps (mining, pre-processing of the mineral ore, its subsequent disposal and mine reclamation) and benefits. Between which can be mentioned: the large potential capacity due to the vast availability of natural metal oxide bearing silicates and the permanence of CO_2 storage; production of environmentally safe and stable materials over geological time frames; economic viability through production of value-added by-products during carbonation process and the possibility of performing it with existing technologies. Further disadvantages include the lack of demonstration units (pilot-scale), the slow process of geological mineralization is usually masked by other phenomena like sequestration by dissolution, residual trapping and stratigraphic trapping and serious environmental impact from mining materials and carbonation process (Olajire, 2013).

Industrial Uses

The CO_2 that has been capture could be used directly or as feedstock for chemical processes that produce valuable carbon containing products. This would guarantee the reduction only if:

I. The use of captured CO_2 must not simply replace a source of CO_2 that would then be vented to the atmosphere.
II. The compounds produced using captured CO_2 must have a long lifetime before the CO_2 is liberated by combustion or other degradation processes.
III. When considering the use of captured CO_2 in an industrial process, the overall system boundary must be carefully defined to include all materials, fossil fuels, energy flows, emissions and products in the full chain of processes used to produce a unit of product in order to correctly determine the overall (net) CO_2 avoided.

Between the current industrial uses of carbon dioxide can be mentioned, the production of chemicals, refrigeration systems, inert agent for food packaging, beverages, welding systems, fire extinguishers, water treatment processes, horticulture, precipitated calcium carbonate for the paper industry and many other smaller-scale applications.

Other uses include:

I) Organic chemicals and polymers: CO_2 is used as a substitute for other carbon building blocks. Since CO_2 is an inert gas whose carbon is in a highly oxidized state, it requires development of efficient catalytic systems and, in general, the use of additional energy for CO_2 reduction.
II) Fuel production: CO_2 could become the raw material for producing carbon-based fuels with the help of additional energy. Since energy is conserved, this cannot provide a net reduction in carbon dioxide emissions as long as the underlying energy source is fossil carbon.

Methanol production is an example of the synthesis of liquid fuels from CO_2 and hydrogen, that are produced through reforming or partial oxidation or auto thermal reforming of fossil fuels, mainly natural gas. Alternatively, it can be used captured CO_2 and hydrogen from water hydrolysis powered for instance by solar energy.

III) Biomass production: Biomass can be produced in industrial settings, where elevated concentrations of CO_2 from the off-gas of a power plant would feed micro-algae designed to convert CO_2 into useful chemicals. If the biomass is put to good use, it can recycle carbon by returning it to its energetic state.
The biomass production is ultimately limited by the efficiency of converting light into chemically stored energy (Karimi et al, 2022).

Chemical product class or application	Yearly market (Mt yr^{-1})	Amount of CO_2 used per Mt product ($MtCO_2$)	Source of CO_2	Lifetime[b]
Urea	90	65	Industrial	Six months
Methanol (additive to CO)	24	<8	Industrial	Six months
Inorganic carbonates	8	3	Industrial, Natural[a]	Decades to centuries
Organic carbonates	2.6	0.2	Industrial, Natural[a]	Decades to centuries
Polyurethanes	10	<10	Industrial, Natural[a]	Decades to centuries
Technological	10	10	Industrial, Natural[a]	Days to years
Food	8	8	Industrial, Natural[a]	Months to years

[a] Natural sources include both geological wells and fermentation.
[b] The fraction of used CO_2 that is still stored after the indicated period of time drops to zero.

Table 2: Industrial applications of CO_2. Source: IPCC report on CCS

Storage

Permanent Storage refers to the injection of CO_2 into a suitable deep rock formation. As according to the Directive 2009/31/EC of the European Union, "*This technology should not serve as an incentive to increase the share of fossil fuel power plants. Its development should not lead to a reduction of efforts to support energy saving policies, renewable energies and other safe and sustainable low carbon technologies, both in research and financial terms*".

On the other hand, when talking about Enhanced Hydrocarbon Recovery (EHR), the recovery of hydrocarbons in addition to those extracted by water injection or other means; the Directive states, "*EHR is not in itself included in the scope of this Directive. However, where EHR is com-bined with geological storage of CO_2, the provisions of this Directive for the environmentally safe storage of CO_2 should apply…*".

The geological formations suitable for CO_2 storage must lie at depths below 800-1000 m, where the injected CO_2 remains in a supercritical state and has a liquid-like density (about 500-800 kg/m3). However, this density allows the buoyant forces to drive CO_2 upwards, consequently, a well-sealed caprock above the selected storage reservoir is important to ensure that CO_2 remains trapped underground.

Storage mechanisms in geological formations

→ Physical trapping, stratigraphic and structural:

Since CO_2 is lighter than water it tends to go up in the reservoir rock for staying trapped over the impermeable confining strata. Physical trapping of CO_2 below low-permeability seals (caprocks), such as very-low-permeability shale or salt beds, is the principal mean to store CO_2 in geological formations. Sedimentary basins have traps or faults that can act as permeability barriers or as preferential pathways for fluid flow. These traps are suitable for CO_2 storage as long as pressure is not overcome.

→ Physical trapping, hydrodynamic:

Hydrodynamic trapping can occur in saline formations that do not have a closed trap, but where fluids migrate very slowly over long distances. When CO_2 is injected into a formation, it displaces saline formation water and then migrates buoyantly upwards, because it is less dense than the water. Later it is trapped in local structural or stratigraphic traps within the sealing formation. In the longer term, significant quantities of CO_2 dissolve in the formation water and then migrate with the groundwater.

→ Geochemical trapping:

CO_2 is dissolved in formatting water eliminating the buoyant forces that drive it upwards. Next, it will form ionic species as the rock dissolves. Finally, some fraction may be converted to stable carbonate minerals (mineral trapping) that is the most permanent form of geological storage.

Storage site-selection

For the identification of the suitable storage sites, the CCS directive, and the relative Italian implementation decree, foresee an exploration phase for obtaining the relevant data through underground studies.

Geological storage sites should have:

I. adequate capacity and injectivity,
II. a satisfactory sealing caprock or confining unit and
III. a sufficiently stable geological environment to avoid compromising the integrity of the storage site.

In order to assess the basin suitability, it should be taken into consideration; the *basin characteristics* (tectonic activity, sediment type, geothermal and hydrodynamic regimes), *basin resources* (hydrocarbons, coal, salt), *industry maturity* and *infrastructure,* and *societal issues* (level of development, economy, environmental concerns, public education and attitudes).

The efficiency of CO_2 storage in geological media, defined as the amount of CO_2 stored per unit volume, increases with increasing CO_2 density. Storage safety also increases with increasing density. Sedimentary basins with a low temperature gradient, are more favourable for CO_2 storage, because carbon dioxide reaches higher densities at shallower depths. Meaning the storage formation will be at lower depths and so less drilling and compression costs.

For the storage capacity adequate porosity and thickness are critical, as for injectivity the permeability will be crucial. To ensure that CO_2 doesn't escape into overlying, shallower rock units and to the surface; the storage formation should be capped by extensive confining units (such as shale, salt or anhydrite beds).

Pressure and flow regimes of formation waters in a sedimentary basin are important factors since they can generate technological and safety issues. While deep saline formations with fluids having long residence times are conducive to hydrodynamic and mineral trapping.

Targets for the carbon dioxide storage are:

- Mature sedimentary basins: have well-known characteristics; hydrocarbon pools and/or coal beds have been discovered and produced; some petroleum reservoirs might be already depleted or abandoned and the infrastructure needed for CO_2 transport and injection may already be in place.
- Saline formations: are deep sedimentary rocks saturated with formation waters or brines containing high concentrations of dissolved salts. If they are not target for other utilizations like geothermal energy production or water desalination, then they can be used for storage of CO_2 since they are unsuitable for agriculture or human consumption. Estimating the storage capacity of saline formation is a challenge and can only be determined only on a case-by-case. Nonetheless it has been calculated that saline aquifers by its own would be able to contain even more of the total amount of CO_2 emitted in the atmosphere for the next 100- or 350-years considering emission rates progressively higher and pair to the actual ones.
- Coal seams: coal contains fractures that impart some permeability to the system, between them solid coal has a very large number of micropores into which gas molecules from the fractures can diffuse and be tightly adsorbed. Gaseous CO_2 injected through wells will flow through this system, diffuse into the coal matrix and be adsorbed onto the coal micropore surfaces, freeing up gases with lower affinity to coal. If the coal is never mined, depressurized or disturbed, it is likely CO_2 will be stored for geological time.
- Other geological media: other geological media and/or structures, including basalts, oil or gas shale, salt caverns and abandoned mines, may locally provide good options for geological storage of carbon dioxide.

Wells design

The main well design considerations include pressure, corrosion-resistant materials and production and injection rates.

The number of wells required for a storage project will depend on the total injection rate, permeability and thickness of the formation, maximum injection pressures and availability of land-surface area for the injection wells.

Monitoring technologies will depend on the scope:

- For monitoring injection rates, wellhead and formation pressures, the current state of the technology is more than adequate to meet the needs since they are a common oil field practice.
- Monitoring the distribution and migration of CO_2 in the subsurface is site-specific; direct techniques: tracer injection in the wells, sampling for CO_2 or tracers in soil gas and near surface water-bearing horizons or infrared spectroscopy for measuring surface CO_2 fluxes. Indirect techniques include a variety of seismic and non-seismic geochemical and geophysical techniques.
- For monitoring injection well integrity.
- For monitoring local environmental effects.

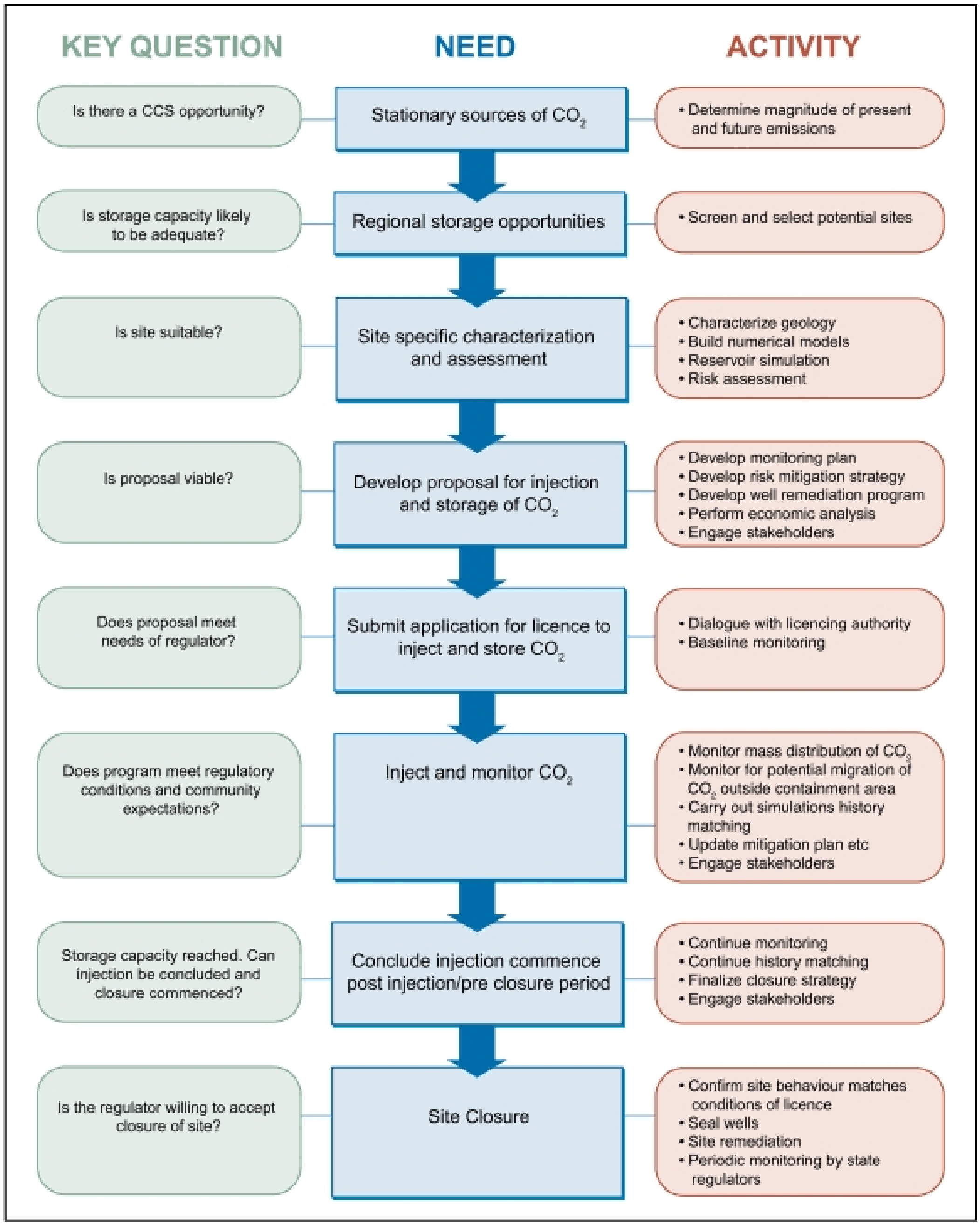

Figure 4: Life cycle of a CO_2 storage project showing the importance of integrating site characterization with a range of regulatory, monitoring, economic, risking and engineering issues

Risks on achieving CCUS a sustainable project

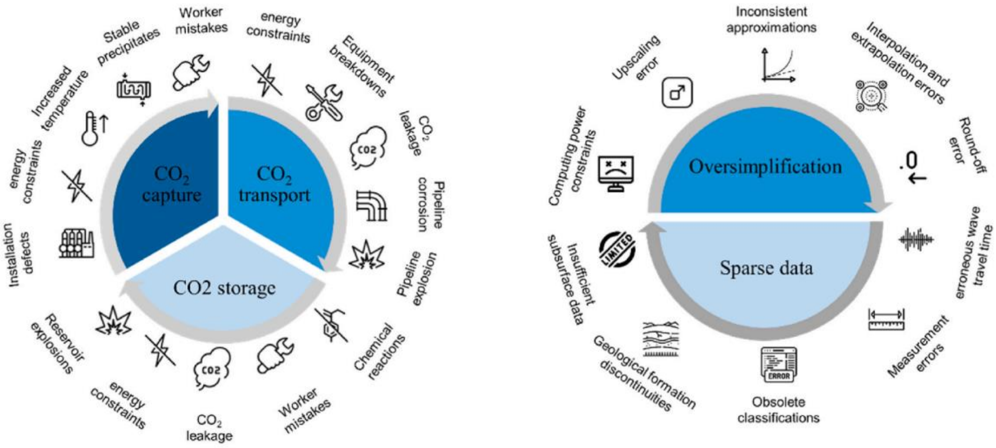

Figure 5: Technical risks and uncertainties; on the left, for each phase, on the right due to insufficient data and oversimplifications. Source: Mahjour and Faroughi (2023)

The development of CCUS requires the balance of risks and benefits along the value chain through optimal commercial solutions.

Operational risks:

→ In the cases a solvent is used for the post combustion capture, large quantities of solvent rich wastewater could be generated. Impurities in captured CO_2 streams may have significant implications.

Economical risks:

→ Price (variation) risks: the value of the CCUS application depends on the alternative that is the cost associated to the emission of the corresponding CO_2. Prices of tCO_2e have been increasing in the past years and so de-risking investments requires business models that guarantee stable revenue streams over long time periods. For the companies in charge of transport and/or storage also long-term commitments are needed to go ahead with the investment. This generates an interest on the aggregation of stakeholders that can make front of risks.

→ Volume (certainty) risks: Emitters require certainty over the possibility of disposing the captured CO_2 through the lifetime of the emitting asset. This could represent a risk for Alperia, as will be later exposed, when a stable CO_2 supply is required; further, leading into a mismatch, when specific flow rate feedstocks are required. The creation of a market-based hub/pool/exchange could connect sources and secure a stable demand and supply.

→ Lack of business support

Social risks:

- → Safe and health considerations related to unintentional carbon dioxide releases.
- → Public perception on CCS technology, lack of knowledge related to the subject and lack of familiarity with the magnitude of its benefits for mitigating climate change.

Environmental risks:

- → CO_2 leakage from transport stage.
- → CO_2 leakage from storage sites.
- → Uncertainty of potential impacts due to geological complexity and of safety from long-term storage.

Governmental risks[1]:

- → The European CCS Directive places too much of the financial risk on the private sector limiting long-term liability that is needed in order to insure the financial incentive for investment in CCS.
- → CCS projects require a high level of confidence between the private sector and local governments, investments can be impacted by political changes. Therefore, for these projects to succeed, it is crucial to have effective communication between the government and the private sector. Clarity and consistency are expected from the Italian government.
- → International politics are also essential; the fact that countries that do not comply with their duties are not subject to sanctions or financial fine allows them to continue burning fossil fuels without experiencing negative effects.

Technological risks:

- → Increasing development of new technologies and processes could signify new risks.
- → The large-scale nature of capture technology available in the market presents challenges for smaller hard-to-abate industries in implementing capture solutions.

[1] More details and clarification in the following chapter

Policy and Regulatory Framework

In February of 2024 the European Commission lunched a communication "Towards an Ambitious Industrial Carbon Management for the EU". This document aims to bring together the existing policy in order to "*create an enabling environment to develop and scale up industrial carbon management approaches*". Reaching this basin requires an industrial carbon management strategy, based on three pathways:

- ✓ Capturing CO_2 for storage (CCS): CO_2 emissions of fossil, biogenic or atmospheric origin are captured and transported for permanent and safe geological storage.
- ✓ Removing CO_2 from the atmosphere: permanent storage involving biogenic or atmospheric CO_2.
- ✓ Capturing CO_2 for utilisation (CCU): industry uses that capture CO_2 in synthetic products, chemicals or fuels.

In the cases where the captured CO_2 is not directly used on-site, it will require a transport infrastructure, which will be the common enabler of the mentioned pathways.

EU Policies

Regarding the storage of CO_2, since 2009, with the last revision done in December 2018, the Directive 2009/31/EC ensures the safety and environmental integrity for the CO_2 storage. Briefly the directive includes:

- ✓ Selection of storage sites and exploration permits
- ✓ Storage permits
- ✓ Operation, closure and post-closure operations

Transportation of CO_2 is supported under the TEN-E Regulation (Trans-European Network for Energy) that takes CO_2 networks as a priority thematic area for selecting the Projects of Common and Mutual Interest (PCIs and PMIs), energy infrastructure projects connecting EU countries with each other (PCIs) and with countries outside the EU (PMIs). The status of this projects is important since it makes them eligible for funding under the Connecting Europe Facility for Energy (CEF). This Regulation under the cross-border CO_2 network necessity, settles: "development of infrastructure for transport and storage of carbon dioxide between Member States and with neighbouring third countries of carbon dioxide capture and storage captured from industrial installations for the purpose of permanent geological storage as well as carbon dioxide utilisation for synthetic fuel gases…"

As incentive for CCS and CCU, the Net-Zero Industry Act (NZIA) encompasses final products, components, and machinery necessary for manufacturing net-zero technologies, including Carbon capture and storage technologies and CO_2 transport and utilization technologies; between others. Includes, as well, accelerated permitting procedures. By 2030, the act aims to create a Union market for CO_2 storage services, and it also includes a target for the EU to have available capacity to store 50 million tonnes of CO_2 per year by 2030.

Policies connected to EU

In order to achieve the climate neutrality by 2050, it was settled in 2020 the long-term strategy of the European Commission for climate neutrality that contains a detailed analysis of possible solutions for the transition to the net zero GHG emissions economy. Each Member State of the EU prepared their own national long-term strategies and submit them to the UNFCC. In accordance, Italy published in January of 2021 its national long-term strategy on the reduction of the GHG emissions. These national long-term strategies were required to ensure consistency between long-term-strategies and the 10-year NECPs (National energy and climate plans), this last one outline how EU countries intend to meet the EU energy and climate targets for 2030.

The European Climate Law (Regulation 2021/1119) establishes a framework for the reduction of the sources of anthropogenic greenhouse gas emissions and for the enhancement of removals by sinks. The regulation declares "*Solutions that are based on carbon capture and storage (CCS) and carbon capture and use (CCU) technologies can play a role in decarbonisation, especially for the mitigation of process emissions in industry*".

The Communication on Sustainable Carbon Cycles (Regulation 2024/3012) establishes the certification framework for permanent carbon removals, carbon farming and carbon storage in products. Permanent carbon removal refers to human activities removing CO_2 from the atmosphere and storing it securely and durably for several centuries. To mention; BECCS and other biomass-based methods (BioCCS), chemically binding CO_2 permanently into products, other technological solutions that lead to permanent storage. Nonetheless this regulation doesn't apply to emission falling within the scope of ETS Directive, "with the exception of the capture and storage of CO_2 emissions from biofuels, bioliquids and biomass fuels". Leaving out the CO_2 capture from power plants flue gas.

The Strategic Energy Technology Plan (SET Plan) seeks to enhance the transition towards a climate-neutral energy system through the development of low-carbon technologies in a fast and cost-competitive way. Established in 2007, one of the action areas for research and innovation is the Carbon capture and storage that is implemented by one of the Implementation Working Groups (IWGs).

The Revised Renewable Energy Directive (2023/2413/EU; RED II), originally established in 2009 (Directive 2009/28/EC; RED), revised in 2018 (Directive 2018/2001/EU) and later in 2023 (RED III), promotes the use of energy from renewable sources and includes the CCS as an emission saving for the calculation of GHG emissions.

The ETS Directive (Emission Trading System Directive 2003/87/EC, and its improvement and extend Directive 2009/29/EC) has put a price on CO_2 emissions and, since 2013, has incentivised the capture of CO_2 for permanent storage. The EU ETS reform brought in several changes to support industrial carbon management, including a broadened scope of CO_2 transport for storage. Furthermore, the directive offers the possibility to participants to avoid surrendering emissions allowances if CO_2 is successfully captured and storage.
Article 12(3a) of the ETS Directive provides this rule since amended by Directive 2009/29/EC. In accordance with Article 12(3a) of the ETS Directive, the exception to surrendering allowances in case of CCS only applies when the emissions are stored in a facility with a permit in force in accordance with the CCS Directive, reflected in the CCS activities in Annex I of the ETS Directive.
In addition, Article 49(1) of MRR (Monitoring and Reporting Regulation) sets that operators can subtract CO_2 emissions from their total emissions if it is originated from fossil fuel in activities covered by Directive 2003/87/EC and is not emitted from the installation but is instead:

(a) Transferred for Long-Term Geological Storage: (1) To a capture installation for transport and storage; (2) To a transport network for long-term geological storage; (3) Directly to a storage site permitted under Directive 2009/31/EC.
(b) Used for Chemical Binding: Transferred out of the installation and used to produce precipitated calcium carbonate (PCC), where the CO_2 becomes chemically bound.

This consolidates a base for Alperia, in particular for Bolzano plant, which falls under ETS covered sectors.

For what concerns the rest of Alperia Group, the sector in charge of the natural gas sailing is comprised in the ETS 2 (Directive (EU) 2023/959), 2023 new emission trading system that covers the CO_2 emissions from sectors not included in the existing EU ETS. This directive release sectors from the obligation of surrendering allowances, as settled by Article 12(3b): “An obligation to surrender allowances shall not arise in respect of emissions of greenhouse gases which are considered to have been captured and utilised in such a way that they have become permanently chemically bound in a product so that they do not enter the atmosphere under normal use, including any normal activity taking place after the end of the life of the product” .

In 2021, it was established the Industrial Carbon Management Forum (ICM Forum), in the beginning named CCUS Forum. It aims to bring together, once a year, representatives from the EU institutions, EU and non-EU countries, NGOs, business leaders and academia to facilitate the deployment of CCUS technologies.

Despite the mentioned policies supporting and enhancing industrial carbon management, operational large-scale projects are limited in Europe as well as in the rest of the globe. Furthermore, a number of challenges are present, notably:

- difficulties in building a viable business, because of significant up-front investment capital required, uncertainty of future CO_2 prices and the need for extra attention for matching supply and demand for low-carbon products,
- lack of a comprehensive regulatory framework across the entire value chain, notably for industrial carbon removals and for certain CO_2 uses.
- CO_2-specific cross-value chain risks, such as liability for leakages or the unavailability of transport or storage infrastructure.
- Insufficient coordination and planning, especially in cross-border contexts.
- Insufficient incentives for private and public investment to proof the business case for industrial carbon management.

The London Protocol and the London Convention are the global agreements that protect the marine environment from pollution caused by the dumping of wastes and other matter at sea. Under the London Convention Contracting Parties are required to issue a permit for the dumping of wastes and other matter at sea, and generally prohibit the dumping of certain hazardous materials. CO_2 streams from CO_2 capture processes for storage is included in the list of wastes or other matter that may be considered for dumping. The Protocol allows that two or more countries export CO_2 for disposal in sub-seabed geological formations. However, to do so they must first deposit a formal declaration of provisional application with the Secretary-General of the International Maritime Organization (IMO).
Nevertheless, due to Alperia's geographical location far from the sea, the exportation of CO_2 via maritime routes becomes challenging, leading to the dismissal of this alternative.

Italian Policies

The Italian law "*LEGGE 4 giugno 2010, n. 96*" is the gratification of obligations deriving from Italy's membership to the European Community where the Government implements the community directives, highlighting the adoption of Directive 2009/31/EC relative to the carbon dioxide geological storage.

On the other side the legislative decree "*DECRETO LEGISLATIVO 14 settembre 2011, n. 162*" stablishes a framework of measures aimed at guaranteeing the geological storage of CO_2 in suitable geological formations. The contents of the directive can be summarized in:

- ✓ Definition of the competent authority
- ✓ Identification of the suitable areas that could be used for the CO_2 storage
- ✓ The constitution of a database for the storage activity
- ✓ The definition of the procedures for the allowance of the storage activity and the eventual survey activities aimed to evaluate the site suitability
- ✓ Obligations for the closure and post-closure of the facilities and the financial guarantees
- ✓ Requirements for monitoring and inspection

This decree has also established the creation of a CCS Committee by the "Ministero dell'ambiente e della sicurezza energetica", with the aim of managing the data related to the subject, evaluating storage capacity, which serves as a technical-scientific guarantee element for the development of CCS technologies. At present, there is no additional information available regarding this Committee beyond its announced creation in June 2024.

In addition, article 28(1) about "access to the transportation network and storage sites" establishes that "operators of transportation networks and storage sites of CO_2 are required to provide connection and access to their transport network and storage sites to other operators, according to transparent and non-discriminatory manner." The "Ministero dello Sviluppo Economico, Ministero dell'Ambiente e della Tutela del Territorio e del Mare" of Italy in order to evaluate the CO_2 storage demand in Italy have hypothesized the following scenario:

- beginning of CO_2 commercial activity by 2035;
- reduction of CO_2 by 2050 as indicated by the European 2050 ROADMAP;
- reduction of CO_2 by 2020 (-17%) respect to 2005 values and by 2050 (-80%) even if it still not mandatory;
- by 2050 annulment of emissions coming from the electricity sector, substantial reduction in residential and transport sectors, shift towards electric mobility of a 50%;
- a CCS presence of 22% in the 2050 emissions annulment scenario, susceptible of incrementation due to the nuclear quote.

An initial calculation methodology, based on the mentioned scenario, gives Italy for 2050 a storage demand of 308 Mt with a CCS competence quota equal to 60 MtCO_2 with an annual reduction estimated at 2050. In 2050 the storage demand, assuming the entry into operation of the CCS plants linearly gradual from 2025, is 0.75 GtCO_2 and with a non-variative situation until the end of the century, for the 2100 should be guarantee a storage capacity of 3.8 Gt.

A second approach, that has as reference the annual data of electricity production from coal and gas and of industrial production for non-energetic uses of cement and refinery, predict the following scenario:

- an electricity production responsible of approximately 35 MtCO_2 in 2010;
- emissions associated with cement, refinery, etc, estimated around 40 MtCO_2 in 2010;
- emissions equal to 58.8 MtCO_2 coming from the primary consumption for the electricity production powered by natural gas.

The annulment of CO_2 coming from electricity production powered by carbon and gas will have to be total (100% CCS), while for the industry it will be adopted an IEA quota (International Energy Agency) of the 20%. It will be obtained, by 2050, with the same procedure, a cumulative demand of CCS of approximately 1.25 GtCO_2.

By 2100 with stable context, the storage quota would arrive to 6.25.

The EU GeoCapacity (Assessing European Capacity for Geological Storage of Carbon Dioxide) estimated, after a three-year project started in 2006, that Italy has:

- Annual total emissions of CO_2: 212 Mt
- Annual CO_2 emissions from large point sources: 140 Mt
- CO_2 storage capacity in deep saline aquifers: 4669 Mt
- CO_2 storage capacity in hydrocarbon fields: 1810 Mt
- CO_2 storage capacity in coal fields: 71 Mt

Italy made a preliminary report published in 2012 in implementation of the Legislative Decree n. 162, where it foresees the individuation of the suitable areas for doing exploration and storage of CO_2. Nonetheless the environmental report is still in attendance.

Italy's national long-term strategy

As mentioned above, Italy issued (in 2021) its national long-term strategy on the reduction of the GHG emissions that allocates the feasible paths for achieving, by 2050, a condition of climate neutrality. Between the actions for compensating residue emissions of GHGs, it is mentioned the CO_2 capture and the eventual geological storage or utilization (CCS-CCU); inside this strategy some key points are as follow:

As energy supply should be considered the biomethane or similar fuels (free of GHG emissions) produced with hydrogen derived from renewable sources and CO_2 captured.

The strategy settles as one of the compensating measurements for the emissions coming from the non-energetic sector, the utilization of the available potential estimated on national level for the storage of the captured CO_2 (not yet published). Applicable technology to big industries (cement and steel) and to the electricity generation sector: this last one could even achieve negative emissions if the capture is applied to plants feed with "bio" sources (biomethane, biomass).

In the decarbonization scenario, the actions are classified into three categories:

1. Reduction of energy demand, specifically, a declining on the consumption from private mobility and civil sector;
2. a radical change in the energetic mix towards renewables, electrification of final uses and employment of alternative fuels (hydrogen/e-fuels);
3. increase of CO_2 absorption, through CO_2 capture and storage.

The draw upon CCS is, nonetheless, to be considered since it requires different evaluations and verifications. In particular: its requirements depend on the productivity options that will be adopted in specific industrial productions; it can be hypothesize further changes in technology, in habits and in the production ways specifically in the cases where emissions are harder to overthrow; and finally, to not neglect that safe storage sites have to be localize as well as adequate transfer plans in case of being necessary.

Furthermore, it is anticipated that the Italian Ministry of Energy (MASE) will publish a study on a supply chain, wherein detailed specifications are expected regarding the conditions for access to CO_2 transport and storage.

Fundings

Estimations for the capture costs from point sources range from EUR 13/t and EUR 103/t of CO_2 depending on the industry, capture technology and CO_2 concentration.

One of the key funding programmes for research and innovation is the Horizon Europe. CCS is explicitly mentioned in cluster 5: “Climate, Energy and Mobility”, under the second pillar of the structure, “Global challenges and European industrial competitiveness”, which was allocated the largest share of the budget at €53.5 billion.

Nevertheless, so far, the website doesn’t present forthcoming grants for the carbon capture in power plants.

The EU ETS Innovation Fund, is available to provide some financing for deployment of selected innovative large scale CO_2 projects; it aims to bolster the commercial implementation of innovative decarbonisation technologies, including CO_2 capture and storage. It is sourced from revenues generated by the EU Emissions Trading System (EU ETS). The Innovation Fund has allocated support to 26 large- and small-scale CCS and CCU projects with more than €3.3 billion in grants.
Activities under Annex 1 of the EU ETS directive can submit a request for funding the CCS project, where the budget for small size projects is of €100 million that may be redistributed between the call topics submitted until April 2025.

The Connecting Europe Facility (CEF) Energy is another key EU support mechanism for the development of cross-border energy and transport infrastructure projects. It relies on the revised Trans-European Networks for Energy (TEN-E) regulation. Different types of CO_2 infrastructure can be eligible under the list for grants; so far, CEF has granted around €680 million to CO_2 projects of common interest (PCI). By the date there are no current grants available for CCUS.

InvestEU destinates founds to the development of the energy sector, stablishing that it will promote the deployment of low-emission technologies and will support the decarbonisation and substantial reduction of emissions of energy-intensive industries: projects that include carbon capture, transport, storage/use (CCUS) technologies. Nonetheless, due to the higher-risk nature of CCS and CCU projects, InvestEU Fund-supported finance of financial institutions could complement grant funding from other EU or national sources or could be provided as “blending operations” combining resources from InvestEU and other Union programmes. For blending operations, it is intended an operation supported by the Union budget that combines non-repayable forms of support, repayable forms of support, or both, from the Union budget with repayable forms of support from development or other public finance institutions, or from commercial finance institutions and investors.

Furthermore, the Recovery and Resilience Facility is available to Member States to support investments in carbon capture. To be considered that is of performance-based nature, meaning that the Commission only pays out the amounts to each country when they have achieved the targets submitted in the national recovery and resilience plan which details the reforms and public investments planned to implement by 31 December 2026. Even though CCS is not explicitly mentioned under the decarbonization of industry measures, it can be found in other countries plan.
The commission has approved €1.1 billion Italian State aid scheme to support investments in equipment necessary to foster the transition to a net-zero economy, where CCS equipment is included, and it will be granted no later than December 2025.

The Environmental State Aid Guidelines apply to State aid granted to facilitate the development of economic activities that improve environmental protection. Between these activities are consider CCS/CCU technologies due to their nature of reduction and removal of GHG emissions and it also applies to infrastructure for carbon dioxide for storage/use projects.

Further, the Just Transition Fund is one of the three pillars of the Just Transition Mechanism. CCS projects can be supported if the investments contribute in one of the approved Just Transition Fund territories, if they significantly reduce GHG emissions bellow the EU ETS benchmark or if they are needed to protect a significant number of jobs. In Italy the fund is destinated exclusively to the area of Sulcis Iglesiente and the province of Taranto.

CCS is also included in the EU sustainable finance taxonomy; a classification system developed to identify and define economic activities that are considered environmentally sustainable for establishing the degree to which an investment is environmentally sustainable. Carbon capture utilisation and storage technologies fall inside the activities that contribute to climate change mitigation objectives. CCUS technologies can be found under Annex I, section 5.10 about Landfill gas capture and utilisation; section 5.11, Transport of CO_2 and section 5.12, Underground permanent geological storage of CO_2.

The European Investment Bank has included carbon capture and storage in its €45 billion financing package to support the Green Deal Industrial Plan.

GHG inventories and accounting

Accounting for CCS presents many challenges. Currently, there is no existing framework for CCUS reporting. Under the Kyoto mechanism, CCS is not explicitly address in any form in CO_2 reporting schemes. The lack of knowledge regarding the rate of leakage or possible accidental releases from storage options represent another challenge, as well as the additional energy required for the different phases.

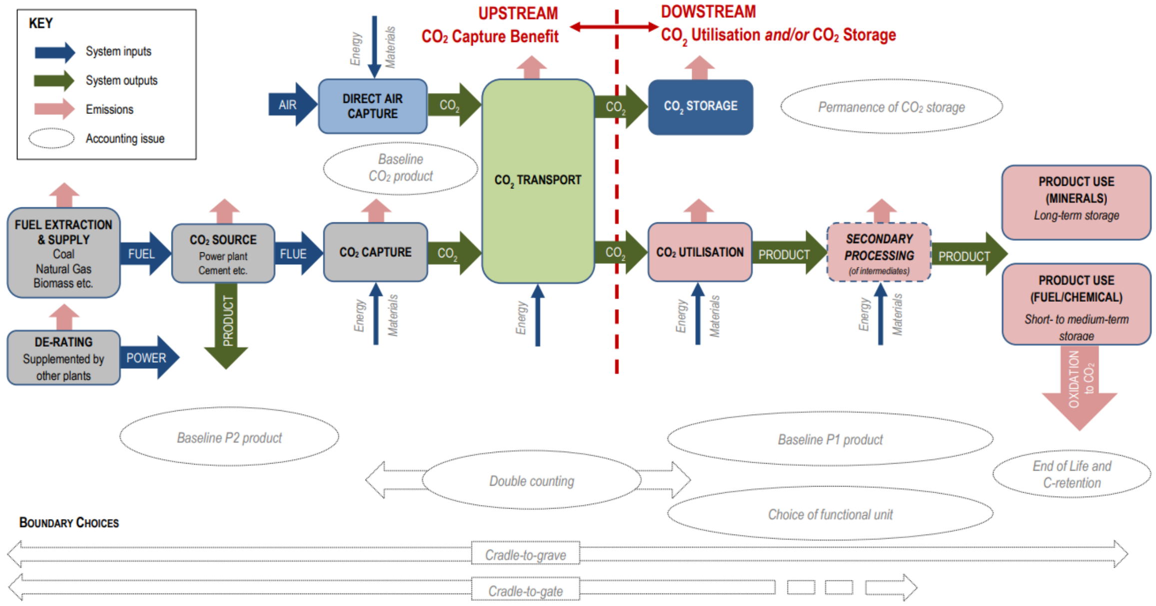

Figure 6: schematic overview of CCUS system components, accounting concepts and issues. Source: IEA GHG R&D Programme (2019)

The IPCC report on CCS elucidates that CCS projects have not been delineated in national inventory reports of countries, except for Norway. Norway's inventory report describes the CO_2 capture and storage activities without reporting them as emissions, but rather as CO_2 "removed from the atmosphere", where this CO_2 is initially captured from an oil and gas production field and subsequently injected. In instances where injection ceases due to maintenance, the CO_2 is vented to the atmosphere, and emissions are consequently reported under the inventory.

The IPCC Guidelines and Good Practice Guidance reports don't specifically address CCUS, but the IPCC report on CCS suggests that its general framework and concepts could be applied.
The amount of carbon captured could be reflected in the sector and category producing the emissions; in this manner, CCS would be treated as a mitigation measure, resulting in a lower emission factor. Under this option, transparency could be reduced in the cases where transport and storage include captured CO_2 from multiple sources, thus unlinking the capture process. Alternatively, this carbon could be accounted for in a category created specifically for the CCS activity in the reporting framework and would consequently be reported as removals (sinks) of CO_2. In this case, the CO_2 flow would be tracked from the source up to the storage, generating a more transparent accounting that is consistent with the UNFCCC agreements. Furthermore, the CO_2 would be reported as a removal in the inventory without modifying the emissions from the combustion process. The IPCC report states: "UNFCCC (1992) defines a sink as 'any process, activity or mechanism which removes a greenhouse gas, an aerosol, or a precursor of a greenhouse gas from the atmosphere'. Although 'removal' was not included explicitly in the UNFCCC definitions, it appears associated with the 'sink' concept. CCS systems do

not meet the UNFCCC definition for a sink but given that the definition was agreed without having CCS systems in mind, it is likely that this obstacle could be solved". Nevertheless, considering the GHG Protocol definition of removal: "absorption or sequestration of GHGs from the atmosphere", which excludes CCS; and the definition of GHG sink: "any physical unit or process that stores GHGs; usually refers to forests and underground/deep sea reservoirs of CO_2"; it becomes apparent that these concepts are not equivalent. Consequently, the suggestion of IPCC may not be entirely valid.
Despite this inconsistency, the main options for incorporating CCS in national GHG inventories are; as a source reduction, wherein the CCS system is considered a mitigation strategy for reducing emissions to the atmosphere; or as sink enhancement, wherein the CCS system is considered analogous to CO_2 removal by sink in the LULUCF sector.

The IPCC report on CCS suggests potential sector categories that can be incorporated into the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, particularly under the "*Energy*" volume, "*Carbon dioxide transport, injection and geological storage*" chapter. On detail, "GHG emissions from stationary combustion" for the capture and injection phase, "GHG emissions from mobile combustion" for the transportation phase and "Fugitive emissions from fuels" that may occur during capture, compression, liquefaction, transportation and injection of CO_2 into the storage reservoir. It should be noted that no methodologies for estimation of fugitive emission from ship, rail or road transportation are included in the IPCC Guidelines nor does physical leakage of stored CO_2.

For the accounting of stored CO_2, there are two approaches mentioned in the IPCC report: (1) assigning credits proportional to the CO_2 storage period after acknowledging that its storage is not permanent and (2) providing assurance of indefinite storage.

(1) Consists in defining an artificial equivalence, where the (impermanent, uncertain) capture and storage for a *t* time interval would be paired with permanent storage; and the storage for an amount of years equal to *t* would give one full credit and so for one year would result in a number of credits equal to 1/t. Nonetheless this accounting presented some discussion, resulting in another derivative, the so call temporary or rented credits. These would have full value over a time period but would result in debits or have to be replaced by permanent credits at expiration.
(2) Combinations of reserve credits and insurance replacing lost CO_2 by sequestration reserves or other permanent emissions reductions.

GHG Protocol

The GHG Protocol, under the Land Sector and Removals Guidance, defines **removal** as "transfer of a greenhouse gas from the atmosphere to storage within a pool. Removals can be from biogenic or technological sinks and stored in land-based, product or geologic carbon pools."

It considers two types of **sinks**; *technological*, i.e. mechanical or chemical processes that remove CO_2 from the atmosphere and store CO_2 and *biogenic*, i.e. biological processes that remove CO_2 from the atmosphere.

And **capture** is defined as "a type of GHG flux that alone is neither an emission nor a removal. GHG capture is the collection of a greenhouse gas from a source for storage within a pool. It is a flux between non-atmospheric pools – rather than an exchange with the atmosphere – in which GHGs are collected prior to release to the atmosphere and transferred to storage in non-atmospheric pools, preventing a GHG emission".

The Protocol names "geologic storage pathway" to the consecutive and interlinked stages associated with the acquisition and storage of carbon in geologic reservoirs.

Geologic storage pathway	Type of geologic storage	Pathway description	Example	Does this constitute as a removal?
Captured GHG pathway	Captured GHG	GHGs are created but captured from an industrial point source prior to release to the atmosphere and stored in geologic reservoirs	Point source fossil carbon capture and storage (CCS)	No
Removal pathway	Technological removals with geologic storage	CO_2 removed from atmosphere via technological sinks and stored in geologic reservoirs	Direct air carbon capture and storage (DACCS)	Yes*
	Biogenic removals with geologic storage	CO_2 removed from atmosphere via biogenic sinks, harvested and used as a product then biogenic CO_2 is captured and stored in geologic reservoirs	Bioenergy carbon capture and storage (BECCS)	Yes*

Table 3: Description and examples of different geologic storage pathways based on the origin of CO_2. Source: GHG Protocol (2022), Land Sector and Removals Guidance (Draft for Pilot Testing and Review)

The Alperia case would fall into captured GHG without constituting a removal. Instead, this pathway would be considered in the GHG inventory as reduced emissions over time because, in previous years, emissions were released from the company's operations or value chain and in the reporting year GHGs would be instead captured and stored. The Protocol allows companies implementing this solution to not report emissions in the respective scope 1, scope 2 or scope 3 category for any CO_2 that is captured and stored (if detailed geologic storage requirements are met). While any GHGs not captured and all emissions from the capture process must be, certainly, accounted for. Fugitive emissions would correspond to scope 1, while emissions from other processes in the geologic storage pathway in the relevant scope 3 category.

If the capture GHG is destinated to storage, companies may account for and report **Net removals with geologic storage** (or not report emissions associated with captured GHG with geologic storage) if certain requirements described in the Guidance are met.
In the cases where no single entity owns or controls both the sink and the pool of the CO_2 removals, in order to report this scope 1 net removal:

- → The multiple entities involved in the geologic removal and storage pathway shall develop a contractual agreement which specifies: (1) The ownership of the CO_2 sinks and pools and resulting removals, and the responsibility (obligations) of the GHG sources and resulting emissions across the entire geologic removal and storage pathway; and (2) Which single entity accounts for the removals as scope 1, and mechanisms to avoid double counting.
- → In such cases, a single ton of CO_2 removal with geologic storage shall not be reported by more than one entity under scope 1.

In the case capture facilities are in the value chain (Alperia's clients), corresponding emissions avoided should not be reported under scope 3, while any fugitive emissions at the facility or in the storage pathway should be accounted under scope 3 category.

By the first quarter of 2025 an updated version of standards and guidance of the GHG Protocol will be published where the CCUS will be widely considered, and so a deeper understanding and further refinement of the accounting process will be achieved.

Application for Alperia

Alperia Ecoplus Srl (AEP) is a society specialized in district heating, being one of the biggest operators in Italy, with around 248 GWh produced and distributed. It owns and manages six plants in the Alto Adige: Bolzano, Merano, Verano, Sesto, Chiusa and Lazfons. It also manages the district heating of Silandro from which possess 49% of the quote.

Although Alperia owns other subsidiaries, the primary focus will be on AEP, as it is the largest contributor to emissions when considering only Scope 1 emissions. In 2022, AEP's carbon dioxide equivalent (CO_2eq) emissions were 184,6 gCO_2eq per kWh. Projections estimate emissions of 161,0 gCO_2eq/kWh for 2024, 195,5 gCO_2eq/kWh for 2027, and 144,2 gCO_2eq/kWh for 2031. Emission levels are expected to see an increment from 2028 due to the implementation of a gas turbine power plant at the Bolzano hospital.

However, to contextualize these values, the average emission value for Italy in 2022 was 368 gCO_2eq/kWh (Energy Institute, 2024), highlighting that AEP's emissions remain below the national average.

Plants configuration

Moving into a detailed analysis of the emissions sources, Alperia Ecoplus owns the following plants:

<u>Bolzano direct heating system</u>:

- A production central called Bolzano Sud, consisting of 9 production units. Two combined heat and power plants (CHP, cogeneration), fed with natural gas with an electric power of 1.824 kW and a thermal power of 1,87 MW each. Five boilers fed with natural gas, four of 8 MW and one of 3,5 MW and an additional boiler fed with gasoil of 10,3 MW.
  Last, a heat recovery from the Bolzano waste to energy plant, where the recovered thermal power is of 30 MW. This thermal energy produced is transferred to Alperia's district heating system, while all the process, and so emissions, are in charge of Eco Center S.p.A.
- A production central called Infranet composed of two production units, both are cogeneration units with internal combustion engine fed with natural gas with an electric power generation of 140 kW and a thermal power generation of 0,21 MW.
- Bolzano's hospital central projected for 2026, composed of a gas turbine with an electric power of 1,72 MW and a thermal power of 7,13 MW and two natural gas boilers with a thermal power of 6,43 MW each.

In 2022 the thermal and electric power produced by these plants was of 30.152,9 MWh, leading to 7.990,83 tCO_2eq of scope 1 emissions and so 265,0 gCO_2eq/kWh.

<u>Chiusa direct heating system</u>:

- The production central is composed of five production units. One biomass boiler of 3 MW, one natural gas boiler of 8 MW, two cogeneration units with internal combustion engines fed with natural gas with an electric power equal to 1,06 MW and a thermal power of 1,25 MW each. Last, another cogeneration unit with internal combustion engine fed with natural gas with an electric power of 140 kW and a thermal power of 0,21 MW.

In 2022 the total thermal and electric power produced in Chiusa was of 20.042 MWh with total emissions of 2.012,8 tCO_2eq and so 100,43 gCO_2eq/kWh.

<u>Lazfons direct heating system</u>:

- Production central composed of three boiler production units; two fed with biomass, one of 1,2 MW and the other of 0,34 MW; and one backup gasoil boiler of 2,6 MW.

In 2022 the total thermal power produced in Lazfons was of 2.670,3 MWh that led to 31,87 tCO_2eq of scope 1 emissions and so 11,94 gCO_2/kWh.

<u>Merano direct heating system</u>:

- Maia Bassa central composed of two natural gas boilers with a recovered thermal power of 2,9 MW each and a gas turbine with an electric power of 6,55 MW and a recovered thermal power of 10,59 MW.
- Bosin central composed of two natural gas boilers with a recovered thermal power of 9,17 MW each.
- Merano Sud biomass central composed of one natural gas boiler with a recovered thermal power of 8,0 MW, one natural gas internal combustion engine with an electric power of 250 kW and a recovered thermal power of 0,375 MW, and finally one biomass boiler with a recovered thermal power of 8,0 MW.
- Bauhof central composed of a natural gas boiler with a recovered thermal power of 8,0 MW.
- Terme Merano central composed of two natural gas internal combustion engines with an electric power of 320 kW and a recovered thermal power of 0,425 MW each and two natural gas boilers with a recovered thermal power of 1,86 MW each.
- Meranarena central composed of a natural gas internal combustion engine with an electric power of 440 kW and a recovered thermal power of 0,549 MW.

In 2022 the thermal and electric power produced by these plants was of 156.033,9 MWh, leading to 33.533,84 tCO_2eq of scope 1 emissions and so 214,9 gCO_2eq/kWh.

<u>Sesto direct heating system:</u>

- The central is composed of two biomass boilers with a thermal power of 4,5 MW each and one backup gasoil boiler with a thermal power of 8 MW.

In 2022 the thermal power produced by the plant was of 27.612,4 MWh, leading to 534 tCO_2eq of scope 1 emissions and so 19,34 gCO_2eq/kWh.

<u>Verano direct heating system:</u>

- The central is composed of one biomass boiler with a thermal power of 0,9 MW and one gasoil boiler with a thermal power of 0,9 MW.

In 2022 the thermal power produced by the plant was of 1.787,7 MWh, leading to 14,5 tCO_2eq of scope 1 emissions and so 8,09 gCO_2eq/kWh.

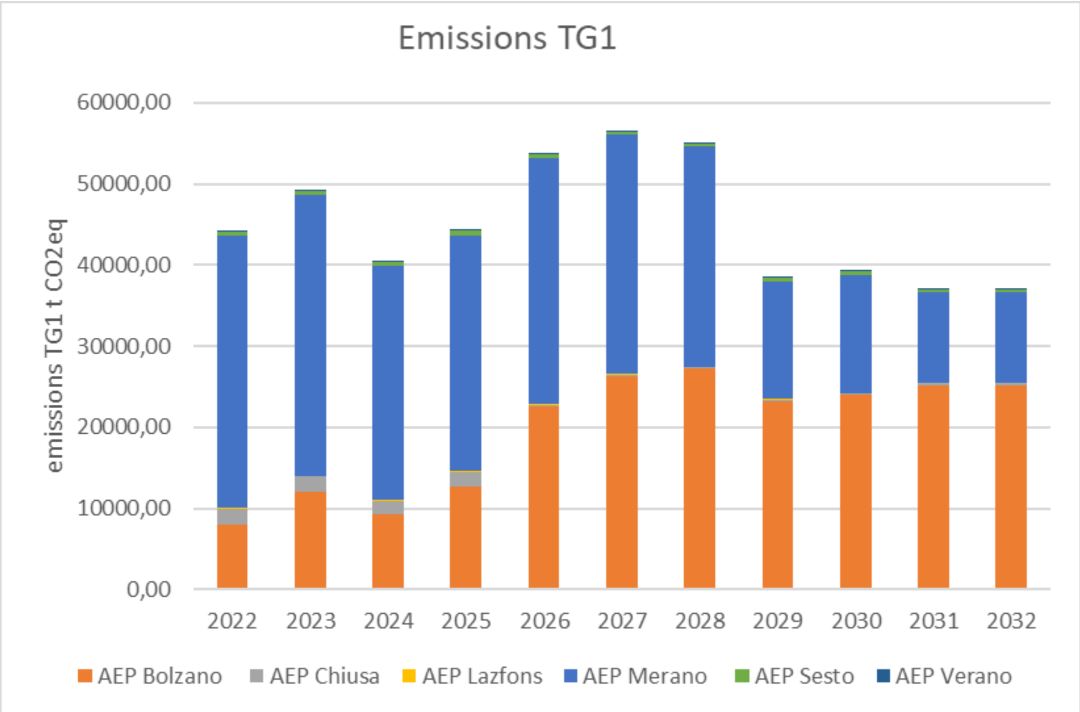

Figure 7: Comparison of Scope 1 emissions across Alperia Ecoplus (AEP) plants

As it can be seen in the presented numbers, the locations with the highest impacts are Bolzano and Merano.

Forecasts illustrate that scope 1 emissions per kWh of produced power will be:

gCO_2eq/kWh	**2022**	**2024**	**2027**	**2031**
Bolzano	265,01	250,66	299,24	288,55
Merano	214,91	247,28	198,20	95,05

Table 4: gCO_2eq/kWh records and forecasts for Bolzano and Merano

While the corresponding scope 1.a stationary emissions:

tCO_2eq	**2022**	**2024**	**2027**	**2031**
Bolzano	7.990,83	8.718,20	26.243,38	25.163,15
Merano	33.533,85	30.197,16	29.500,07	11.180,73

Table 5: tCO_2eq records and forecasts for Bolzano and Merano

It has to be considered that direct emissions are not the only factor affecting the decision making for the selection of the most adequate plant for the project.

In some technologies, the stability of the plant in terms of fluctuations in the flue gas flow rate is also a requirement. Seasonal variations are not allowed since they would imply the suspension of the capture plant and the subsequent energy and cost penalty.

Consequently, the operating hours and the CO_2 flow rate of Bolzano Sud and Merano most significative plants, in terms of capture project suitability, were calculated:

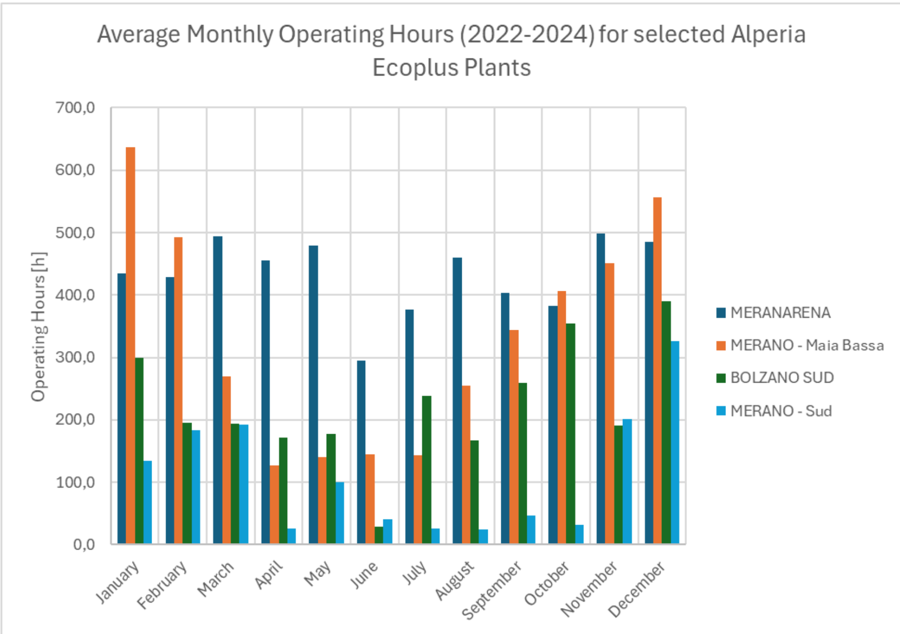

Figure 8: Average monthly operating hours from 2022 to 2024 for selected Alperia Ecoplus plants

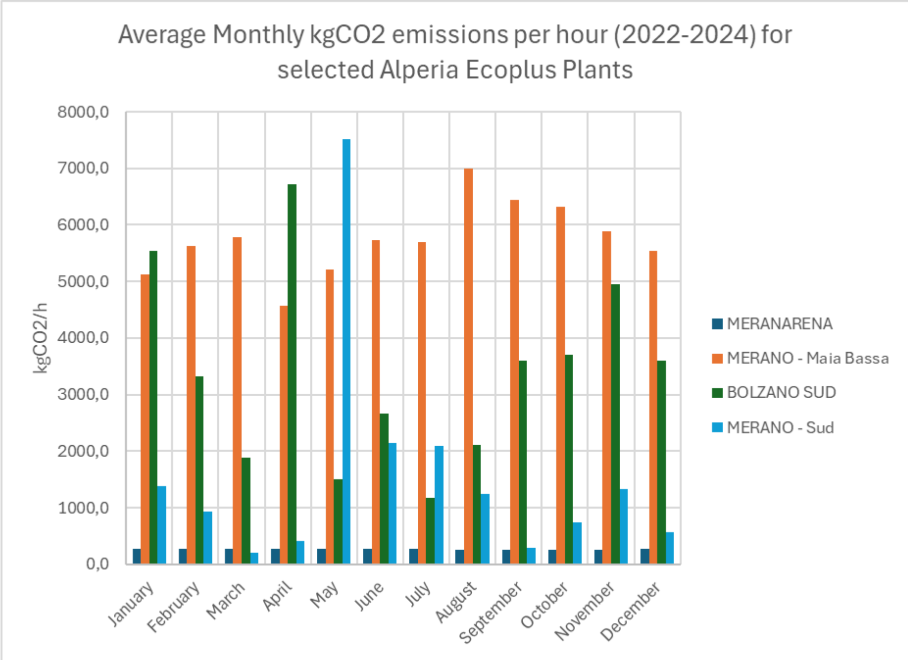

Figure 9: Average monthly flow rate from 2022 to 2024 for selected Alperia Ecoplus plants

	IQR op hours	IQR kgCO_2/h
Bolzano Sud	93,73	1952,84
Merano Sud	156,24	1033,54
Merano Maia Bassa	316,51	535,30
Merano Arena	82,51	9,64

Table 6: Interquartile range (IQR) for operating hours and flow rate for selected Alperia Ecoplus plants

The calculation of the interquartile range (IQR) gives an idea of the dispersion of the data. The lower values reported are for the Merano Arena and Bolzano Sud, indicating lower variability between months. It is important to note that the values for each month represent the averages from the past three years. This pattern is also evident in *Figure 8*, where Maia Bassa exhibits the greatest fluctuations in operating hours, making it the least suitable option.

On the other hand, regarding the CO_2 flow rate, Merano Arena exhibits the lowest interquartile range, reflecting not only its lower variability but also the stability of its emissions throughout the months. Maia Bassa follows, displaying a relatively consistent pattern compared to the other plants. The highest seasonal variation in CO_2 flow rate is observed at Bolzano Sud. Merano Sud also shows fluctuations in the flow rate; however, the elevated value recorded in May should not be considered representative, as it results from an anomaly.

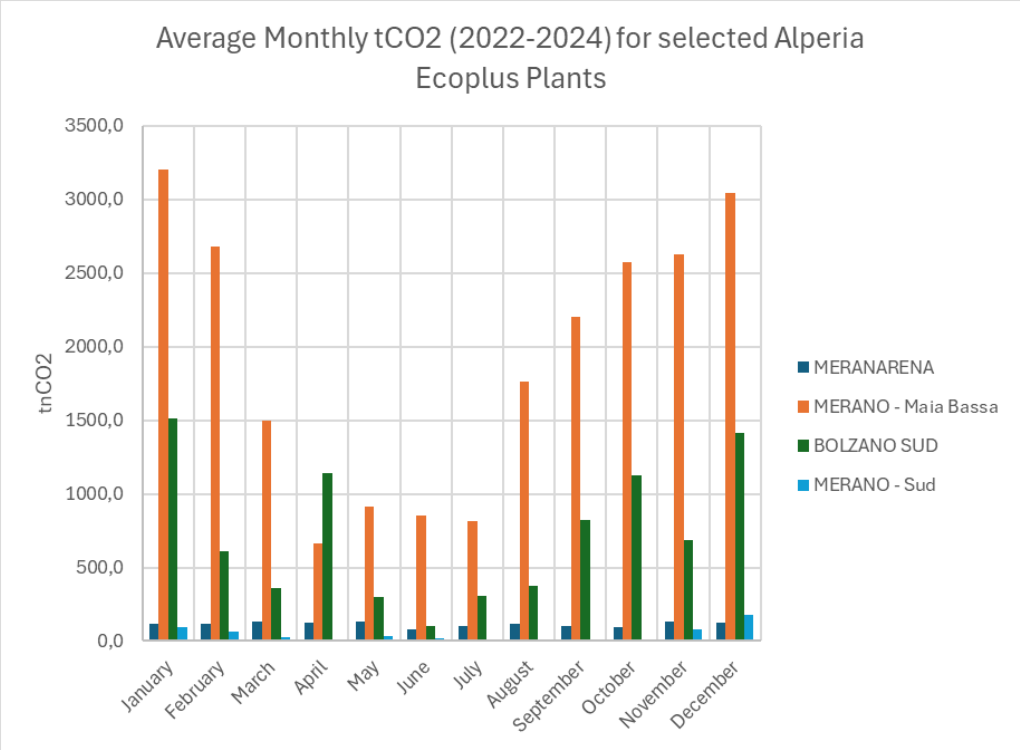

Figure 10: Average monthly tCO_2 emitted from 2022 to 2024 for selected Alperia Ecoplus Plants

The total tCO_2 obtained as the addition of the averages from each month for the past three years are: Merano Arena, 1379.7 tCO_2/y; Maia Bassa, 22820.9 tCO_2/; Merano Sud, 541,1 tCO_2/y and Bolzano Sud, 8752.7 tCO_2/y.

According to the three performance indicators analysed, Merano Sud will be dismissed as a potential site for the Capture Project. This is due to its low CO_2 emissions, which fall below the operational capacity of capture technologies, and the significant variations observed in its operating hours.

Merano Arena will also be dismiss, even though the plant has a steady operational time, the CO_2 flow rate is quite low, and even if a technology could be able to work in such low flow rates it wouldn't be economically feasible.

Maia Bassa demonstrates the highest potential among the Merano plants, primarily due to its substantial CO_2 emissions. It reports the largest annual CO_2 emissions, all concentrated in a single location. The most accurate reflection of current conditions comes from 2024 data, as the plant underwent modifications. In 2024, the CO_2 emissions totalled 17.329,40 tCO_2, a slightly lower value compared to the previously reported average.
Bolzano Sud also aligns with the Capture Project requirements, given its relatively stable operating hours and annual CO_2 emissions of approximately 9 $ktCO_2$.

Bolzano Sud

The following image exhibits the geographic layout of the current Bolzano's plants. Additionally, *Table 7* outlines the projected emissions, highlighting the impact of the new hospital plant and the biomass consumption from Bolzano Sud plant.

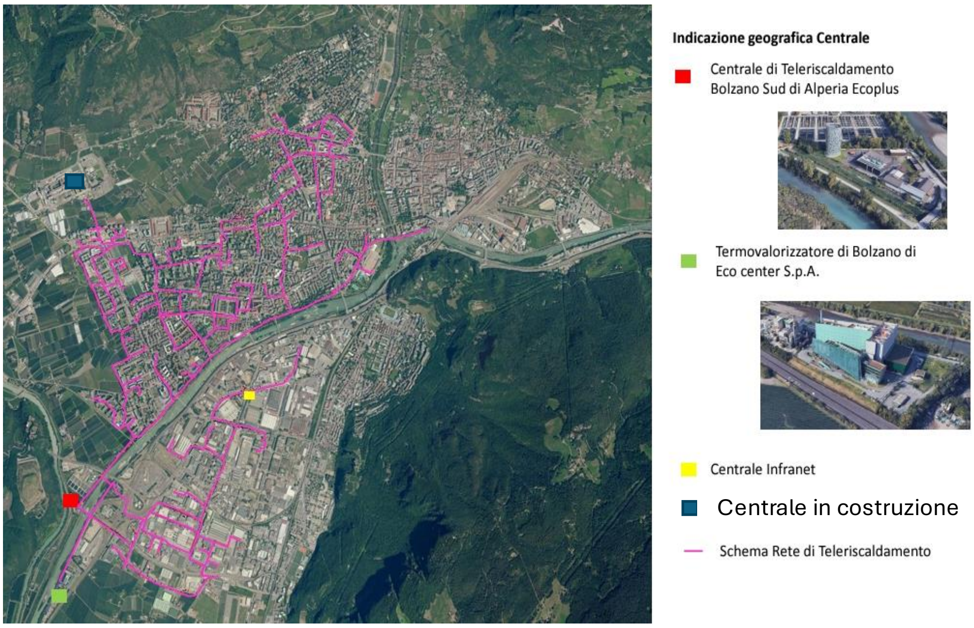

Figure 11: Bolzano direct heating system

[tCO_2e]	2023	2024	2025	2026	2027	2028	2029	2030	2031
Emissions from Natural Gas cons.	11960,89	7523,41	12725,65	22518,91	26243,38	27199,39	22769,04	23531,25	24744,57
- of which Hospital Gas turbine	0,00	0,00	0,00	12273,17	12470,74	12470,74	12470,74	12470,74	12470,74
- of which INFRANET	1262,86	1697,60	1185,43	1216,75	1216,75	1216,75	1216,75	1216,75	1216,75
- of which CHP BZ SUD	9203,59	4072,86	6525,68	1872,14	1872,14	1872,14	1872,14	1872,14	1872,14
- of which BZ SUD boilers	1494,43	1752,95	5014,54	7156,85	10683,75	11639,76	7209,41	7971,63	9184,95
Emissions from Biomass cons.[2]	0,00	0,00	0,00	0,00	0,00	0,00	400,83	418,57	418,57
Total emissions	11960,89	7523,41	12725,65	22518,91	26243,38	27199,39	23169,86	23949,83	25163,15
- of which Bolzano SUD	10698,03	5825,81	11540,22	9028,99	12555,89	13511,90	9482,38	10262,34	11475,66
BZ SUD + Hospital GT emissions	10698,03	5825,81	11540,22	21302,16	25026,63	25982,64	21953,12	22733,08	23946,40

Table 7: Estimation for Bolzano emissions, total and for each plant

[2] all from Bolzano Sud

The potential CCUS project will be calculated having as basis the Bolzano Sud production central and the projected gas turbine at the hospital. Infranet central will be leaved by side due to its lower energy production and so lower emissions, additionally, the infrastructure belongs to third parties hindering the capture project.
It is important to consider that, the fluxes from the two centrals are geographically separated, presenting a challenge for the capture plant that will require further assessment.

For achieving the Business Strategies, Alperia must reduce its total emissions (three scope types) around 400.000 tCO_2eq by 2031. Yet, *Table 7* shows only scope 1 stationary emissions, meaning the reduction that could be achieved through the CCUS project implementation in Bolzano Sud and in the projected gas turbine would be, by 2030, only of 22.733 tCO_2eq. Without considering the amount of CO_2 that actually contributes to CO_2-equivalent emissions, the efficiency of the capture technology and how the GHG Protocol considers this type of activities, since even though the main objective is the reduction on the impact of Alperia emissions, it is relevant at company level to frame the project into GHG standards in order to obtain the respective accreditations.

In the following figure it can be seen Bolzano Sud plant; in detail, its five chimneys from the boilers, two chimneys from the CHPs and the emergency gasoil boiler's chimney.

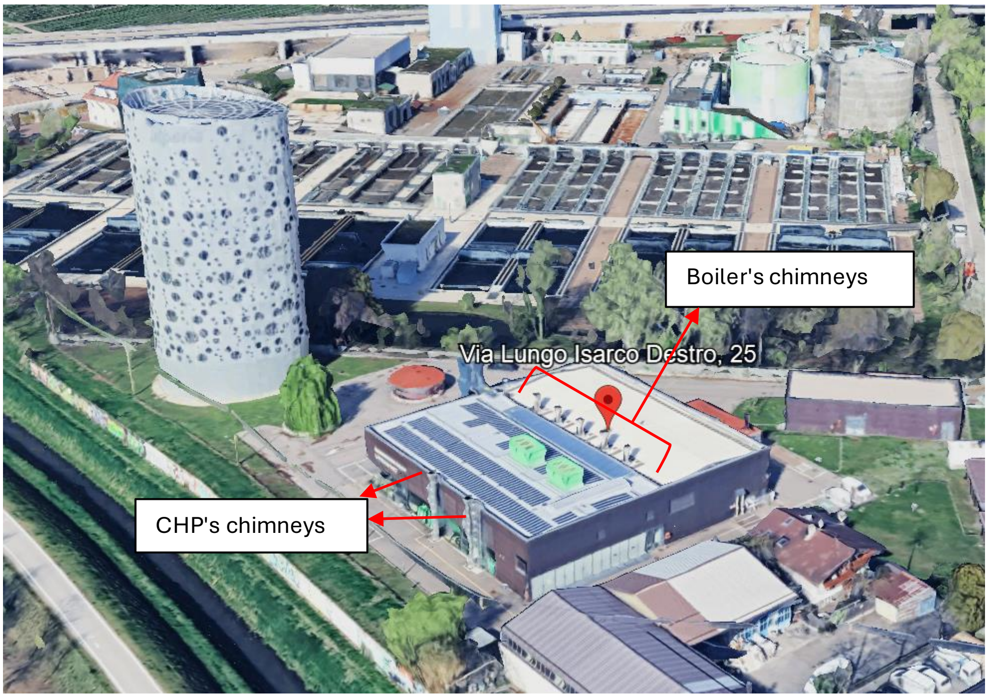

Figure 12: Bolzano Sud district *heating plant*

The total area available for the project, encompassing capture installations and utilization or storage facilities for subsequent land transportation, is approximately 3.298 m2, as illustrated below.

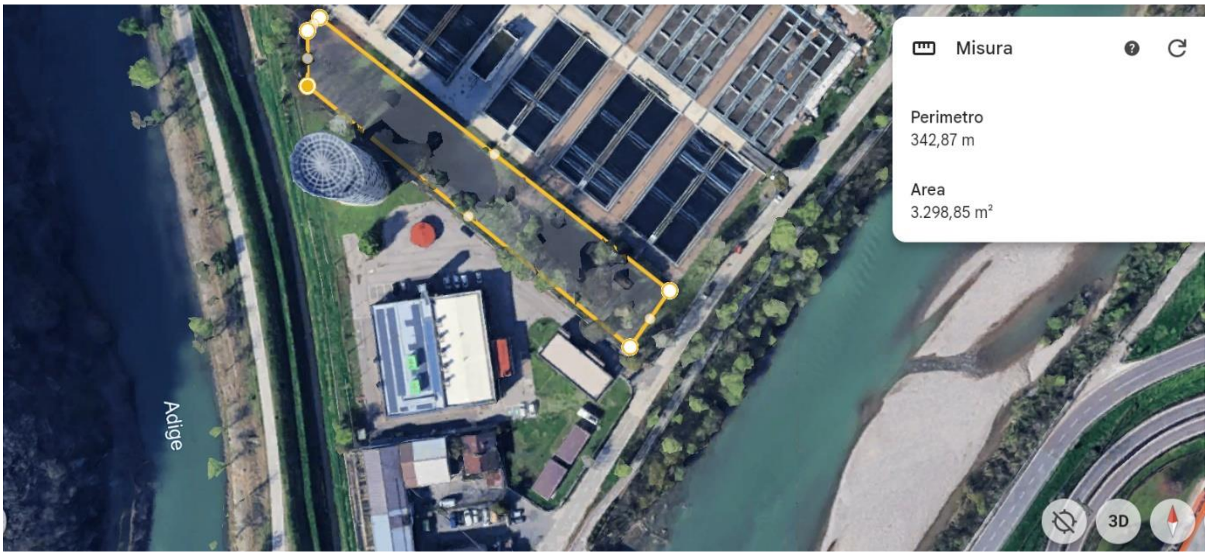

Figure 13: Available surface for the CCUS project

<u>Merano Maia Bassa</u>

As mentioned earlier, the central with the highest potential for a capture project in Merano is Maia Bassa. Emissions in tCO_2 equivalent are reported in the following table.

[tCO_2e]	2023	2024	2025	2026	2027
Total emissions Maia Bassa	24.306,19	17.363,52	17.364,11	17.364,11	17.364,11

Table 8: tCO_2eq registered and projected emissions from Maia Bassa's central (Merano)

Projected emissions from 2027 and onwards remain constant.

The reduced emissions in 2024 compared to 2023 are attributable to a decrease in the electric energy sold to the client. This suggests that the production capacity remains larger, potentially leading to increased production and so emissions. Furthermore, emissions are approximately 20ktCO_2, which is comparable to the Bolzano scenario, and potentially more advantageous due to the localization of all emissions at a single site.

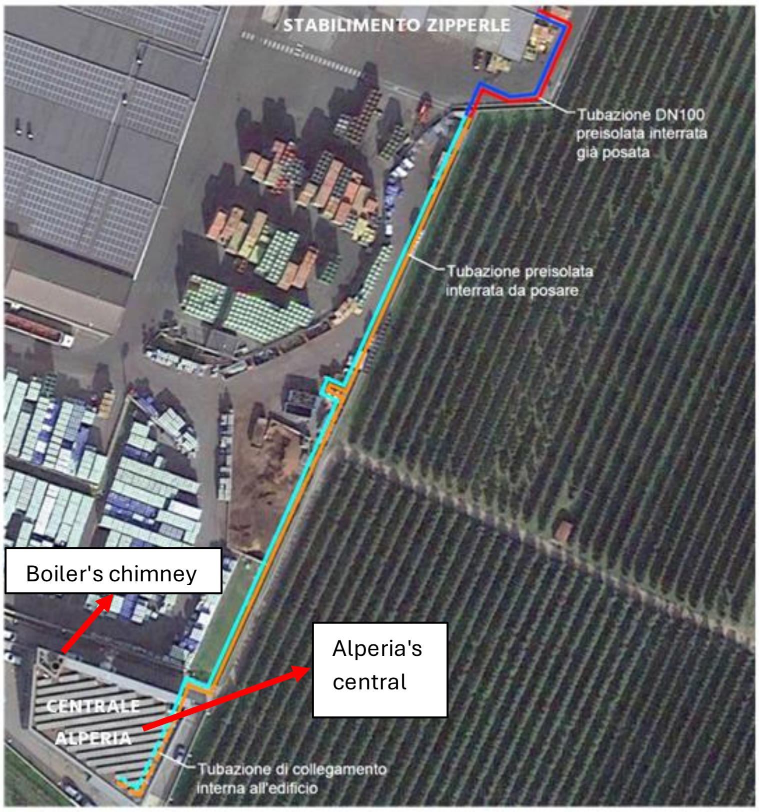

Figure 14: Merano Maia Bassa Central

Finally, it is important to address the potential inherent in Alperia plants regarding biomass production. The capture of CO_2 produced from the power generation through biomass as feedstock is called Bioenergy with Carbon Capture and Storage (BECCS), as earlier mentioned. This modality presents more opportunities compare to CO_2 capture from natural gas conversion, mainly in regulatory aspects. This method is considered to achieve "negative emissions" since the biomass used is plant material that absorbs CO_2 as it grows, then if the process does not emit CO_2, the overall effect can be to reduce atmospheric CO_2.
The GHG Protocol considers it a net biogenic CO_2 removal and thus can be accounted for under the removals category, where it can be classified as a Scope 1 net removal or Scope 3 net removal, depending on the entity that owns and controls the storage.

So far, Alperia biomass utilization occurs in the same plants that utilize natural gas, meaning that, under a capture project, the emissions would be treated jointly, causing the carbon to lose its biogenic condition. This may constitute a significant consideration for the Group when making future decisions regarding their facilities.
Nonetheless as IPCC reports, the overall economics of CCS with biomass combustion depends on local circumstances, especially biomass availability and cost, which indeed is a factor in the Alto Adige, since the demand of biomass is higher than the offer.

In the following sections, emission values will be derived from projections for the year 2030, as Alperia's CCUS project is scheduled to commence in that year.

Another assumption, unless specified, will be the % of capture efficiency. The US Department of Energy establishes as target a 90% CO_2 removal efficiency. In addition, numerous sources in the literature (Ciferno et al, 2009) utilize this percentage, thus it will be considered that the capture technology possesses the efficiency to remove 90% of the CO_2 from the flue gas.

Carbon capture

The most suitable carbon capture technology for both Bolzano and Merano is post-combustion capture, as fuel combustion occurs in the presence of air. This process captures carbon dioxide from a low-pressure (approximately 1 bar) and low CO_2 content (3-20%) gas stream, typically at high temperatures (120-180°C).

The flue gas analysis will be focused exclusively on the Bolzano Sud plant.

Emissions monitoring from 2024 indicate that the absolute static pressure in the conduits consistently remains below 1 bar, averaging approximately 0.9 bar across all conduits.

Regarding CO_2 content, monitoring data from the past three years show that natural gas boilers produce a gas stream with approximately 10% CO_2 (v/v), while oil boilers yield around 13% CO_2 (v/v). In 2022, internal combustion engines recorded CO_2 concentrations of approximately 9% (v/v), which decreased to 5-6% (v/v) in subsequent years. These values remain below the upper limit of 20% recommended for the post-combustion capture process.

The monitored values for the gas stream temperature ranged from an average minimum of 147°C to an average maximum of 212°C. Internal combustion engines exhibited values exceeding the recommended temperature range. This indicates that flue gas temperature is a parameter that should be carefully considered during the design phase.

NOx, SOx and particular matter are impurities allowed in low percentages in the post-combustion capture process. The gas stream from Bolzano Sud doesn't present concentrations of sulphur oxides and particular matter has been found only in 2023 in one of the chimneys, with only 2,5mg/Nm3, leading to its dismissing. Nitrogen oxides are present in the system flue, ranging from an average minimum of 63 mg/Nm3 to an average maximum of 188 mg/Nm3. In the case a solvent technology is chosen, the NOx presence must be evaluated since it can be detrimental for CO_2 capture solvents, and it can lead to hazardous degradation products. A pretreatment could be required before the post combustion takes place.

Commercially available capture technologies

Multiple companies in the market offer post-combustion technologies. Suppliers considered include:

Carbon Clean: Founded in 2009 with its first project in 2016, offers two types of technologies:

- Cyclone CC Modular Technology: modular, prefabricated and skid-mounted carbon capture solution. Combines two technologies; Rotating packed beds (RPBs) process equipment technology and Carbon Clean's proprietary amine-promoted buffer salt solvent technology. It reduces the overall cost of carbon capture by up to 50% and has a physical footprint up to 50% smaller than conventional carbon capture units.
- CaptureX Semi-modular Technology.

Guarantee a reduction in heat requirements and improvement of efficiency of heat transfer, collectively reducing the cost to regenerate solvents. There are lower degradation and corrosion rates, improving solvent make-up and waste disposal, and a lower pump and cooling water duty.

Ensure a reduction in heat requirements and an improvement in heat transfer efficiency, collectively lowering the cost of solvent regeneration. Reduce degradation and corrosion rates, enhancing solvent longevity and reducing waste disposal; additionally, decrease pump and cooling water requirements.

Aker Carbon Capture – SLB Capturi

- Just Catch: easy to fabricate, transport, install and operate, compact design, short delivery time and low cost. Utilizes SLB Capturi's solvents and key features. It requires a minimum of 100 ktCO_2/y and seasonal variations necessitate turning off the system, resulting in energy losses.

Offer the pre-qualification assessment, feasibility study, an optional mobile test unit and preparation for front-end engineering design (in case of not being required, saves cost and time), the front-end engineering design, execution and operational support.

Linde: Linde has been developing and optimizing gas processing, separation and liquefaction technologies for 140 years. It also focusses on CO_2 plants, offering capturing, purification and liquefaction.

- OASE blue technology: uses an amine-based solvent and generates a CO_2 product purity of 99.9 vol% (dry).
- Amine wash.
- HISORP CC: based on adsorption and cryogenic separation technologies. It doesn't require steam and either chemical washing agents.

The capture technologies require at least 100ktCO_2 per year.

Nuada

- Ground-breaking MOF (metal organic frameworks) <u>solid sorbent materials</u> that operate via vacuum swing adsorption (VPSA). The CO_2-rich flue gas is conditioned and routed to the carbon capture unit where carbon dioxide is selectively captured by the MOF filters. The lean flue gas returns to the stack to be released to the atmosphere. Once the MOF filters are suitably saturated, they are regenerated and using vacuum, release the CO_2 into a high-purity stream (99%). During this regeneration, the CO_2-rich feed gas is diverted to another parallel column, providing continuous removal.

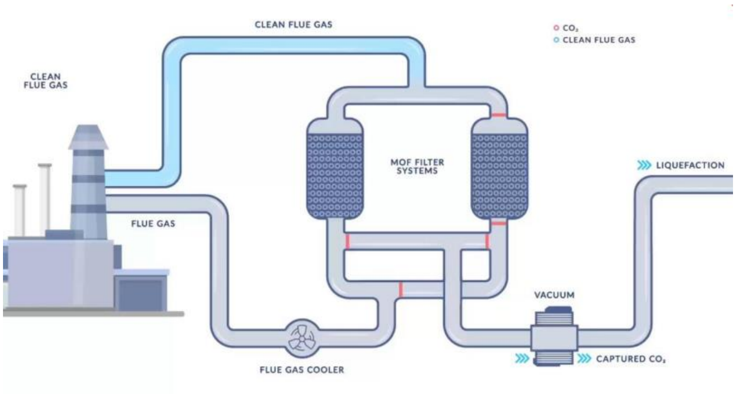

Figure 15: Nuada's capture system

The technology is an electrified solution where seasonal variations and changes in flue gas composition do not represent any issues. It recovers 95% of the CO_2 and is an energy-efficient solution, consuming 200 kWh/tCO_2.

Nuada offers a prefabricated, containerized plant for quick and accurate in-field assessment of the technology. The system is housed in a 12,2 m ISO container and evaluates CO_2 removal at a 1 TPD (one tonne per day) scale. The service includes transport, installation, operation by their engineers, testing, and decommissioning of the pilot plant, which is configured according to Alperia's flue gas specifications. The pilot phase lasts six months, after which the industrial plant would be implemented.

It is important to note that Nuada has only operated at the pilot scale so far and is about to implement its first industrial-scale plant.

<u>TPI – SIAD</u>: Tecno Project Industriale (TPI) is an Italian society from SIAD group that offers capture technology for low CO_2 concentration sources (up to 5% v/v) obtaining 99,998% pure CO_2. The main characteristics are:

- Capacity availability from 24 to 150 MTPD (metric tonnes per day), approximately between 10 – 60 ktCO_2/year.
- Low steam consumption.
- Based on MEA (amine solvent), without expensive formulations or licensing fees

The captured CO_2 could be used by SIAD, particularly in the food/beverage industry, cultivation, water treatment, metals production or as a refrigerant gas with reduced environmental impact.

To obtain further assessments and continue the analysis of the most suitable technologies, all the above-mentioned providers were contacted. While some responses are still pending, Linde and SLB had to be excluded due to their minimum capture capacity being 100 ktCO_2/y, with a lower threshold of approximately 70 ktCO_2/y under specific conditions, which can't be applicable for Bolzano or Merano, as their direct emissions range between 10-30 ktCO_2 per year.

Only two technology providers can be considered for the implementation of the carbon capture, and will be utilized for the following estimations:

- **Nuada**, with a capture efficiency of 95% and an energy consumption of 200 kWh/tCO_2. As a free heat stream process, operational complexity may be reduced. However, a significant drawback lies in its technical stability. Since the technology has only been developed at a pilot scale, its performance and reliability at an industrial level remain to be demonstrated.
- **TPI**, with a more established technology and presence in Italy, relies on an amine-based solution, which generally requires approximately 900 kWh/tCO_2 and has a lower capture efficiency of around 90%. Its capability to operate under seasonal variations is still to be clarified by their response.

Capture Cost

Regarding the cost of capturing CO_2, some aspects may be considered:

- If a solvent is used for the carbon capture, then, under equal conditions, the CO_2 capture cost is inversely related to the partial pressure (and so to the concentration) of the CO_2 in the flue gas. A higher partial pressure allows a faster transfer of the CO_2 from the exhaust gas to the substance use for capture. This way, the capture installations may be smaller, leading to lower costs; further, it will decrease the energy requirement and so the operative costs.
- In general terms, the incrementation of the capture capacity of a facility would decrease the capital cost per production unit (economies of scale).

The system boundary outlined below encompasses only the capture and compression stages necessary for the production of liquid CO_2. The CO_2 emission flow rates considered are those released at the facility both before and after the implementation of the post-combustion capture technology. Consequently, transport, storage/utilization, and any potential leakage from these subsequent stages are excluded from the cost analysis.

Several studies estimate the cost of carbon capture at industrial level. From IPCC report on CCS, different studies are reported from power plants ranging between 300 and 700 MW. These plants, even though much larger than Alperia facilities, have been used for obtaining an average and for understanding the cost order of magnitude.

Another study (Pieri and Angelis-Dimakis, 2021) utilizes 23 data points from NGCC plants, characterized by emissions higher than 4.5 $MtCO_2$, for generating estimation curves and obtaining a representative model. They derived equations for calculating the total capital requirement (TCR) and the operation and maintenance cost (O&M), after performing a statistical analysis, for plants operating with chemical absorption and for natural gas combined cycle (NGCC) plants. Nonetheless these equations couldn't be directly applied to Alperia's scenarios because the regression analysis was performed using (0.1, 0.1) as the zero data point, indicating 0.1 $MtCO_2$, and so, exceeding Alperia's emissions.

Consequently, in the first place, for an OPEX estimation, an extrapolation was performed for the fixed and variable operating and maintenance cost (FOM & VOM) between the amount of CO_2 captured in the reference plants from the IPCC report and the amount of CO_2 that would be captured at Alperia facilities. The FOM & VOM utilized was obtained after clearing the equation of the LCOE (levelized cost of electricity) and extracting the variables from each of the reference plants characteristics; afterwards, the extrapolation was performed.
In order to verify the magnitude of the obtained OPEX, this value was multiplied by the simulated capture energy requirement and the hypothesized tCO_2 captured. The OPEX in €/y obtained was compared with the one achieved after the interpolation with the corresponding values calculated using the equations from the study mentioned above. Because the values were of similar magnitude they were accepted.
The OPEX was estimated for the 2030 predicted captured emissions of Bolzano Sud and Bolzano's Hospital separately; the addition of this two and, finally for Merano Maia Bassa. For all cases the value achieved was:

OPEX (€/MWh)	11,1

On the other hand, to calculate the CAPEX, the equations provided in the mentioned study were applied to derive two TCR values, using the average captured CO_2 from IPCC-reported plants as input. This is because, unlike Alperia's captured CO_2 value, the reported CO_2 falls within the range utilized in the study. From these TCRs, the average was extracted obtaining a TCR in k€ representative for a 1,2 MCO_2/y capture plant. After, considering the average size of the plants (540 MW), a linear interpolation was performed to Alperia's plants size. This value was compared to those obtained through linear extrapolation with the specific studies of the IPCC; because the order of magnitude between them was quite similar, the estimations were accepted. Later on, for enhancing the calculated result, another linear interpolation was done but considering the % increment in the energy requirement for both capture technologies available. Below, the corresponding CAPEX obtained.

		Bolzano Sud	**Bolzano's Hospital**	**BZ (Sud + Hospital)**	**Merano Maia Bassa**
emissions for 2030 (tCO_2/y)		10.242,17	12.446,23	22.688,40	17.329,98
CAPEX (€/kW)	**Absorption (amine solvent)**	316,67	309,68	312,53	316,67
	Adsorption (MOF + vacuum)	83,42	81,36	82,20	83,42

Table 9: CAPEX (€/kW) *estimations for the* studied *facilities and for both carbon capture technologies under examination*

The cost of captured CO_2 was calculated as follow:

$$\frac{€}{tCO_{2capt}} = \frac{LCOE_{capt} - LCOE_{ref}}{\frac{tCO_{2capt}}{kWh}}$$

Equation 1: Cost of captured CO_2 (€/tCO_2captured)

LCOE is the Levelized Cost of Electricity and represents the price at which electricity must be sold for a capture investment to be profitable. The formula for LCOE, as outlined in the IPCC report, incorporates all expenses related to producing a specific amount of electricity annually. In the reported equation, the difference between the LCOE before and after the implementation of carbon capture technology provides an estimate of the cost of the capture project.

For the purposes of this analysis, this difference will be simplified by considering only the capital expenditure and operating expenditure components. The capture cost is then calculated by dividing these costs by the tonnes of carbon dioxide captured per unit of energy consumption. It is assumed that energy consumption remains unchanged after the application of the capture technology compared to the ex-ante state. Further, for all facilities it was hypothesized a fixed charge factor of 12,9% and a plant capacity factor of 77,14%.

Under Nuada's capture technology, the estimated cost was approximately 65 €/tCO_2, while for the amine-based technology, the cost was estimated at approximately 93 €/tCO_2. These estimates are consistent with values reported in the literature. For example, Rubin, Davison, and Herzog (2015) estimate the cost of captured CO_2 to be approximately €70/tCO_2 for an average natural gas combined cycle (NGCC) plant with a typical output of 661 MW. While IEA (2020), reported 81 €/tCO_2 for a capture rate of 90% for coal and gas-fired power plants. This price is expected to see a decrement, subsequent to the development and stabilization of the technologies; where in the power sector the cost of applying CCS could be reduced up to approximately 30% (Irlam, 2017).

Carbon storage

In order to ensure the safety of a storage site, the seepage and leakage risks must be carefully evaluated, as well as other geological risks factors such as seismicity and natural degassing. A potential site must be characterized by a thick and low permeability cover such as shales and mudstone and it should be located at a depth of at least 800 m, in addition, above the deep reservoir there should not be any significant discontinuity. Assuming a hydrostatic pressure gradient and a geothermal gradient of 25 °C/km, CO_2 would reach its supercritical condition (31.1 °C and 73.9 bar) around the 800 m depth, at these conditions there is an increase of CO_2 density and a corresponding decrease in volume. The reservoir must be also characterized by high transmissivity, high permeability, low temperature (between 31 and 120 °C) for not influencing physiochemical behaviour of CO_2, and high pressure (between 80 and 250 bar) to optimize the overall trapping mechanism (Buttinelli et al, 2011).

A potential storage site must have an effective caprock lying on the reservoir with a saline aquifer for the injection of CO_2, CO_2 cannot be injected into dry rocks.

As mentioned earlier, only sedimentary basins contain geological media generally suitable for CO_2 storage and/or sequestration, in detail: (1) oil and gas reservoirs (geological and solubility trapping), (2) deep sandstone and carbonate aquifers (solubility, hydro-dynamic and mineral trapping), (3) coal beds (adsorption storage and trapping), and (4) salt beds and domes (cavern trapping).

Since Alperia has concession in the Trentino-Alto Adige region, this will be considered the target region to identify if there is storage suitability.

The use of depleted natural gas fields will be dismissed as storage option due to the absence of this fields in the region according to the information published by the Ministry of environment and energetic security of Italy through the webGIS UNMIG tool (DGISSEG).

In the article “CO_2 storage potential of deep saline aquifers: The case of Italy” (Donda et al, 2010) it was estimated the CO_2 storage capacity of the Italian deep saline, terrigenous formations. After outlining the suitable sedimentary basins through the country, the geological and physical properties were studied in order to calculate the regional CO_2 storage potential based on the bulk volume of the aquifers.

In *Figure 16*, a simplified geological map of Italy shows the location of 14 potential areas suitable for geological storage of CO_2.

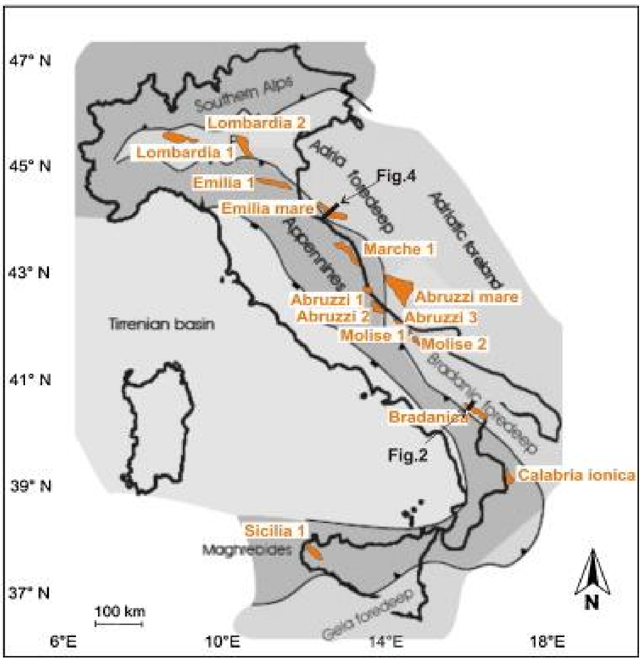

Figure 16: potential areas suitable for CO_2 geological storage. Source: Bertello et al, 2008

As a first approach it can be seen that the Southern Alps area, where Alto Adige is located, presents no potential formations for a storage project.

Further, in the article "The geo-database of caprock quality and deep saline aquifers distribution for geological storage of CO_2 in Italy" (Buttinelli et al, 2011), the potential storage reservoirs in deep saline aquifers were identified through the study of the available Italian deep-drilling data from the project "Visibility of Petroleum Exploration Data in Italy (ViDEPI)" published by the Ministry of the Economic Development of Italy. They evaluated the caprock efficiency through numerical parameterization of rock permeabilities using stratigraphic and fluid chemistry information; physiochemical characteristics of the geological formations; strategic information such as the distribution of deep aquifers, seismogenic sources and areas, seismic events, Diffuse Degassing Structures, heat flow, thermal anomalies, and anthropogenic CO_2 sources. And obtained, as a result, the presence of some potential areas for geological storage of CO_2, as represented in the following figure:

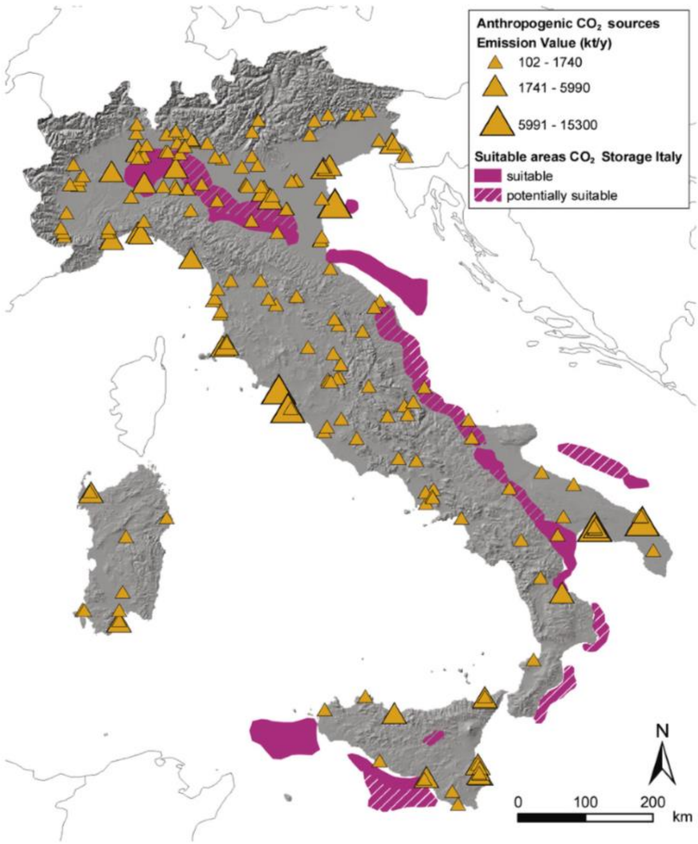

Figure 17: Distribution of potential areas for geological storage of CO_2 (mostly as a good caprock above a deep saline aquifer). Source: Buttinelli et al, 2011

No suitable areas are identified in the Alto-Adige region; only in the Alps fore-deep domains (southern-east of the region of interest) there are some areas "potentially suitable".

A deeper analysis has been performed with the assistance of the geology team from Hydrodata SpA, arriving to the conclusion that even though in the region there are some sedimentary basins, the requirement of a well-sealed caprock in the shallower strata in order to prevent CO_2 leakage is a missing feature.

In conclusion, storage is dismissed from the available solutions for CCUS for Alperia.

Storage by thirds

Due to the infeasibility of CO_2 storage at viable sites for Alperia, attributable to its plant's location and the group's operational area, the possibility of storing CO_2 within the domain of other companies will be evaluated.

Currently, in Ravenna, Italy, it has been lunched a project that represents an opportunity for hard-to-abate industries.

Developed by Eni and Snam in a Joint Venture, the Project Ravenna CCS consists in the realization of a CO_2 storage infrastructure in the depleted gas fields of the Adriatic, at approximately 3.000 m depth.

The project consists in two phases; phase 1 (started in 2024) foresees the capture, transport and storage of 25 thousand tCO_2 per year emitted from the Eni central of natural gas treatment in Casalborsetti. Once captured, the carbon dioxide is transported through conducts that were used before for the natural gas delivery, up to the offshore platform of Porto Corsini Mare Ovest for, finally, being injected.
Phase 2 provides the storage of CO_2 from others hard-to-abate industries (from Italy and abroad) in the same gas field. The aim is to manage a maximum of 4 million tCO_2 per year from 2027 until 2030. From 2030 on, thanks to the depleted gas field capacity, it will be possible to inject up to 16 million tCO_2 per year as a function of the market demand.

Phase	**Capture** Cattura, purificazione e compressione	**Onshore Transport** Rete di trasporto onshore	**Ship Transport** Trasporto via nave	**Storage** Hub di raccolta Centrale di compressione Pipeline offshore Piattaforme e pozzi di iniezione
Owner	Emitters	snam	eni	eni snam
Description	The capture, purification and compression of CO_2 oversees the emitters.	Snam will oversee the onshore transport network, which will be connected to Ravenna's storage site.	Eni will oversee the transport of liquid CO_2 via ship from the port near the emitters to Ravenna's reception port.	The storage system will be managed by Eni-Snam joint venture and will be composed of: one unique collection hub for all the CO_2 (located at Casalborsetti), a compression station, the links between this station and the offshore platform, additional linking lines between the platform and the depleted fields of the Adriatic where CO_2 will be permanently stored.

Table 10: Snam and Eni CCS Ravenna's project, description of each phase and CO_2 holder, "non-binding, for informational purposes only"

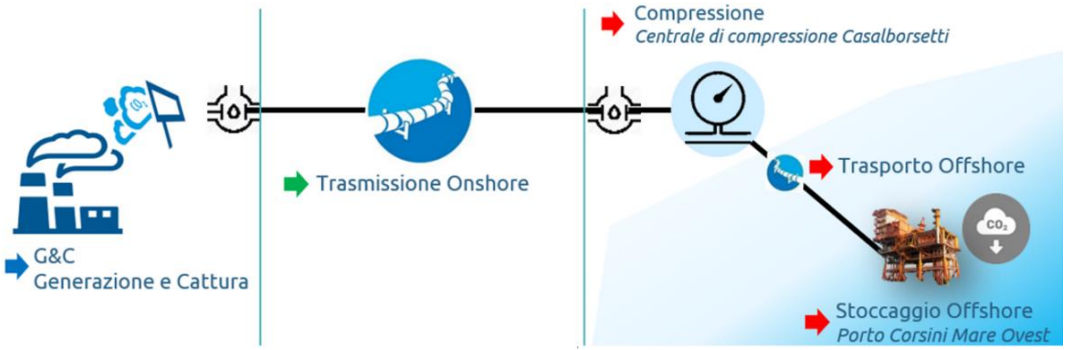

Figure 18: Carbon dioxide pathway through CCS stages under Ravenna's project

Admitted as a project of common interest (PCI) by the European Commission, the storage hub will have a key role in the creation of a supply chain for the decarbonization.

For achieving the second phase, the necessary practices for obtaining the allowances will be implemented in collaboration with the entities, stakeholders, and the territory.

The opportunity for Alperia is situated within phase 2 of the project, wherein it could, from 2027 on, integrate into the supply chain, thereby becoming a stakeholder of Eni and Snam. Subsequently, following the capture of its CO_2 emissions, Alperia would transmit the volume to the Casalborsetti compression station.

For doing so the CO_2 volume could be sent through the following transport modalities, according to Snam and Eni:

1. Gaseous phase via pipeline: through an extensive underground network, that will extend from the storage hub in Ravenna to the areas with a high concentration of industrial facilities.
2. Liquid phase via ship: offers substantial flexibility for various industrial areas/clusters with geographic locations proximate to ports.
3. Liquid phase via train or truck: as option for lower amounts of CO_2 volume.

The second modality won't be considered because of the geographic location of Alperia's plants. The liquid phase modality via ground would represent an optimal solution due to the amounts of CO_2 Alperia would hypothetically capture. Furthermore, there is no certainty the pipeline will arrive to the Alto Adige, at least not in the beginning of the second phase, mainly due to the low concentration of industries in the region, which can be seen in the market survey performed by the project holders:

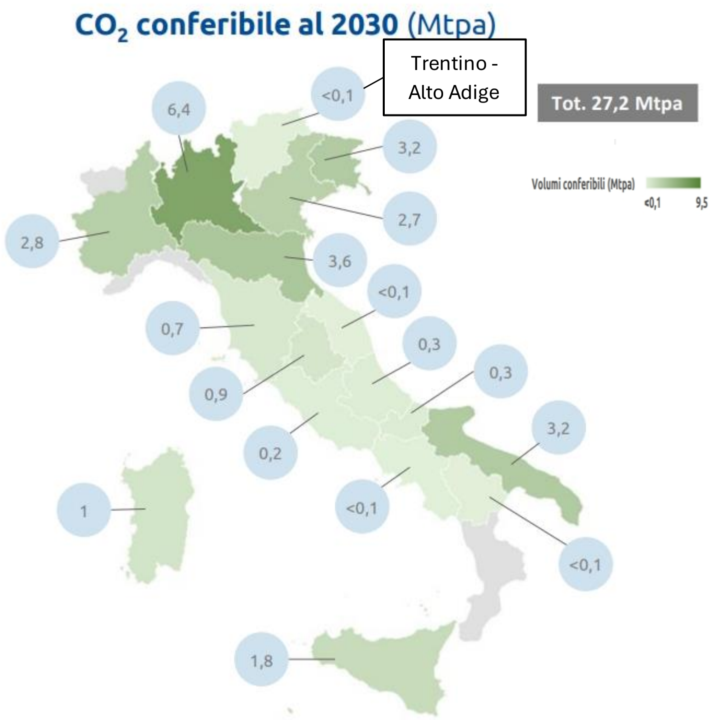

Figure 19: Regional distribution of volumes of conferrable CO_2 *by 2030. Source: Eni-Snam's market survey*

The definition of requirements and costs is in accordance with the Italian regulation that must settle the terms and conditions for the CO_2 management. This process is guided by the provisions set forth in the Italian 2011 decree, which addresses public connectivity and accessibility to transport networks and storage facilities.

The CCS supply chain can benefit from the optimization of investments aimed at creating economies of scale associated with CCS. By aggregating CO_2 sources that are in proximity, it is possible to generate a higher gas flow rate (The European House – Ambrosetti).
The same principle applies to industries, where companies with CO_2 capture projects located in the Trentino-Alto Adige region can consolidate their CO_2 volumes, enabling joint transportation. This aggregation reduces transportation costs and associated GHG emissions.

Carbon transport

Transport is the stage that links the sources with the storage sites of carbon dioxide. It can be performed with CO_2 in gas, liquid or solid state.

The United Nations Sub-Committee of Experts on the Transportation of Dangerous Goods (UN TGD Sub-Committee) classifies CO_2 with the UN 1013 number, class 2.2 (non-flammable-non-toxic gas). While carbon dioxide as refrigerated liquid, is classified with the UN 2187 number, also class 2.2.

Under the Basel Convention on the Control of Transboundary Movements of Hazardous Waste and their Disposal there is no indication that CO_2 would be defined as a hazardous waste, except in relation to the presence of impurities such as heavy metals and some organic compounds that may be entrained during the capture of CO. The Basel Convention does not appear to directly impose any restriction on the transportation of CO_2.

Returning to the studied project, despite the uncertainty regarding the destination of CO_2, an analysis will be conducted considering the information provided in the previous section. It will be assumed that the transportation of the CO_2 volume is under responsibility of Alperia, and that it must be delivered to Casalborsetti compression station.

The distance between Bolzano, Trentino and Casalborsetti, Ravenna averages approximately 366 km, considering both highway and rail routes. In the scenario where flue gas is captured from Merano, Maia Bassa, the distance is approximately 352 km.

Transport through pipeline requires the consideration of certain design factors such as overpressure protection and leak detection. Due to the large volume CO_2 occupies at

atmospheric pressure, the gas has to be compressed to occupy less space. In this modality, the CO_2 stream should preferably be dry and free of hydrogen sulphide to prevent corrosion. This study will not delve into quality requirements because the CO_2 obtained after the capture stage will be 99% pure, according to technology providers, meeting composition specifications.
Furthermore, in the event that Alperia selects pipeline transportation for its sequestered carbon, the infrastructure employed would be provided by external entities, rendering the design parameters unnecessary as well.
It is worth mentioning that because of the scale of the project (<100 ktCO_2/y), generally considered too small for pipeline transport, the network projected by thirds, may not arrive up to Alto Adige unless coupled with other projects to increase the delivered volume.
The details of this projected network depend on the about-to-be-published study from the Italian Energy Ministery (MASE).
Another possibility would be a multimodal configuration, where the CO_2 would be transported by other options up to the nearest pipeline connection. Nonetheless, this would require CO_2 reconditioning due to discrepancies in the CO_2 requirements, rendering it a not viable option and, in conclusion, if the pipeline network doesn't arrive to the region, the CO_2 would have to be transported up to Casalborsetti.

Marine transport is not a viable option due to Alperia's lack of access to ports. Although storage is planned at Ravenna's offshore site, the delivery point is at Casalborsetti compression station (onshore site), with subsequent operations managed by Eni-Snam.

For the reason that a rail network already connects the carbon source (Bolzano/Merano) to its destination (Ravenna), a combination of transport methods is unnecessary. This simplifies the decision to a single-mode solution using either trains or trucks to transport CO_2 in liquid form.

If the captured CO_2 is in a gaseous state, it must be compressed and liquefied before transport; process typically managed by the providers of the capture technology.

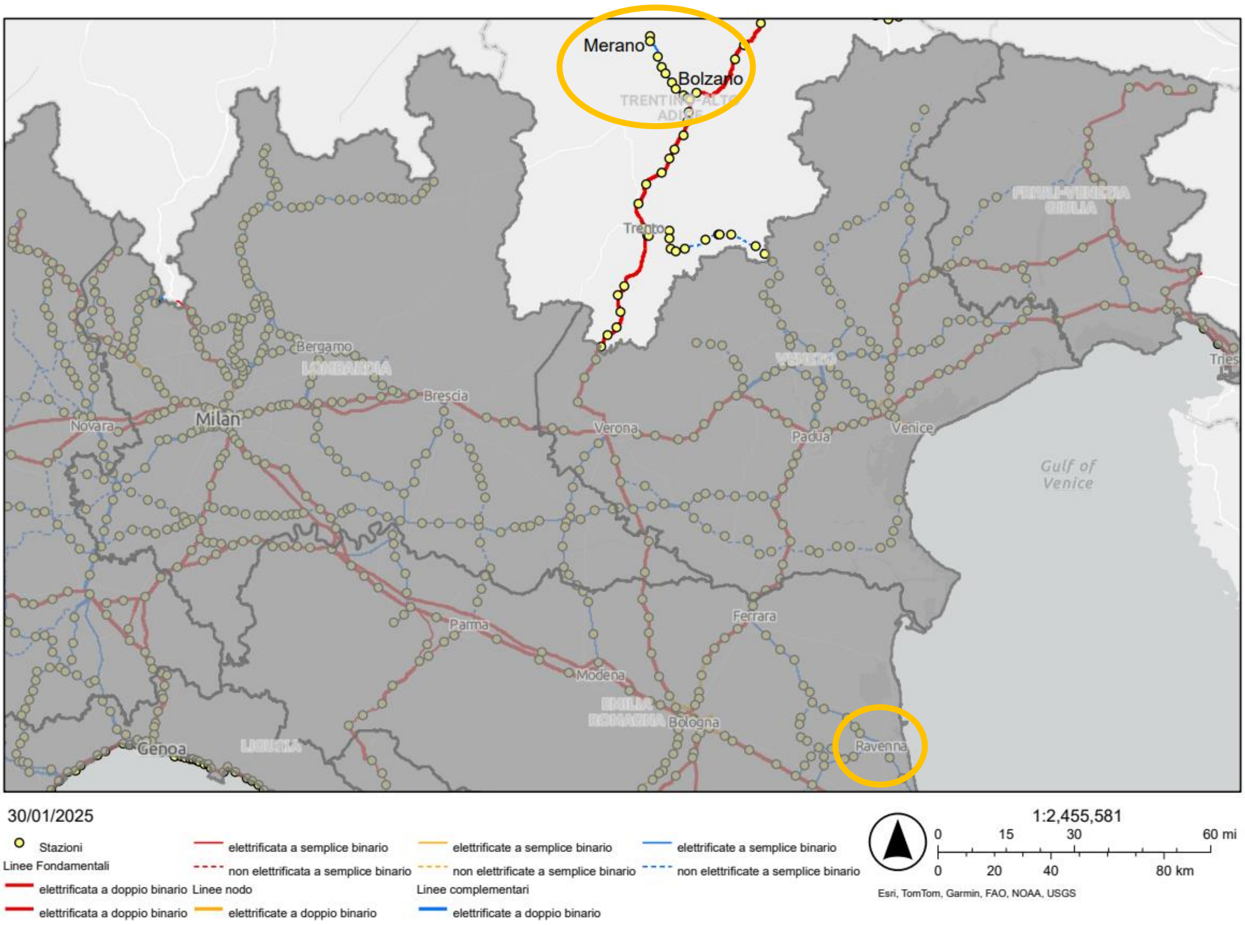

Figure 20: Italian rail network, connections between Trentino-Alto Adige and Ravenna and system specifications. Source: Rete Ferroviaria Italiana (RFI)

An important factor to be considered for these transportation modes is that they emit greenhouse gasses, and so, will need to be included under scope 3 emissions.

"The cost of CO_2 transport by truck and rail in the United States" study (Myers, Li and Markham, 2024) analyses the different transport modes available for liquefied CO_2:

- Tanker trailer (TT), equivalent to articulated truck, gross volume = 25 m3;
- intermodal container truck (IT), equivalent to rigid truck, gross volume = 22 m3;
- tanker rail (TR), gross volume = 83,14 m3 and
- intermodal container rail (IR), gross volume = 81,80 m3.

Because of the lower capacity of IT compared to TT, transportation with the first one would require more trips to move the same amount of CO_2 and so more trucks, trailers, intermodals, maintenance, fees, labour, fuel; in conclusion a higher cost and higher environmental impact.
As the project scale decreases additional labour is required for operation and management of intermodals, leading to higher costs.
The decline of cost with project scale increase, occurs more gradually for IT than for TT. While for RT the trend of reducing costs with increasing project size holds.

Intermodal rail has the highest starting cost of any of the options. Driven mostly by the high cost of intermodals and so the additional labour requirements to load and unload the intermodals from rail car.

The following figures, extracted from the above-mentioned study, map the cost ranges as a function of the transport distance and the scale of the capture project.

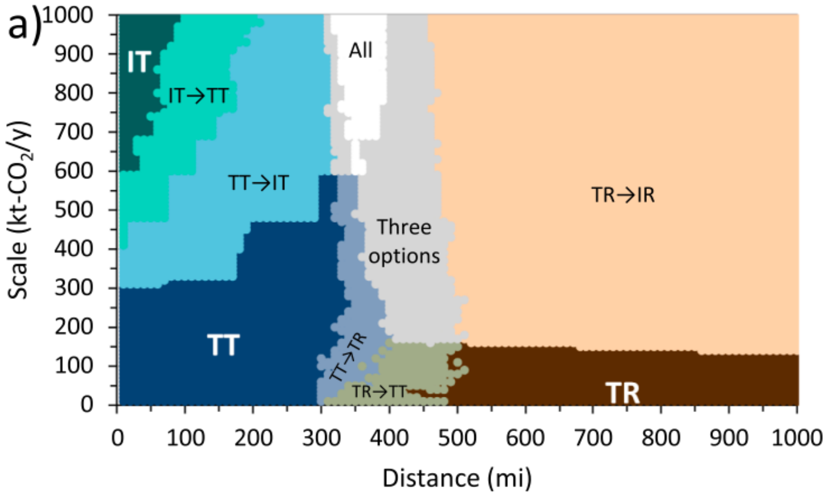

Figure 21: Mapping of the lowest bare cost[3] options for the transport distance and the scale of the project. TT: Tanker Trucks, IT: Intermodal Trucks, TR: Tanker Rail, IR: Intermodal Rail

With the distance for the project under study being around 360 km (~224 mi) and a scale of approximately 30 ktCO_2/y, the lowest cost (excluding financing) would be associated with tanker trucks.

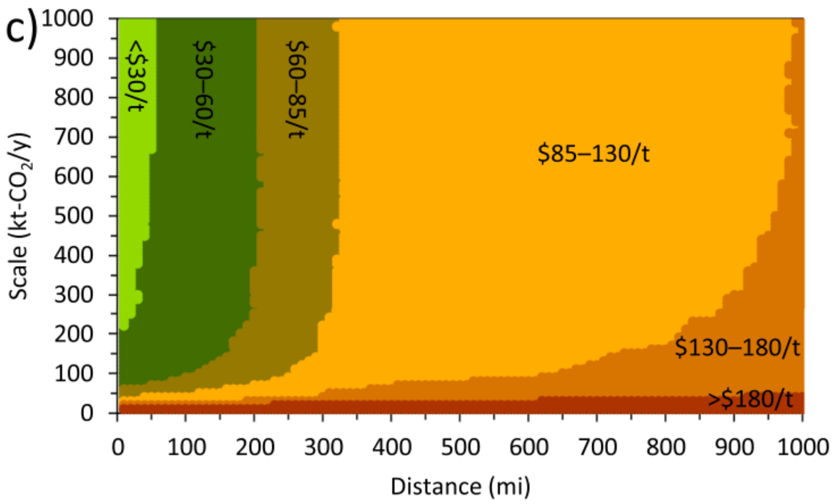

Figure 22: Mapping of the bare cost ranges of the cheapest option for the transport distance and the scale of the project

[3] bare cost: levelized cost without including financing

For what can be seen in the last figure the project would fall in the highest bare cost ranges. Further on, more precise estimations will be performed.

In addition, for the projected distance, pipeline does not figure as the most convenient solution, while truck would be preferred instead of rail mainly because of the base rate (largest cost constituting rail). Lower base rates could be negotiated with rail operators if larger projects are formed by partnering with other emission-intensive industries.

In conclusion, using commercially available technology and grid electricity, CO_2 can be transported as a cryogenic liquid via truck or rail with a net CO_2 delivered of 90-98%. In general, truck is the cheapest option for distances up to ~644 km. For project scales greater than ~400 ktCO_2/y, transport in rigid truck is cheaper than transport in articulated. Intermodal transport on rail is never the cheapest option but is competitive with tanker rail transport at scales over ~200 ktCO_2/y.

Attention should be paid in the coming years to the evolution of the trans-European CO_2 transport network. The Joint Research Center (JRC) from the European Commission has estimated the potential and extent of the future network that will act as a backbone infrastructure that may eventually facilitate additional connections with smaller emission sources through alternative transportation methods. In the presented scenarios, the network arrives to Italy representing an opportunity for the capture projects.

Transport Cost

To estimate costs, the current study considers transport via an articulated vehicle with 5 or more axles, equipped with refrigeration and utilizing diesel fuel. According to the International Transport Forum (ITF), in Italy, the permissible maximum weight for lorries of the aforementioned type is 44 tonnes. Given the limited availability of public data, it will be adopted from Myers et al (2024) study, that approximately 65% of the gross weight pertains to the load. Additionally, the study assumes refrigerated conditions of -28°C at 1.5 MPa. The corresponding CO_2 density would be 1042 kg/m3, allowing the transport to carry 28,6 tCO_2 while ensuring it remains in a liquid state.

To calculate the scope 3 emissions associated with this transport phase, conversion factors from DEFRA UK will be utilized. For freighting goods transport and HGV refrigerated (diesel) activity, specifically for articulated >33t vehicles:

- for 100% laden (considered for the outward trip) = 1,20873 kgCO_2eq/km and
- for 0% laden (considered for the return trip) = 0,73105 kgCO_2eq/km.

The cost estimations will be conducted utilizing the indicative reference values of operating costs for Italian freight transportation enterprises engaged in hire or reward operations, as published in 2024 by the "*Ministero delle Infrastrutture e dei Trasporti (MIT)*" for a vehicle of *category D* characterized by:

- Vehicle weight > 26 tonnes
- Semi-trailer weight > 19 tonnes

			Costi per 1 km	
SEZIONE	CRITERIO	COMPONENTI	VALORE MINIMO	VALORE MASSIMO
AUTOMEZZO	ACQUISTO	VEICOLO	0.26716 €	0.79435 €
		RIMORCHIO	0.08816 €	0.28780 €
		SEMIRIMORCHIO	0.06808 €	0.67100 €
	MANUTENZIONE	VEICOLO	0.24186 €	0.48372 €
		RIMORCHIO	0.03888 €	0.07776 €
		SEMIRIMORCHIO	0.06750 €	0.13500 €
	PNEUMATICI	VEICOLO	0.06752 €	0.21727 €
		RIMORCHIO	0.02600 €	0.50804 €
		SEMIRIMORCHIO	0.02600 €	0.30938 €
	REVISIONE	UMC	0.00045 €	0.00045 €
		OFFICINE PRIVATE AUTORIZZATE	0.00079 €	0.00194 €
	BOLLO	VEICOLO	0.00158 €	0.01125 €
		MASSA RIMORCHIABILE	0.00513 €	0.00969 €
	ASSICURAZIONE	-	0.01611 €	0.06811 €
COSTO PERSONALE	STIPENDI	-	0.36057 €	0.49807 €
	TRASFERTE	-	0.00776 €	0.07624 €
	STRAORDINARI	-	0.00015 €	0.03408 €
ALTRO	ENERGIA	GASOLIO	0.54445 €	0.93726 €
		ELETTRICO	-	-
	PEDAGGIAMENTI	-	0.20054 €	0.20054 €

Table 11: Reference values of operating cost for Italian category D freight. Source: MIT, 2024

From these values the average was calculated for each component, excluding "rimorchio" (trailer).

The CAPEX is represented by the acquisition cost. It is important to note that additional elements may be included in the CAPEX if, for instance, loading or discharging equipment is required.
It is assumed that Alperia does not possess this type of vehicle in its assets, and that in each scenario presented subsequently, they will be acquired. Over time, integrating them into the company's assets may lead to a potential reduction in capital costs.

The values are provided in €/km. To obtain a one-time investment CAPEX, it should be considered the service life of the trucks, and the annual distance travelled. The typical service life considered for accounting depreciation is 5 years, while the annual distance can be calculated for the specific project under consideration, through the multiplication of the distance between the source and Casalborsetti compression station by the number of trips required per year (tCO_2 captured * 28,6 tCO_2/trip) by 2 (to account for the round trip).

The OPEX comprises the remaining parameters, specifically: (1) maintenance, (2) tires, (3) revisions, (4) taxes, (5) insurance, (6) driver costs, (7) fuel, and (8) tolls.

			Bolzano SUD	**Bolzano's Hospital**	**Merano Maia Bassa**	**Bz SUD + Hospital**
km per trip (destination: Casalborsetti)			366	366	395	366
tCO_2 captured /for transport per year (by 2030, 90% capture efficiency)			9.217,96	11.201,61	15.596,99	20.419,56
t LCO_2 capacity per truck/trip		28,60				
n° trips per year (one way)			322,31	391,66	545,35	713,97
HGV - refrigerated - diesel ($kgCO_2eq/km$)	>33 t (0% laden)	0,73105				
	>33 t (100% laden)	1,20873				
Scope 3 emissions added (tCO_2eq/y)			228,82	278,07	417,85	506,89
Total km (one way)			117.964	143.349	215.413	261.313
CAPEX	Total (€/km)	0,900				
	Total (k€)[4]		1.062,02	1.290,57	1.939,35	2.352,59
OPEX	Total (€/km)	2,359				
	Total (k€/y)		556,57	676,34	1.016,35	1.232,91

Table 12: Transport stage CAPEX and OPEX for each potential project.

Considering solely the operating expenses, the cost of transport would be approximately 60 €/tCO_2 captured. Nonetheless, this cost will depend on the specific conditions of each project, undergoing variations as a function of travelled distance and amount of trips required, that is defined according to the tCO_2 captured at the source.

Carbon usage

As previously discussed in the technologies analysis, storage is not the only solution for the captured CO_2; utilization also presents a possible destination that will be examined below.

The techno-economic viability of a CCU unit is a complex issue that depends on a wide range of variables, from technical and economic factors to regulatory and socio-economic considerations. The stage of development of the technology can significantly impact its economic viability, generally emerging technologies have an increase in performance and a decrease in cost. Other factors affecting the economic viability are the value of the products generated from CO_2 utilization, policies, regulations, and incentives related. Further on, viability also depend on market dynamics: evolution of the

[4] includes the useful life of the vehicles considered to be of 5 years

price of H_2 , energy, equipment, CO_2, utilities, decisions on CO_2 taxation, production scale, evolution of sales price of e-fuels, and O_2 (Marques et al, 2024).

Methanol

Methanol (CH3OH) is a pathway to a low-carbon future since it can help achieving decarbonization goals when it is made from renewable sources.

Between its current and potential uses can be mentioned:

- Combined with gasoline in vehicles: It can be mixed with gasoline in various ratios, from 3% to pure methanol. Concentrations up to 15% can be utilised in regular gasoline cars, while higher concentrations can be used in flex-fuel vehicles.
- Cleaner marine fuel: The growing demand for cleaner marine fuel is creating an opportunity for methanol to be used as a safe, cost-effective alternative fuel for ships to help the shipping sector meet increasingly strict emissions regulations. Mainly due to its benefit of staying liquid at ambient temperatures and hence doesn't require storage in pressurised fuel tanks.
- Pharmaceutical sector: Methanol is being increasingly used as a solvent to produce cholesterol, streptomycin, vitamins, hormones, and other products in the pharmaceutical sector.
- Chemical manufacturing: Methanol is a key raw material to produce chemicals such as formaldehyde, acetic acid, and plastics. It is being used to produce aromatic compounds and chemicals currently produced from petroleum.

From the perspective of the current project, methanol represents a potential utilization pathway for the captured carbon.

Methanol is a beneficial product because: (1) may be stored as liquid at ambient conditions, making it easy to store, transport and distribute; (2) used as an automotive fuel can be dispensed in regular filling stations, requiring only minimal and relatively inexpensive modifications; (3) can be blended with gasoline in various ratios from 3% to pure methanol, concentrations up to 15% can be used in regular gasoline cars while higher concentrations can be used in flex-fuel vehicles; (4) is compatible with internal combustion engines and hybrid (fuel/electric) systems; (5) used as a marine fuel fulfils the more stringent emission standards in Emission Control Areas (ECAs) and new global emission standard set by the International Maritime Organization (IMO); between others. Among methanol disadvantages can be mentioned: (1) corrosive to some metals, may also attack some plastics, resins and rubbers; (2) can absorb moisture from the atmosphere requiring the storage in a sealed container; (3) has relatively low volumetric energy content compared to some fuels (about half the volumetric energy density of gasoline and diesel fuel); (4) has low vapour pressure at low temperatures and poor lubrication properties and (5) its incomplete combustion can lead to formaldehyde and formic acid pollutants, it is highly flammable and toxic.

According to the International Renewable Energy Agency (IRENA) renewable methanol can be produced using renewable energy and renewable feedstocks via two routes, from biomass obtaining the so-called "Bio-methanol" or from CO_2 captured from renewable sources (bioenergy with carbon capture and storage [BECCS] and direct air capture [DAC]) and green hydrogen (hydrogen produced with renewable electricity), obtaining "Green e-methanol".

Under these definitions is still not clear if the utilization of captured CO_2 from Bolzano plants would fall into green methanol. Besides, IRENA in its innovation outlook about renewable methanol (2021), details that the production costs of green e-methanol depend on the cost of hydrogen and CO_2. On the specifically, "the cost of CO_2 depends on the source from which it is captured, e.g. from biomass, industrial processes or DAC." mentioning industrial processes as a possible source. Furthermore, according to the report, carbon dioxide feedstock can be divided into two categories:

- CO_2 from various industrial sources, including power plants, and steel and cement factories: this CO_2 comes mostly from the burning of fossil fuels (studied situation). Even though recycled, it would still amount to fossil-based CO_2, which is non-renewable and makes the overall process net CO_2 positive. However, given that the CO_2 from these sources would otherwise be released into the atmosphere, using it for the production of methanol with green hydrogen would result in a low-carbon methanol.
- CO_2 obtained from the atmosphere either directly by direct air capture (DAC) or through biomass would result in renewable methanol.

This leads to the conclusion that if Alperia's captured CO_2 from the flue gases (non-renewable CO_2) is reacted with hydrogen produced through the electrolysis of water using renewable energies (green hydrogen), then the synthesized methanol will be classified as low-carbon e-methanol.

The 2018 EU Directive on the promotion of the use of energy from renewable sources (RED II) defines the *Renewable liquid and gaseous transport fuels of non-biological origin* (RFNBO) as liquid and gaseous fuels which energy content is derived from renewable sources other than biomass. To ensure that renewable fuels of non-biological origin contribute to greenhouse gas reduction, the electricity used for the fuel production should be of renewable origin.

For produced methanol to fit into this category the energy required for the reaction (and is not clear if also for the obtention of its raw materials, H_2 and CO_2) should be of renewable origin.

Additionally, this 2018 amendment (RED II) has imposed the share of renewable energy within the final consumption of energy in the transport sector to be at least 14% by 2030 (minimum share). While in the 2023 amendment (RED III) the share has been increased to at least 29% by 2030. The last one also mandates that RFNBOs must account for at least 42% of hydrogen used in the industrial sector by 2030, and at least 60% by 2035; in the transport sector, a binding combined sub-target of 5.5% by 2030 was set for the share of advanced biofuels and RFNBOs in the renewable energy supplied to the transport sector.

If the e-methanol effectively meets the specifications, it will possess added value as a product offered by Alperia, contributing to the decarbonization.

In the 2023 revision on the ETS directive, renewable liquid and gaseous fuels of non-biological origin and recycled carbon fuels are considered important for reducing greenhouse gas emissions in sectors that are hard to decarbonise. Where recycled carbon fuels and renewable liquid and gaseous fuels of non-biological origin are produced from captured CO_2 under an activity covered by this Directive, the emissions should be accounted for under that activity. To ensure that renewable fuels of nonbiological origin and recycled carbon fuels contribute to greenhouse gas emission reductions, and to avoid double counting for fuels that do so, it is appropriate to explicitly extend the empowerment in Article 14(1) of Directive 2003/87/EC to the adoption by the Commission of implementing acts laying down the necessary adjustments for how to account for the eventual release of CO_2, taking also into account the treatment of those fuels under Directive (EU) 2018/2001.

Methanol production

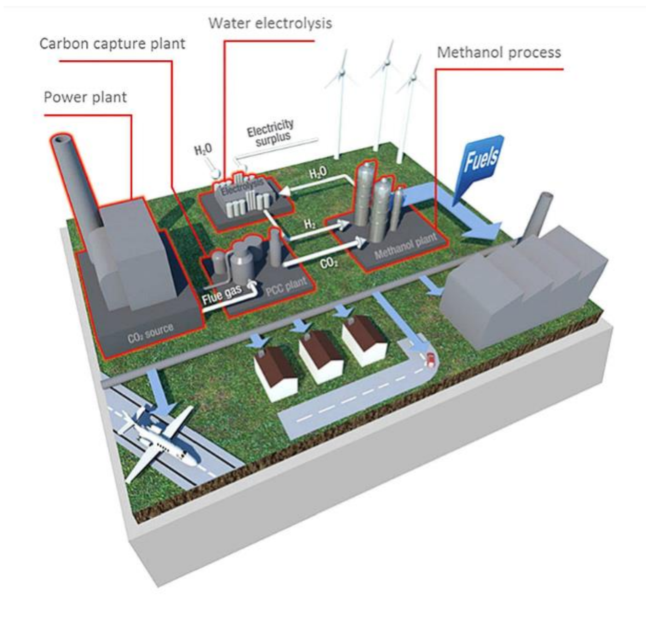

Figure 23: schematic plant to convert CO_2 to methanol using hydrogen from solar generated electricity via electrolysis. Source: Bowker, 2019

The synthesis of methanol from CO_2 is an exothermic reaction:

$$CO_2 + 3H_2 \leftrightarrow CH3OH + H_2\ O \quad \Delta H° = -49.5\ kJ/mol$$

To produce one tonne of methanol, about 1,37 t of CO_2 and 0,19 t of H_2 (approximately 1,7 t of H_2 O and so 1,5 t of O_2 in case of water electrolysis) are needed. According to the Innovation Outlook from IRENA, under the assumption CO_2 is already provided, to produce one tonne of methanol about 10-11 MWh of electricity are required. Most of this energy is destined to the electrolysis of water and only, approximately, the 10% to the methanol synthesis itself (~ 1 MWh).

As mentioned before, the emission values will be considered from predictions for the year 2030. Furthermore, the focus will be placed on the Bolzano direct heating system, temporarily setting aside the Merano Maia Bassa plant.

Total estimated emissions from Bolzano Sud for the year 2030 are 10.262,34 tCO_2eq while from the Hospital are 12.470,74 tCO_2eq, a total of 22.733,08 tCO_2eq.
Nevertheless, the reported values are in tCO_2 equivalent. The corresponding tonnes of carbon dioxide are calculated through the use of the GHG conversion factors published by the UK Government. For each cubic metre of natural gas used as gaseous fuel, there is 2,04542 kg CO_2eq, where 2,04140 kg CO_2eq of CO_2 per unit, 0,00307 kg CO_2eq of CH4 per unit and 0,00095 kg CO_2eq of N2O per unit. Whereas in biomass combustion, emissions are considered to be composed of carbon dioxide only.
This way, the CO_2 estimated to be emitted by 2030 in the Bolzano Sud plant is of 10.243 tonnes and in the Hospital plant 12.446 tonnes, making a total of 22.689 tCO_2. The total amount of captured CO_2, considering the 90% capture removal, would be 9.219 from BZ Sud, 11.202 from the Hospital; 20.420 total tCO_2 per year.

If this captured CO_2 is 100% destinated to the methanol synthesis, it would be necessary 2.832 tonnes of H_2 and so 14.905 tonnes of methanol would be obtained per year; approximately 41 tonnes of CH3OH per day. For this amount of hydrogen, a 17 MW electrolyser would be sufficient, for which it will be assumed the used of 4 electrolysers of 5 MW.

Current Technology Providers for e-methanol having as input CO_2 and H_2 from water electrolysis are:

- Thyssenkrupp/Uhde/Swiss Liquid Future - Germany, for a production capacity between 3.600 and 72.000 t/year.
- bse Engineering/BASF - Germany, for a production capacity between 8.200 and 16.400 t/year.

Methanol Cost

The cost of methanol depends strongly on the costs of the raw materials, making CO_2 and H_2 production most of the production cost. To produce 41 t of methanol, approximately 455 MWh are needed (414 MWh for the electrolysis and 41 MWh for the synthesis).

In order to achieve this numbers, it is considered that Alperia would install not only the methanol but also the electrolyser plant to provide the H_2 required and not making it a limiting factor.

The previous version of the IRENA report, along with past studies and publications (Specht et al, 1998; Cifre and Badr, 2007; Clausen et al, 2010; Kim et al, 2011) present similar estimations on the production cost using captured CO_2, presenting values between €510 and €900 per tonne of CH3OH.

Cost of Hydrogen: The electrolysis of water is an energy intensive process, around 50 MWh are needed for producing one tonne (Simbeck and Chang, 2002; IRENA, 2018). The cost of H_2 is thus closely linked to the cost of electricity required.

According to PUN, "Prezzo Unico Nazionale", the average price of the electric energy for the year 2024 in Italy was of 108,42 €/MWh; to this value it must be added the price of the GO, "Guarantee of Origin", which certifies the energy comes from renewable sources, and so, the obtained hydrogen would be green. The average of the GO for year 2024 was of 0,47 €/MWh according to the GSE (Gestore Servizi Energetici).
However, because the estimations are being performed for 2030, the forecast of the market prices will be considered for the cost calculation.
According to data from the European Energy Exchange (EEX) market data hub, the projected Italian energy price for 2030 is approximately 77,88 €/MWh. The European Renewable Power GO for 2028 is estimated at 1,4 €/MWh (employing 2028 since is the last available prediction). Consequently, the renewable energy price is estimated to be 79,28 €/MWh.
With this value the cost of green hydrogen would be of around 3.964 €/tH_2 for producing 1 t of methanol (approx. 4 €/kgH_2).

To this it will be added the capital cost of the hydrogen due to the electrolysers, since it's a parameter with a high impact (Marques et al, 2024). The electrolysers CAPEX will be taken from a study done in Sardinia (Pettinau et al, 2024), where a 5 MW PEM electrolyser has a capital cost of 6.3 M€ including cost from the cooling system up to the installation. For the proposed solution the total capital cost would be of 25.200 k€.

Cost of CO_2: Following CO_2 capture, it is necessary to assess whether additional compression is required to reach the pressure needed for methanol synthesis. This step would incur additional costs beyond those already estimated in the capture cost section.

For simplicity it will be assumed that the CO_2 is already acquired, and therefore, the cost of capturing it will not be considered. Subsequently, this CO_2 utilization analysis will be integrated with the CO_2 capture analysis to provide a comprehensive understanding of the total cost.

Cost of CH3OH: Regardless of the origin of the raw materials, the cost of methanol production can be approximated by adding the cost of the hydrogen, the cost of the CO_2 and the cost to produce them in a large-scale methanol synthesis unit. The last one will be estimated at 45 €/t methanol, as specified in IRENA 2021 report.

According to Bellotti et al (2017) for a 10 ktCH3OH/y capacity plant, the capital cost (CAPEX) is of 2.170 €/tCH3OH per year while for a 50 ktCH3OH/y capacity plant, it is of 1.500 €/tCH3OH per year. Through a linear interpolation for the hypothesized methanol plant (14.905 tCH3OH/y) and considering that from the total CAPEX only 9% is destined to the methanol reactor (the rest comes from electrolysers and the CCS system); the methanol CAPEX would be of 2.500 k€.

Further into the economic assumptions, the capital cost of the compression system for the hydrogen and for the oxygen won't be considered.

The annual operating expenditures (OPEX) will be considered as composed only by the energy costs.

Given the substantial capital cost estimated for hydrogen production, a grant of 25.000 k€ will be assumed in the following calculations to obtain meaningful results. This assumption is based on the information presented in Section 3.3, which outlines the availability of fundings for CCUS projects.

Electricity purchased from renewable sources	€/t
Cost of Green H_2	3.964,00
Cost of CH3OH	79,30

Table 13: Cost of "Green Hydrogen" and Methanol (€/t), electricity for production considered purchase from renewable sources

	Methanol	CO_2	H_2	O_2
tonnes	1,00	1,37	0,19	1,50
t/y	14.905,33	20.420,30	2.832,01	22.358,00
energy cost k€/y	1.181,69		11.226,10	
capital cost k€	2.541,27		25.200,00	
total annual cost k€/y	40.149,06			
price €/t	400 - 800			125,00
k€/y	6.000 – 12.000			2.794,75
grant k€	25.000			
cost of Methanol €/tCH3OH without carbon credit	832,44			

Table 14: Economic analysis of methanol production; raw materials detail

The obtained cost of methanol per tonne (832,44 €/tCH3OH) is similar to the values reported in the beginning of this section.

The Payback Period (PBP) is calculated in order to measure how much time it would be required to recoup the founds:

$$PBP = \frac{Total\ Initial\ Investment}{Annual\ Net\ Income}$$

The total initial investment is equal to the capital cost, and the annual net income is obtained as: $Total\ Annual\ Revenues - Total\ Annual\ Cost$.

O_2 sell at €125	O_2 vented to atm.	
PBP	**PBP**	**methanol price (€)**
-0,8	-0,4	400
-1,3	-0,6	500
-4,1	-0,8	600
3,3	-1,4	700
1,2	-5,7	800

Table 15: Payback period estimation (including a 25M€ grant) for different methanol market prices

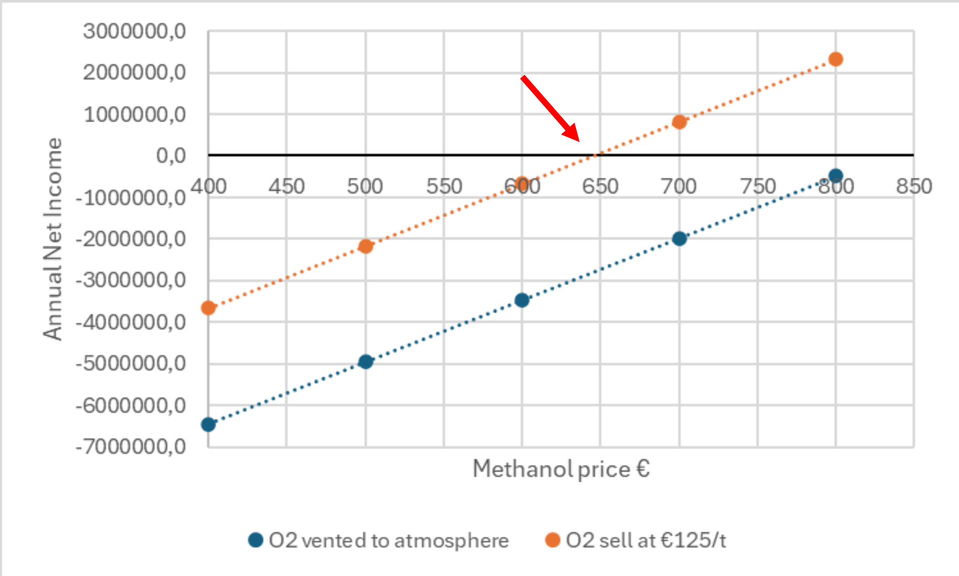

Figure 24: Annual net income resulting from the different methanol prices. The red arrow indicates the break-even point

Under the hypothesis a 25.000 k€ grant is obtained for financing the H_2 production, two results arise; without the commercialization of oxygen the solution is not feasible for any of the expected prices of methanol. As an alternative, the oxygen co-produced from the water electrolysis could be sell, its price is around 125 €/tO_2, reducing overall cost of producing methanol. Under this scenario the break-even point would be reached for a methanol price of around 650 €, where the annual net income starts being positive and so the project becomes feasible. For a price of 700 € the payback period of the project would be of 3,3 years, nonetheless, there is no certainty methanol could reach such prices.
For the required H_2 production it would be generated 22.4 kt of O_2 per year, then around 2.8 M€ could be gained. That way, costs of methanol could be offset in the short term. However, as delineated in IRENA's report; "as availability of large amounts of oxygen from the electrolysis increases as a by-product of e-fuels production, the supply will probably outpace demand, leading to lower prices." Consequently, the sale of oxygen is not among the most viable options.

This analysis indicates that, without financial assistance, this utilization alternative would not be viable. Even with external funding, the production of methanol at the Bolzano plants remains unfeasible unless energy costs are significantly reduced, or prices of methanol increase.

As a result, this alternative is currently dismissed as a practical solution, not including it in the final balance. However, it should not be dismissed for future consideration and so, continuous monitoring of market prices are recommended, as changes in economic conditions could improve its feasibility.

Mineral Carbonation

Mineral carbonation is a permanent and safe way for storing CO_2, which does not present potential concerns over long term monitoring and liability issues, compared to geological storage. The stability of mineral carbonation is confirmed by the distribution of carbon in the lithosphere of the Earth.

This process can take place in situ or ex situ. In the case of being performed above ground it can be through indirect or direct processes. Direct mineral carbonation is the reaction of CO_2 with minerals through direct contact or in an aqueous solution in a single step, while the indirect process takes place in more than one stage.

A wide range of mineral resources and different technical approaches can be employed to permanently sequester the CO_2 into stable carbonates through mineral carbonation as mentioned before in this document.
Natural minerals mostly utilized for CO_2 fixation are those rich in calcium and magnesium. Azdarpour et al (2015) performed the carbonation process to silicate minerals, such as serpentine, olivine, pyroxene, wollastonite, and amphibole, arriving to interesting results. These minerals constitute silicate rocks among which mafic and ultramafic rocks; basalts containing calcium silicates are also a target for this process.

Below, a figure representing the distribution of feedstock available around the globe:

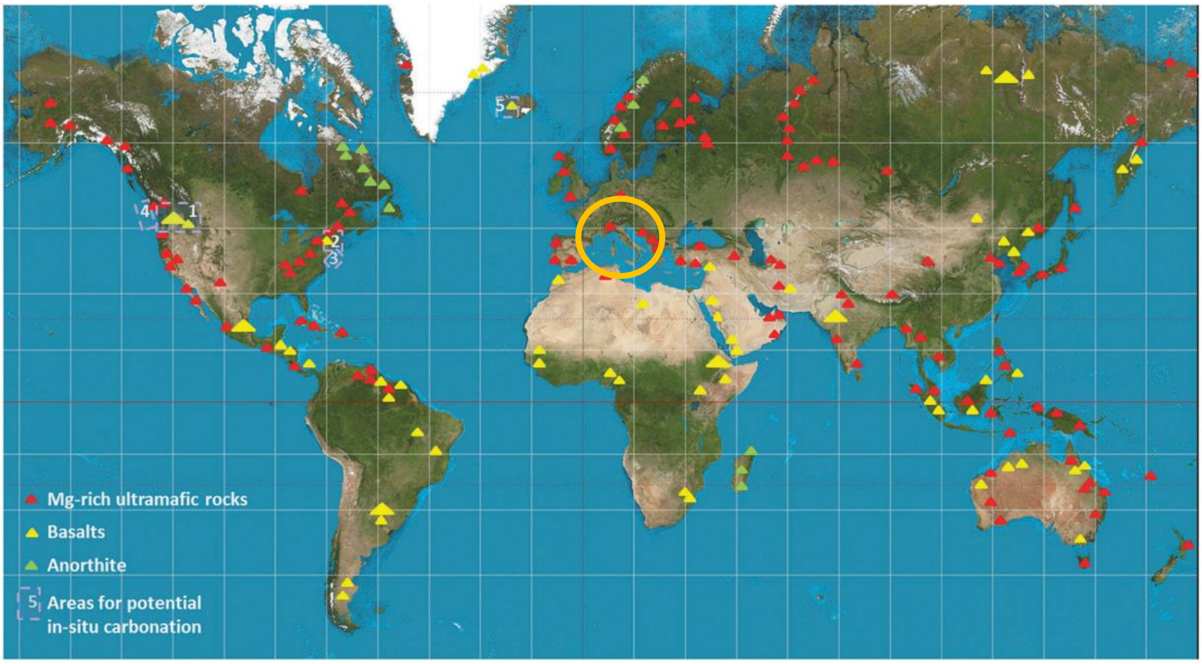

Figure 25: mineral feedstock available worldwide for mineral carbonation. Source: Sanna et al, 2014

It can be seen in an approximate way that only in the west of Italy there is presence of potential feedstocks. According to the geology department of Hydrodata SpA, which was consulted for obtaining detailed information on the lithology of the region; in the Alto Adige region there is presence, in considerable quantities, of Amphibolite, a metamorphic rock that contains amphibole, an inosilicate mineral. Amphibole-rich rock generally has similar contents of major element oxides: MgO (12 wt.%), Al2O3 (13 wt.%), Fe2O3 (9.3 wt.%) and CaO (14.9 wt.%).

An investigation (Chiri and Cabral, 2013) examined the dissolution and carbonation efficiency of amphibole and also of olivine and pyroxene (widely available Mg-rich silicate rocks) using a NH4-based pH swing process to assess the feasibility of using these minerals for CO_2 sequestration.
It was observed that amphibole dissolution is difficult due to the high complexity of the amphibole structure and the difficulty in destroying it, this led to a low Mg extraction (only approximately 30%) and so the carbonation of Amphibole wasn't performed reporting that "pyroxene and amphibole are not good candidates for mineral carbonation".

There are no further studies that deepen on the carbonation of Amphibole and so either of carbon sequestration through mineralization with this rock.

In conclusion, the low availability of adequate minerals for performing in-situ carbonation and the lack of already mined minerals for performing ex-situ carbonation, leads to dismissing the current solution as a possible utilization for the captured carbon dioxide.

Other industries

An analysis will not be conducted on the chemical and cement industries as they are neither applicable nor of interest to the group. This decision is primarily based on their divergence from Alperia's activities.

Discussion

After analysing the emissions characteristics of the plants comprising Alperia Ecoplus; Bolzano and Merano, Maia Bassa have been identified as the most suitable plants for a carbon capture project.

By 2030, Bolzano Sud and the forthcoming gas turbine at the Hospital, are projected to emit approximately 22,7 ktCO_2eq. To justify the investment, the emissions from these plants should be combined to create a source substantial enough to achieve economic feasibility. *Tables 16*, *17* and *Annex 1* present costs separately, although, the economies of scale associated with carbon capture imply that higher combined emissions should reduce overall costs. Thus, evaluating the plants independently is not optimal. However, it remains to be clarified whether flue gases from both sites could be collected before the capture process.

Maia Bassa presents strong potential for the capture project primarily due to its projected 2030 emissions of approximately 17 ktCO_2eq, which originate from a single location. However, there is no available space on-site owned by the Group, meaning additional land would need to be acquired.

All three plants mentioned are subject to the Emission Trading System; Bolzano's facilities fall under ETS 1, while Maia Bassa will be included in ETS 2. This increases the project's attractiveness, as carbon capture would allow the Group to avoid surrendering allowances and reduce their voluntary compensation obligations. These factors contribute to potential economic savings and further justify the investment, in addition to the inherent benefit of reducing Alperia's GHG emissions.

Based on information obtained from the technology providers this far, NUADA's technology is not affected by seasonal variations in plant operations. Conversely, while TPI has not yet addressed this issue, amine-based capture solutions, as reported by other providers, typically experience decrease in performance and increased energy losses during periods of reduced operation. This factor is critical, as the output of both plants varies seasonally. Technology selection will depend significantly on this consideration. Specifically, Maia Bassa would be preferred over Bolzano Sud due to its lower interquartile range (IQR) of the flow rate, despite Bolzano's lower IQR of the operating hours, which indicates more consistent operating times but lower corresponding flow rates. NUADA's technology is also preferable due to its higher capture efficiency and lower energy consumption. However, TPI's more advanced development stage and geographic proximity to Alperia's plants may make it a more practical option. Under the TPI system, the larger energy consumption would lead to greater increase per kWh of fuel consumption and other resource requirements as well as environmental releases. To make a fully informed decision, specific cost data from each provider must be obtained, since *Tables 16* and *17* show the capture cost estimations as a function of CO_2 captured emissions and energy consumption,

suggesting lower costs for NUADA. However, these figures do not reflect the actual prices quoted by the companies.
According to Alperia's 2030 emissions forecasts, implementing TPI's technology would be approximately 30% more expensive than adopting NUADA's solution. Based on the average recorded energy consumption of the plants (detailed in Annex 1) and the estimated CO_2 captured by 2030, the energy requirement, regardless of the technology chosen, is lower for Maia Bassa. This implies a smaller energy penalty and, consequently, a lesser reduction in the plant's overall efficiency compared to Bolzano's facilities. The energy penalty expresses the power output difference between the power plant with and without the carbon capture and it has been expressed in % more input per MWh. Furthermore, the combined energy requirement for the hospital and Bolzano Sud is lower than if the plants operated independently, though it remains higher than that of Maia Bassa.
The cost of captured CO_2 was estimated to range between 57 and 117 €/tCO_2, depending on the technology provider and the facility under focus.

For Bolzano Sud the capture would signify a reduction in expenses related to the surrendering of the ETS1 and the voluntary compensations of around 750 k€/y, after considering the ETS1 carbon price for 2030 to be 70 €/tCO_2eq (Enerdata) and the carbon price for voluntary compensations to be 8,70 €/tCO_2eq, based on the average of current compensations done by the Group.
For the gas turbine, under the same scenario as Bolzano Sud, the capture application would represent a saving of around 900 k€/y. Meanwhile, for Maia Bassa, if the ETS2 carbon price is taken from scenario 1 predictions (conservative), where the estimated price is 222,20 €/tCO_2eq by 2030, the savings could reach 3.500 k€/y. In contrast, under scenario 2, where the carbon price is projected to be 117 €/tCO_2eq by 2030, savings could be around 1900 k€/y.
The savings expressed do not considering the cost of the CCS but only the reduction of the expenses, assuming that the remaining emission after capture are still being compensated.

Once the CO_2 is captured, it can be locally stored in liquid state to reduce volume until transport occurs. Aggregating CO_2 volumes from Alperia's plants or in collaboration with other industries implementing carbon capture is recommended to enhance transport efficiency and reduce costs.
Tables 16 and *17* present transport cost estimates for truck transport using an articulated vehicle with five or more axles, refrigerated, and powered by diesel. This stage may be subject to modifications based on forthcoming definitions by the Italian Ministry of Energy and details from Snam regarding the potential provision of an open-access pipeline network. Active monitoring of developments in this area is recommended.

Furthermore, the estimations have been conducted under the assumption that the captured CO_2 will be stored at the Ravenna site, requiring delivery to the Casalborsetti compression station. The transport costs presented are calculated based on the distance between the plants and this station, as well as the number of trips required. It is important to note that the estimated number of trips is significantly high. However, due to challenges and limitations in applying alternative estimation methodologies, these values were accepted.
The estimated cost of transporting CO_2 is approximately 150 €/tCO_2, with variations depending on each case conditions.

The total CO_2 management cost, encompassing both capture and transport, is as well reported. Storage costs have not been included due to the uncertainty on the scenario in which CO_2 would be outsourced. Consequently, cost estimations related to storage—such as well design, monitoring, and other associated expenses—are not considered representative.

Furthermore, the utilization of captured CO_2 has been dismissed. As discussed in previous sections, methanol production emerged as a costly solution; even with a 25M€ grant, results were unfavourable. It may only become viable if technological advancements reduce costs or methanol market prices rise. Mineral carbonation was also dismissed due to geographical constraints and associated technical challenges.

By 2030, the estimated total costs for the capture and transport phases, including capital and operational expenditures for the first year of investment with immediate application; are approximately 2 M€ for Bolzano Sud, 3 M€ for Bolzano's Hospital, 4 M€ for the combination of these two plants, and 4 M€ for Maia Bassa. Regarding the choice of capture technology provider, implementing TPI instead of NUADA would incur an additional cost of approximately 300 k€, excluding any extra company fees.
Total costs from the second year onward are also reported in *Table 17*, where only the OPEX is included under the assumption that the CAPEX is a one-time investment. The total cost per year obtained is half of the above-mentioned total cost.

As reported in the IPCC report on CCS, mitigation costs are more accurately represented by the avoided CO_2 cost encompassing all expenses. Consequently, for the presented analysis, the cost of CO_2 avoided includes all cost components representing the incremental expense of capturing and transporting CO_2 in comparison to a reference plant, which has been considered as the same plants without the capture application. In this context, the cost of CO_2 avoided, after the CCS application by 2030, ranges between 228 and 314 €/tCO_2eq.

Emissions from 22-24 average		**BZ SUD**	**MAIA BASSA**
CAPTURE TPI	CAPTURED CO_2 (tCO_2)	7.877,39	20.538,82
	CAPEX (k€)	13.859,25	8.478,17

(Absorption - 90% eff. - 900 kWh/tCO_2)	OPEX (€/MWh)	11,14	11,10
	Cost of Captured CO_2 (€/tCO_2)	98,00	97,79
TRANSPORT	CAPEX (k€)	1.062,02	1.939,35
	OPEX (k€/y)	556,57	1.016,35
	Cost of Transported CO_2 (€/tCO_2)	205,47	143,91
TOTAL	EMITTED CO_2 (tCO_2eq/y) (ex-post)	1.105,81	2.704,44
	REDUCED CO_2 (tCO_2eq/y)	7.664,08	20.161,41
	COST (k€/y)	**2.390,60**	**4.964,14**
CAPTURE NUADA (Adsorption - 95% eff. - 200 kWh/tCO_2)	CAPTURED CO_2 (tCO_2)	8.315,03	21.679,87
	CAPEX (k€)	3.250,94	1.988,71
	OPEX (€/MWh)	11,14	11,09
	Cost of Captured CO_2 (€/tCO_2)	65,28	65,06
TRANSPORT	CAPEX (k€)	1.062,02	1.939,35
	OPEX (k€/y)	556,57	1.016,35
	Cost of Transported CO_2 (€/tCO_2)	194,66	136,33
TOTAL	EMITTED CO_2 (tCO_2eq/y) (ex-post)	667,32	1.561,15
	REDUCED CO_2 (tCO_2eq/y)	8.102,58	21.304,71
	COST (k€/y)	**2.161,38**	**4.366,25**

Table 16: Economic analysis of Bolzano Sud and Maia Bassa based on the average CO_2 emissions from 2022 to 2024 for both capture technology providers under assumption

Emissions from 2030 predictions		**BZ SUD**	**BZ HOSPITAL**	**MAIA BASSA**
CAPTURE TPI (Absorption - 90% eff. - 900 kWh/tCO_2)	CAPTURED CO_2 (tCO_2)	9.217,96	11.201,61	15.596,99
	Energy requirement (%/MWh)	19,55%	16,28%	12,69%
	CAPEX (k€)	16.217,80	7.817,63	6.438,24
	OPEX (€/MWh)	11,13	11,13	11,11
	Cost of Captured CO_2 (€/tCO_2)	89,26	99,53	116,84
TRANSPORT	CAPEX (k€)	1.062,02	1.290,57	1.939,35
	OPEX (k€/y)	556,57	676,34	1.016,35
	Cost of Transported CO_2 (€/tCO_2)	175,59	175,59	189,50
TOTAL	EMITTED CO_2 (tCO_2eq/y) (ex-post)	1.255,06	1.525,14	2.154,26
	REDUCED CO_2 (tCO_2eq/y)	9.007,28	10.945,60	15.209,85

	COST (k€/y), 1° year[5]	**2.441,37**	**3.081,75**	**4.778,05**
	COST (k€/y) from 2° year and on	**1.029,01**	**1.365,46**	**2.245,92**
CAPTURE NUADA (Adsorption - 95% eff. - 200 kWh/tCO_2)	CAPTURED CO_2 (tCO_2)	9.730,06	11.823,92	16.463,48
	Energy requirement (%/MWh)	5%	4%	3%
	CAPEX (k€)	3.804,17	1.833,77	1.510,20
	OPEX (€/MWh)	11,13	11,13	11,11
	Cost of Captured CO_2 (€/tCO_2)	56,99	66,72	83,11
TRANSPORT	CAPEX (k€)	1.062,02	1.290,57	1.939,35
	OPEX (k€/y)	556,57	676,34	1.016,35
	Cost of Transported CO_2 (€/tCO_2)	166,35	166,35	179,53
TOTAL	EMITTED CO_2 (tCO_2eq/y) (ex-post)	741,94	901,60	1.286,06
	REDUCED CO_2 (tCO_2eq/y)	9.520,40	11.569,14	16.078,05
	COST (k€/y), 1° year	**2.173,15**	**2.755,77**	**4.324,02**
	COST (k€/y) from 2° year and on	**1.028,94**	**1.365,34**	**2.245,62**

Table 17: Economic analysis of Bolzano Sud and Maia Bassa based on the average CO_2 emissions from 2030 forecasts for both capture technology providers under assumption

For further details, refer to tables in *Annex 1*.

[5] for the first year of investment, immediate application, CAPEX and OPEX included

Alternative solution: business model

The analysis conducted in the present study has revealed significant challenges in implementing Carbon Capture, Utilization and Storage (CCUS) for Alperia. These challenges primarily stem from the low annual emissions generated by the power plants, which render the application of cost-effective capture technology problematic. Similar difficulties are encountered in the transportation of captured CO_2.

Consequently, an alternative solution for the Group has been conceptualized and will be further exposed.

Given the configuration of Alperia's corporate structure, there exists the opportunity to conduct business operations through Alperia Green Future (AGF), which, among other activities, provides high-level consulting services aimed at defining decarbonization strategies for companies and public entities.

As seen before, the majority of Alperia's emissions are derived from indirect activities (Scope 3), predominantly from the use of sold products, sale of fossil fuels (category 11.b). To achieve a reduction in this category, a specialized Energy Performance Contract (EPC) could be implemented, adapted specifically for carbon; thereby defining it as Carbon Contract (CC).

The Carbon Contract would be performed between AGF and the current gas clients, particularly those with CO_2 emissions of sufficient magnitude to suit the capture technologies previously discussed. AGF would provide consulting and carbon management services, wherein through the implementation of the most appropriate technology for the client's industrial conditions, carbon would be captured and transported to storage in Ravenna (the responsibility for transport, whether it lies with Eni-Snam or Alperia, remains to be determined), thereby reducing the client's emissions. In this manner, the client would remunerate a service to achieve decarbonization, thus contributing to their own sustainability objectives. Furthermore, client should be subject to ETS1/ETS2, so that the application of CCS enables the avoidance of surrendering allowances, constituting the economic advantage for the client.

Two types of contracts could be performed:

Guaranteed-savings contract

The client is the entity financing the design and installation of the project by obtaining funds from third parties. In this arrangement, the client assumes the risks associated with debt service.

Alperia would assume the performance risk and would guarantee the reduction of CO_2 emissions and ensure that the resulting savings through the avoidance of surrendering allowances are equal to or exceed the monthly loan payment.

In the event that the savings are lower than the loan payment, Alperia would be obligated to remit the difference to the client. Conversely, if the savings are higher, the client would be required to remit to Alperia a percentage of the additional savings.

These savings would be a function of the amount of captured CO_2, which ultimately depends on the client's flow rate, given that the technology offered would capture 90/95% of CO_2 emissions. The remaining emissions would continue to be registered in the environmental balance of both, the client and Alperia.

Shared-saving contract

In this type of contract, Alperia would be the entity responsible for financing the project, which would be achieved through a loan/fund or by its own resources. Consequently, it would assume both financial and performance risks.

The client, on the other hand, would remit a percentage of the monthly savings, retaining the remaining. This scenario represents an advantage compared to the ex-ante situation where the client remitted the entire percentage to the ETS.

In this case, Alperia's share of the savings would generally be substantial, potentially as high as 90%.

For Alperia, this business model would represent a benefit not only from the economic point of view, but also because it would signify a decrease in the voluntary emissions reduction (VER) that the Group pays for the scope 3 emissions, under its own assumption of the carbon price, after their reduction.

The current guidance of the GHG Protocol mentions the case where the CCUS facilities are in the company value chain and that are then stored in a geological reservoir, which could be extrapolated to the presented solution with the storage at Ravenna's site. According to the Protocol, as reported in section 3.4.1. of the current study, the company should:

- Not report scope 3 emissions associated with the GHGs that are captured and stored and meet the geologic storage requirements.
- Report fugitive emissions released at that facility in scope 3, together with fugitive emissions from geological storage pathway (to be further clarify with Snam).
- The captured GHGs that before were emitted should be reflected as a reduction in scope 3 emissions.

Scenarios

To perform a more detailed analysis, different scenarios have been hypothesized.

For the Capture Project:

1. The client belongs to the ETS1 group and compensates its emissions through voluntary credits. Under this scenario the client buys carbon credits for all off its scope 1 emissions coming from the gas acquired from Alperia.
2. The client belongs to the ETS1 group and doesn't compensate emissions through other way.
3. The client only makes voluntary compensation.

It will be assumed that the price of the carbon credits in the ETS1 is equal to 76,7 €/tCO_2eq, while the price for the voluntary compensations 8,7 €/tCO_2eq.

4. The client belongs to the ETS2, from 2027 and on compensates its emissions through this system. Under this case the price of the credits will be taken from future predictions done by RINA group for the "Gestore dei Servizi Energetici (GSE)". Depending on the real price ETS2 will take, predictions for this fourth scenario could widely variate.

For Alperia, all the emissions reported by the client represent scope 3 emissions and are reported in the corresponding category.
Once the capture is performed, the client will be able to reduce its scope 1 emissions, which would be reflected on a diminishment of the carbon credits it acquires. From this savings Alperia will take a % in order to cover the cost faced for the project. This way, after a certain number of years, depending on the scenario, Alperia would recover its inversion, adding extra earnings and will, at the same time, see a reduction under scope 3 category, that other way could not be addressed.

Conversely, for the transport phase, two scenarios will be postulated because of the uncertainty pending the forthcoming study done by the Energetic Ministry of Italy, which is expected to elucidate the basis for this stage.

1. Alperia performs as intermediary between the client and Eni/Snam, who would carry the responsibility of the management of the carbon dioxide once captured. Under this scenario, the carbon belongs to a third part, meaning leakages or emissions generated in the remaining stages won't have to be reported by Alperia. From this "linking" service, Alperia would take a 10% from the quota the client has to pay to ENI; in the calculations, this percentage will remain fixed. The price settled by the third part, because of lack of information, will be hypothesized considering ENI/Snam variates the fee in the same way as Alperia would do in the following scenario. The price estimation will result from the OPEX added to the CAPEX divided the amount of years the contract last, and all divided by the amount of CO_2 captured, meaning the price is defined as a function of the fee and the amount of CO_2 captured (which has been fixed).
   - → Setting the transport fee at 10%, the price of the transport would be of 39 €/tCO_2;

→ at 30%, 46 €/tCO_2;
→ at 40%, 50 €/tCO_2;
→ and at 50%, 53 €/tCO_2.

2. Alperia oversees the transport of the liquified CO_2 up to the compression station in Casalborsetti. For doing so, the cost and the correlated emissions will be estimated for land transport through truck, as earlier assumed for Alperia's captured CO_2. The client would pay to Alperia all its operation cost plus a % in order to recover the capital inversion.

Sensitivity Analysis

The sensitivity analysis will be conducted by varying the percentage of the fee retained by Alperia for the capture on one side and for the transport on the other.

All the values reported from the client's perspective, were calculated per year.

From the estimations performed for Alperia's facilities, the average was extracted for analysing the proposed business model. In detail, a capital cost of 330,36 €/kW in the case of performing a capture with an amine solvent that would require 900 kWh per tCO_2 and has a 90% capture efficiency; or on the contrary, 80,20 €/kW if using NUADA's technology which consumption is of 200 kWh/tCO_2 and a capture efficiency of 95%. The OPEX utilized was of 11 €/MWh.

The assumptions for the economic analysis were as follows: a ten-year contract, with the client's emissions remaining constant over the years; client savings beginning in the second year of Alperia's investment; the corresponding amortization of the CAPEX, no financing considered; and a tax rate of 24%. The client's plant was considered to have a reference size of 30 MW (an average from Alperia's facilities studied), whose natural gas consumption was modelled equal to 1 million Sm3. Furthermore, the estimations were done considering the costs obtained for Alperia's plants, meaning the clients activity is considered equivalent to a power plant.

For a ten-year contract, none of the modelled scenarios generated earnings for Alperia. This implies that even with a 99% share of the client's savings, following the implementation of the capture project, Alperia's investment would not be fully covered. This outcome is primarily due to the substantial capital costs involved. This situation remains consistent for both capture technologies, despite their significant differences in energy consumption, and different costs associated.

One potential approach to make the model viable would be through the acquisition of external fundings or a loan.

According to the research conducted and reported in section 3.3, fundings are available for CCUS projects. Under this hypothesis, Alperia could potentially obtain, for example, a one-time grant and allocate it to these projects. By securing €2 million, the financial balance would present more favourable figures, particularly if the capture technology is sourced from Nuada, which involves a significantly lower capital cost. In contrast, if an amine-based solution is adopted, Alperia would require a grant of at least €9 million to offset the investment, making the business model challenging to implement without substantial external support.

Under the €2 million fund and Nuada technology hypothesis, the table below presents the results for a capture fee of 40% and two different transport fees. The clients to which the business could be offer are only those belonging to category 1 and 4. In the second case, savings would depend on the carbon credit prices established by the ETS2. ETS scenario 1 is a conservative projection that estimates a price of 222,20 €/tCO_2eq by 2030, while in scenario 2 the carbon price is projected to be 117 €/tCO_2eq by 2030.

Carbon Capture	**scenario 1**		**scenario 2**		**scenario 3**		**scenario 4**	
Output ex-ante (€/y)	172.849,60		155.240,80		17.608,80		449.732,80 (Sce.1)[6] 236.808,00 (Sce.2)	
Output ex-post (€/y) - fee of 40%	-79.510,82		-71.410,77		-8.100,05		-193.385,10 (Sce.1) -130.244,40 (Sce.2)	
Carbon Transport	**Sce. 1**	**Sce. 2**	**Sce. 1**	**Sce. 2**	**Sce. 1**	**Sce. 2**	**Sce. 1**	**Sce. 2**
Fee of 10%								
Output (€/y)	-82.326,00	-74.643,89	-82.326,00	-74.643,89	-82.326,00	-74.643,89	-82.326,00	-74.643,89
TOTAL[7] (€/y)	11.012,78	18.694,90	1.504,03	9.186,15	-72.817,25	-65.135,13	174.021,70 (Sce. 1) 52.654,56 (Sce. 2)	181.703,81 (Sce. 1) 60.336,67 (Sce. 2)
Alperia's NPV (€) (Capture + Transport)	157.531,15	92.597,63	97.309,05	32.375,53	7.484,18	-57.449,34	1.104.471,69 (Sce. 1) 376.268,88 (Sce. 2)	1.039.538,17 (Sce. 1) 311.335,36 (Sce. 2)
Fee of 20%								
Output (€/y)	-88.658,77	-81.429,69	-88.658,77	-81.429,69	-88.658,77	-81.429,69	-88.658,77 (Sce. 1) -88.658,77 (Sce.2)	-81.429,69 (Sce. 1) -81.429,69 (Sce.2)

[6] in parenthesis, the ETS carbon price scenario is specified
[7] total lost/savings per year compared to ex-ante scenario, from the client's perspective

TOTAL (€/y)	4.680,01	11.909,09	-4.828,74	2.400,34	-79.150,02	-71.920,94	167.688,93 (Sce. 1) 46.321,79 (Sce.2)	174.918,00 (Sce. 1) 53.550,87 (Sce.2)
Alperia's NPV (€) (Capture + Transport)	158.106,86	142.753,24	97.884,76	82.531,15	8.059,89	-7.293,72	1.105.047,4 (Sce. 1) 376.844,58 (Sce.2)	1.089.693,8 (Sce. 1) 361.490,97 (Sce.2)

Table 18: Economic analysis for a Transport fee of 10% and of 20% considering in both cases a Capture fee of 40%. Four client's categories specified and for both transport scenarios. Are also detailed the two scenarios for ETS2 carbon price for clients under category 4

Moving on, a capture fee of 50% would only be economically attractive for clients under category 4. The two transport scenarios are presented, along with the percentage fee variation and both ETS price predictions for 2030.

Carbon Transport	**Scenario 1**	**Scenario 2**
Fee of 10%		
TOTAL* (€)	131.297,08 (Sce.1)	138.979,19 (Sce.1)
	30.157,80 (Sce.2)	37.839,91 (Sce.2)
Alperia's NPV (€) (Capture + Transport)	1.488.993,24 (Sce.1)	1.424.059,72 (Sce.1)
	578.739,72 (Sce.2)	513.806,20 (Sce.2)
Fee of 20%		
TOTAL* (€)	124.964,31	132.193,39
	23.825,03	31.054,11
Alperia's NPV (€) (Capture + Transport)	1.489.568,94	1.474.215,33
	579.315,42	563.961,81
Fee of 30%		
TOTAL* (€)	116.520,62	125.407,58
	15.381,34	24.268,30
Alperia's NPV (€) (Capture + Transport)	1.490.336,55	1.513.192,76
	580.083,03	602.939,24

Table 19: Economic analysis for a Transport fee of10%, 20% and of 30% considering in the three cases a Capture fee of 50%. Only for category four clients and for both transport scenarios. Are also detailed the two scenarios for ETS2 carbon price

Finally, a 60% capture fee would be applicable with a transport fee of 10% but could only be feasible if the carbon price is defined according to ETS scenario 1 (222 €/tCO_2eq). Presenting advantages for both the parties. Nonetheless if the price is lower, then the business would no longer be of interest.

Numerous factors could potentially modify the estimated costs. The anticipated Italian study on the creation of a carbon dioxide supply chain may provide further clarifications and guidance, potentially enhancing the project's feasibility. A more viable business model may outcome which may warrant further investigation, considering its potential for reducing Alperia's scope 3 emissions.

Conclusion

The primary objective of this study was to identify the most suitable technologies for mitigating Alperia's greenhouse gas emissions, with a particular focus on Scope 3 emissions, that due to their indirect nature, present significant challenges in being addressed. Subsequent analysis determined that carbon capture, utilization, and storage (CCUS) technologies would be more effectively applied to Scope 1 emissions. This conclusion was based on the GHG Protocol framework and on the technical analysis performed; where, given that the direct emissions from the flue gases generated by the Group's power plants are accounted under Scope 1, then so will be their capture.

The implementation of CCUS would offer Alperia additional benefits, particularly in terms of cost savings, given the plants' status as operators under the EU Emissions Trading System (ETS). By adopting CCUS, the company could avoid the need to surrender allowances under the ETS, thereby reducing compliance costs. This principle extends to the Group's voluntary compensation obligations.

The analysis focused on the district heating plants of Bolzano and of Maia Bassa (Merano) due to their current and projected annual CO_2 emissions. Their geographical distribution, available area, flow rate, operational hours, and plant dimensions were additional factors considered in identifying these plants as the most suitable candidates.

The corresponding technology and suppliers assessment identified post-combustion amine-based absorption and an innovative adsorption process as the most appropriate capture methods.
In contrast, carbon dioxide utilization was considered unfeasible due to high costs and incompatibility with the company operational nature.

After capture, the most viable destination was concluded to be storage in the offshore site in Ravenna (Eni-Snam's project). Transport costs were estimated under the assumption that CO_2 would be collected at the source and delivered to the Ravenna site, with Alperia managing the entire logistical process.

Given the primary objective of reducing Scope 3 emissions and recognizing the associated economic benefits, the study also explored a potential business model targeting Alperia's gas clients subject to the ETS. Under this model, the reduction of client emissions through CCS implementation could be reflected in Alperia's environmental accounting under Scope 3, thereby enhancing the company's overall emissions reduction strategy.

Annex 1

Emissions for 2030 forecasts – amine solvent capture modality

	Alperia SpA with CCUS applicability	STEAM AND SERVICES					SMART REGION
		ECOPLUS (AEP)					GREEN FUTURE
		BOLZANO		MERANO			✓
		BZ SUD	**HOSPITAL**	**MAIA BASSA**	**MR SUD**	**ARENA**	
	ETS	1	1	2	2	2	TBD[8]
	EMISSION SCOPE	Scope 1	Scope 1	Scope 1	Scope 1	Scope 1	Scope 3
	PLANT SIZE (MW)	37,50	21,71	22,94	16,63	0,99	
emissions tCO_2/y (ex-ante)	2030 prediction	10.242,17	12.446,23	17.329,98	1.634,18	674,23	
average from 22-23-24	tot op hours/y	2.667,83	8.688,00	3.966,63	1.333,09	5.191,74	
	$kgCO_2$/h (flow rate)	3.398,14	1.432,58	5.744,00	1.569,60	265,55	
	Energy consumption (MWh)	42.434,16	61.930,76	110.639,06	2.287,37	6.689,11	
CAPTURE	Available Surface (m2)	3.298,00	n.a.	acquisition needed	as required	acquisition needed	
	TECHNOLOGY PROVIDER	TPI	TPI	TPI	TPI	TPI	
	TYPE of CAPTURE	Absorption with amine solvent	Absorption with amine solvent	Absorption with amine solvent	Absorption with amine solvent	Absorption with amine solvent	
	RECOVERED CO_2 (%)	90%	90%	90%	90%	90%	

[8] To be defined as function of costumer profile

	CAPTURED CO_2 (tCO_2)	9.217,96	11.201,61	15.596,99	1.470,76	606,80
	Energy requirement (kWh/tCO_2)	900	900	900	900	900
	Energy requirement (%more input/MWh)	19,55%	16,28%	12,69%	57,87%	8,16%
	CAPEX (€/kW)	432,47	360,09	280,66	810,87	166,97
	CAPEX (k€)	16.217,80	7.817,63	6.438,24	21.281,85	178,62
	OPEX (€/MWh)	11,13	11,13	11,11	11,16	11,16
	Cost of Captured CO_2 (€/tCO_2)	89,26	99,53	116,84	55,36	161,04
TRANSPORT	MODALITY	articulated vehicle with 5 or more axles, refrigerated, diesel				
	ADDED CO_2 (tCO_2eq/y)[9]	228,82	278,07	417,85		
	CAPEX (k€)	1.062,02	1.290,57	1.939,35		
	OPEX (k€/y)	556,57	676,34	1.016,35		
	Cost of Transported CO_2 (€/tCO_2)	175,59	175,59	189,50		
TOTAL	EMITTED CO_2 (tCO_2eq/y) (ex-post)	1.255,06	1.525,14	2.154,26		
	REDUCED CO_2 (tCO_2eq/y)	9.007,28	10.945,60	15.209,85		
	COST (k€/y)	2.441,37	3.081,75	4.778,05		

[9] project or product activity emissions, leakages are not included

Emissions for 2030 forecasts – adsorption capture modality

	Alperia SpA with CCUS applicability	STEAM AND SERVICES				
		ECOPLUS (AEP)				
		BOLZANO		MERANO		
		BZ SUD	HOSPITAL	MAIA BASSA	MR SUD	ARENA
	ETS	1	1	2	2	2
	EMISSION SCOPE	Scope 1	Scope 1	Scope 1	Scope 1	Scope 1
	PLANT SIZE (MW)	37,50	21,71	22,94	16,63	0,99
emissions tCO_2/y (ex-ante)	2030 prediction	10.242,17	12.446,23	17.329,98	1.634,18	674,23
average from 22-23-24	tot op hours/y	2.667,83	8.688,00	3.966,63	1.333,09	5.191,74
	$kgCO_2$/h (flow rate)	3.398,14	1.432,58	5.744,00	1.569,60	265,55
	Energy consumption (MWh)	42.434,16	61.930,76	110.639,06	2.287,37	6.689,11
CAPTURE	Available Surface (m2)	3.298,00	n.a.	acquisition needed	as required	acquisition needed
	TECHNOLOGY PROVIDER	Nuada	Nuada	Nuada	Nuada	Nuada
	TYPE of CAPTURE	Adsorption with solid sorbents	Adsorption with solid sorbents	Adsorption with solid sorbents	Adsorption with solid sorbents	Adsorption with solid sorbents
	RECOVERED CO_2 (%)	95%	95%	95%	95%	95%
	CAPTURED CO_2 (tCO_2)	9.730,06	11.823,92	16.463,48	1.552,47	640,52
	Energy requirement (kWh/tCO_2)	200	200	200	200	200
	Energy requirement (%more input/MWh)	4,59%	3,82%	2,98%	13,57%	1,92%

	CAPEX (€/kW)	101,44	84,47	65,83	300,27	42,36
	CAPEX (k€)	3.804,17	1.833,77	1.510,20	4.992,04	41,90
	OPEX (€/MWh)	11,13	11,13	11,11	11,16	11,16
	Cost of Captured CO_2 (€/tCO_2)	56,99	66,72	83,11	24,89	125,00
TRANSPORT	MODALITY	articulated vehicle with 5 or more axles, refrigerated, diesel				
	ADDED CO_2 (tCO_2eq/y) **	228,82	278,07	417,85		
	CAPEX (k€)	1.062,02	1.290,57	1.939,35		
	OPEX (k€/y)	556,57	676,34	1.016,35		
	Cost of Transported CO_2 (€/tCO_2)	166,35	166,35	179,53		
TOTAL	EMITTED CO_2 (tCO_2eq/y) (ex-post)	741,94	901,60	1.286,06		
	REDUCED CO_2 (tCO_2eq/y)	9.520,40	11.569,14	16.078,05		
	COST (k€/y)	2.173,14	2.755,77	4.324,02		

Emissions from 22-24 average – amine solvent capture modality

Alperia SpA with CCUS applicability	STEAM AND SERVICES				
	ECOPLUS (AEP)				
	BOLZANO		MERANO		
	BZ SUD	**HOSPITAL**	**MAIA BASSA**	**MR SUD**	**ARENA**
ETS	1	1	2	2	2
EMISSION SCOPE	Scope 1	Scope 1	Scope 1	Scope 1	Scope 1
PLANT SIZE (MW)	37,50	21,71	22,94	16,63	0,99

emissions tCO_2/y (ex-ante)	average from 22-23-24	8.752,66	-	22.820,91	541,05	1.379,73
average from 22-23-24	tot op hours/y	2.667,83	8.688,00	3.966,63	1.333,09	5.191,74
	$kgCO_2$/h (flow rate)	3.398,14	-	5.744,00	1.569,60	265,55
	Energy consumption (MWh)	42.434,16	61.930,76	110.639,06	2.287,37	6.689,11
CAPTURE	Available Surface (m2)	3.298,00	n.a.	acquisition needed	as required	acquisition needed
	TECHNOLOGY PROVIDER	TPI	TPI	TPI	TPI	TPI
	TYPE of CAPTURE	Absorption with amine solvent	Absorption with amine solvent	Absorption with amine solvent	Absorption with amine solvent	Absorption with amine solvent
	RECOVERED CO_2 (%)	90%	90%	90%	90%	90%
	CAPTURED CO_2 (tCO_2)	7.877,39	-	20.538,82	486,95	1.241,75
	Energy requirement (kWh/tCO_2)	900	900	900	900	900
	Energy requirement (%more input/MWh)	16,71%	0,00%	16,71%	19,16%	16,71%
	CAPEX (€/kW)	369,58	-	369,58	423,83	369,58
	CAPEX (k€)	13.859,25	-	8.478,17	7.046,11	365,51
	OPEX (€/MWh)	11,14	11,16	11,10	11,16	11,16
	Cost of Captured CO_2 (€/tCO_2)	98,00	-	97,79	90,43	98,12
TRANSPORT	MODALITY	articulated vehicle with 5 or more axles, refrigerated, diesel				
	ADDED CO_2 (tCO_2eq/y) **	228,82	-	417,85		

	CAPEX (k€)	1.062,02	-	1.939,35
	OPEX (k€/y)	556,57	-	1.016,35
	Cost of Transported CO_2 (€/tCO_2)	205,47	-	143,91
TOTAL	EMITTED CO_2 (tCO_2eq/y) (ex-post)	1.105,81	-	2.704,44
	REDUCED CO_2 (tCO_2eq/y)	7.664,08	-	20.161,41
	COST (k€/y)	2.390,60	-	4.964,14

Emissions from 22-24 average – adsorption capture modality

	Alperia SpA with CCUS applicability	STEAM AND SERVICES				
		ECOPLUS (AEP)				
		BOLZANO		MERANO		
		BZ SUD	**HOSPITAL**	**MAIA BASSA**	**MR SUD**	**ARENA**
		VERO	VERO	VERO	VERO	VERO
	ETS	1	1	2	2	2
	EMISSION SCOPE	Scope 1	Scope 1	Scope 1	Scope 1	Scope 1
	PLANT SIZE (MW)	37,50	21,71	22,94	16,63	0,99
emissions tCO_2/y (ex-ante)	average from 22-23-24	8.752,66	-	22.820,91	541,05	1.379,73
average from 22-23-24	tot op hours/y	2.667,83	8.688,00	3.966,63	1.333,09	5.191,74
	kgCO_2/h (flow rate)	3.398,14	-	5.744,00	1.569,60	265,55
	Energy consumption (MWh)	42.434,16	61.930,76	110.639,06	2.287,37	6.689,11

CAPTURE	Available Surface (m2)	3.298,00	n.a.	acquisition needed	as required	acquisition needed
	TECHNOLOGY PROVIDER	Nuada	Nuada	Nuada	Nuada	Nuada
	TYPE of CAPTURE	Adsorption with solid sorbents	Adsorption with solid sorbents	Adsorption with solid sorbents	Adsorption with solid sorbents	Adsorption with solid sorbents
	RECOVERED CO_2 (%)	95%	95%	95%	95%	95%
	CAPTURED CO_2 (tCO_2)	8.315,03	-	21.679,87	514,00	1.310,74
	Energy requirement (kWh/tCO_2)	200	200	200	200	200
	Energy requirement (%more input/MWh)	3,92%	0,00%	3,92%	4,49%	3,92%
	CAPEX (€/kW)	86,69	-	86,69	99,42	86,69
	CAPEX (k€)	3.250,94	-	1.988,71	1.652,79	85,74
	OPEX (€/MWh)	11,14	-	11,09	11,16	11,16
	Cost of Captured CO_2 (€/tCO_2)	65,28	-	65,06	58,11	65,07
TRANSPORT	MODALITY	articulated vehicle with 5 or more axles, refrigerated, diesel				
	ADDED CO_2 (tCO_2eq/y) **	228,82	278,07	417,85		
	CAPEX (k€)	1.062,02	1.290,57	1.939,35		
	OPEX (k€/y)	556,57	676,34	1.016,35		
	Cost of Transported CO_2 (€/tCO_2)	194,66	-	136,33		
TOTAL	EMITTED CO_2 (tCO_2eq/y) (ex-post)	667,32	-	1.561,15		

	REDUCED CO_2 (tCO_2eq/y)	8.102,58	-	21.304,71
	COST (k€/y)	2.161,38	-	4.366,25

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