Current CO₂ Capture and Storage Trends in Europe in a View of Social Knowledge and Acceptance. A Short Review

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Abstract: Carbon dioxide (CO_2) has reached a higher level of emissions in the last decades, and as it is widely known, CO_2 is responsible for numerous environmental problems, such as climate change. Thus, there is a great need for the application of CO_2 capture and storage, as well as of CO_2 utilization technologies (CCUS). This review article focuses on summarizing the current CCUS state-of-the-art methods used in Europe. Special emphasis has been given to mineralization methods/technologies, especially in basalts and sandstones, which are considered to be suitable for CO_2 mineralization. Furthermore, a questionnaire survey was also carried out in order to investigate how informed about CO_2 issues European citizens are, as well as whether their background is relative to their positive or negative opinion about the establishment of CCUS technologies in their countries. In addition, social acceptance by the community requires contact with citizens and stakeholders, as well as ensuring mutual trust through open communication and the opportunity to participate as early as possible in the development of actions and projects related to CO_2 capture and storage, at all appropriate levels of government internationally, as citizens need to understand the benefits from such new technologies, from the local to the international level.

1. State of the Art

Carbon dioxide (CO_2) is considered the main greenhouse gas emission enhanced by human activities [1]. In 2019, CO_2, CH_4, and N_2O reached higher levels than during the last 800,000 years, while CO_2 measured 409.9 ppm. In particular, the highest average concentration of carbon dioxide over Europe reached 429 ppm during the last six-month period of 2021 (Figure 1).

In addition, over the past 60 million years, periods with significantly higher CO_2 concentrations in comparison with the current state have been detected, with the only difference being that the increasing rate of CO_2 is at least 10 times faster during 1900 to 2019 compared to any other period of the last 800,000 years [2].

The high CO_2 release into the atmosphere intensifies climatic changes [3] related to other environmental problems, such as the acidification of the oceans [4]. During recent decades, almost 80% of the world's energy consumption per year, which is more than 500 exajoules, was provided by fossil fuels [5]. Due to the economic development and growth of the world population, the global energy consumption may double in future years. Despite the decrease in the burning of fossil fuels and their substitution by renewable energies, sequestration of CO_2 is mandatory for the purposes of resuming the use of fossil fuels and the avoidance of CO_2 emissions in the atmosphere. Those procedures

involve the capture of this gas at specific designed industrial sites, its transport, and final permanent underground storage in ideal geological formations. Potential risks, such as CO_2 leakage, geological disasters, and contamination of underground water, must be taken under consideration.
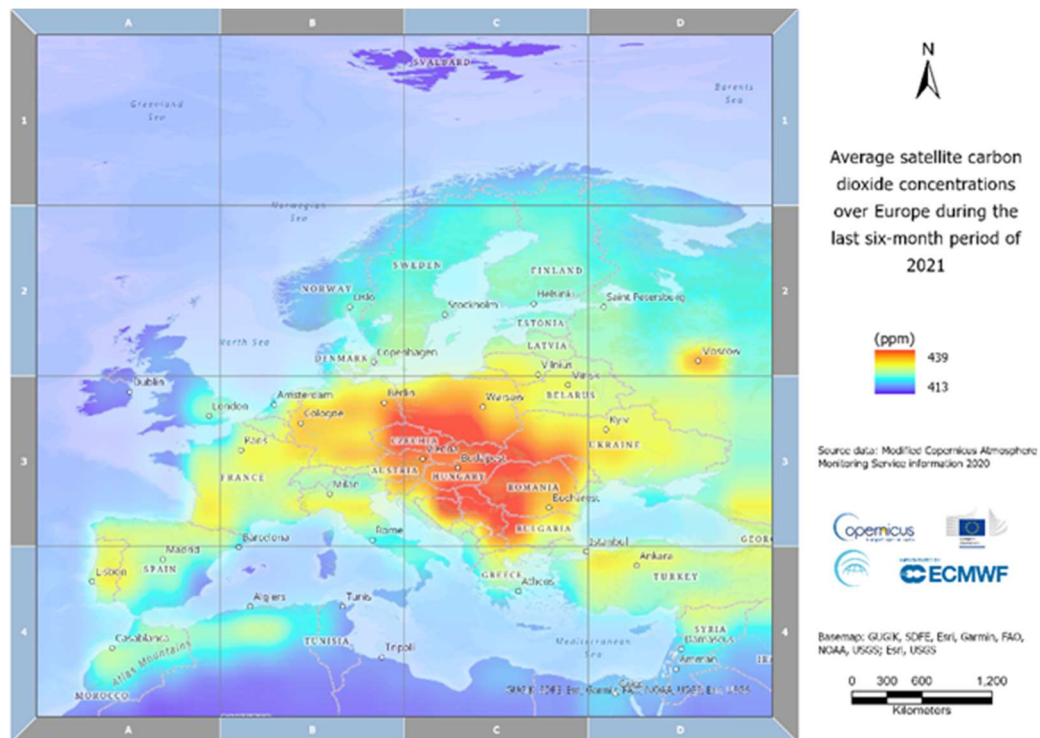

Figure 1. Visualization of the mean spatial distribution of carbon dioxide over Europe during the last period of 2021. Red and blue colors represent the highest and the lowest average values of CO_2. Data were retrieved and modified from Copernicus Atmosphere Monitoring Service (CAMS).

CO_2 capture and separation processes are considered expensive procedures. There are three main technology options to capture CO_2 from fossil fuel power generation plants [6], namely: (i) post-combustion (CO_2 is separated from the flue gas); (ii) oxy-fuel combustion (uses nearly pure oxygen for the combustion of fuel, and CO_2 is then removed from the generated gases, formed principally from water vapor and CO_2); and (iii) pre-combustion (CO_2 is removed from the fuel before combustion). Unfortunately, the application of CO_2 capture technologies may reduce the net efficiency of a plant by up to 14% [7]. In addition, the cost of electricity would increase by 30–70% [6,8] (depending on the fuel used, plant type, and capture technology). The main advantage of post-combustion capture is that it can be integrated into existing power plants without altering the combustion process. It can also be removed from the air after it has been emitted using a technology called direct air capture (DAC). However, with only a few operational projects worldwide, the development of DAC technology is still in its early days, and the large amount of energy required to separate CO_2 from ambient air makes it costlier. Thus, researchers are focusing on the development of low-cost and low-energy-consuming CO_2 separation processes. Geological CO_2 storage provides the potential for permanently storing large quantities of CO_2 through various options to mitigate the effects of climate change [9]. These options include deep saline aquifers [10], coal beds [11], deep ocean, deep sea sediments, abandoned coal mines [12], and depleted hydrocarbon fields [13]. Enhanced oil and/or gas recovery (CO_2-EOR and CO_2-EGR, respectively) are processes that combine the extraction of crude oil and/or natural gas with simultaneous CO_2 storage [14]. CO_2 mineralization is an additional option for CO_2 storage that involves the chemical reaction of several rock types (such as basalts, sandstones, and serpentinites) with supercritical CO_2,

resulting in the formation of carbonate minerals and the subsequent CO_2 sequestration in the formed carbonate minerals [15–17]. Mineralization or mineral sequestration are techniques that have gained ground due to the stability of the final created system [18]. Mineralization involves the reaction of cations (Mg^{2+}, Ca^{2+}) from the selected geological formation with the stored CO_2, resulting in the formation of carbonates, CO_3^{2-} or HCO^{3-}. In addition to geological formations, other feedstocks, such as industrial waste materials such as steel slag or fly ash, could be used [19]. Silicate ores with $MgO-$ and $CaO-$ were thermally activated in order to react with CO_2, but this procedure increased the cost [20]. For the maintenance of cost, the use of abundant rocks was proposed. Olivine, serpentine, wollastonite, calcium silicate, and serpentine are the most tested materials for such an application [19], as they are extensively available on enormous scales [21]. During the mineral sequestration procedure, an exothermic reaction takes place between the basic minerals and CO_2 gas that is effectively stored as a carbonate [22]. This formation can exist in two phases: the solid one, which is more thermodynamically stable, and the dissolved (bi) carbonate in water.

The variety of minerals that can lead to carbonation reactions are often observed through natural processes and, at the same time, contribute to an increased storage capacity; moreover, the stability of CO_2 storage in stable solids results in no CO_2 being released from the storage site. Furthermore, energy in the form of heat that is released through CO_2 sequestration reactions can potentially be used for power source purposes [21,23,24]. Therefore, CO_2 interacts with calcium or magnesium oxides to form permanent and stable carbonate-bearing materials through the reaction: $MO + CO_2 \rightarrow MCO_3$ + released heat, in which M represents the divalent metal. The quantity of heat produced depends on the type of metal, as well as on the type of metal oxide material included. The aforementioned reaction produces heat that is associated with the fact that the thermodynamic state of the mineral sequestration process is developed initially at relatively low temperature conditions and subsequently leads to calcination conditions. In this method, it is important to further promote carbonation-related processes but also to cautiously exploit heat in order not to cause any significant problems associated with the environment [25]. There are two ways to accomplish mineral carbonation. The first is the in situ methodology, which includes the injection of CO_2 within a suitable geological formation to produce stable carbonate minerals that commonly include calcite ($CaCO_3$), magnesite ($MgCO_3$), siderite ($FeCO_3$), as well as dolomite ($Ca0.5Mg0.5CO_3$). The minerals developed are regarded as thermodynamically stable, and thus, sequestration through this method is considered to be permanent and safe [26]. This method proposes a different approach from common geological storage practices, and for this reason, CO_2 is injected underground under special conditions in order to enhance the natural mineral carbonization process. The second is the ex situ method, where the process is carried out aboveground [27,28]. The mineral carbonation process paths have been described by Olajire et al. [25] in great detail. Most scientists prefer in situ mineralization, and this happens as no other facilities or even mining are needed, with CO_2 being injected into rocks that include a relatively high pore volume, promoting subsurface reactions. Furthermore, mobilization of the reactants, although not necessary, may occur in restricted amounts. By the end of the processes, the amount of newly formed minerals produced is higher than that of minerals derived through industrial waste processing [25,29]. On the other hand, there are still many challenges concerning mineralization methodologies that include choosing appropriate rocks that contain the proper minerals and metals and also possess the necessary physicochemical properties to favor carbonation. An additional factor that scientists must consider is the released heat factor produced from these reactions [25]. An important risk factor concerns the possible lack of sufficient amounts of carbon to achieve CO_2 storage [30–32], although the risk can be decreased through dissolving CO_2 in water prior to or during injection into geological formations, since this form is generally denser than CO_2 in gas or at supercritical form [33–35]. It should be noted that, in general, the in situ methods should be deployed in cases of high CO_2 volumes [36].

Ca and Mg oxides and/or hydroxides are considered proper for mineral carbonation, and this is due to their alkalinity. Even magnesia (MgO) and lime (CaO) are amongst the most common earth metal oxides that appear in nature, which are often bonded in the form of silicates (e.g., olivine and/or serpentine) with high MgO contents [36]. Carbonation of Ca seems to be more effective; otherwise, MgO seems to be more frequent in nature [36]. Ophiolite rocks and especially basalts present as magnesium, calcium, and iron silicates [37]. Ultramafic and mafic rocks generally exhibit high MgO, CaO, and FeO concentrations, and they also display low alkali contents. Their primary minerals mainly consist of olivine, serpentine, and enstatite, as well as wollastonite [25]. Minerals such as olivine and serpentine, but also rocks such as peridotite and mafic gabbro, are commonly found in ophiolitic geotectonic zones, based on Coleman et al. [38] and Nicolas et al. [39]. Numerous studies and projects have been made of natural minerals for CO_2 sequestration.

The European Union produced almost 2.54 billion metric tons of CO_2 during 2020, with this value was 13% lower compared to the emissions of 2019 due to the reductions in travel, industrial activities, and power supply caused by the lockdowns of the COVID-19 pandemic period. Despite that, the levels are still high and require a critical solution. The main contributor to Europeans' CO_2 emissions is Germany, compared to other big countries, e.g., France, Poland, or Italy, due to its industrial activities and coal burning [40]. The mineralization procedure has also drawn attention in the European Union area, as CO_2 emissions require a critical management. The present study aims to review CO_2 mineralization procedures investigated in European Union areas. The region was specified as the geological formations have different characteristics from one area to another that directly affect CO_2 mineralization. Moreover, the investigation of the temperature and pressure conditions of the region is mandatory, as the areas' circumstances also impact the mineralization process. As sandstones and basalts were feedstocks of high importance for the creation of stable carbonates, the present study mainly focuses on such geological formations. European areas with a high interest in the exploitation of a CO_2 mineralization process will be highlighted for potential further investigations in the future.

This review, by following the principles of sustainable development, attempts to discuss and highlight the most recent developments and trends in Europe regarding the crucial CO_2 capture and storage issue. Europe, on the one hand, presents particularly high emissions, but on the other hand, it presents a geo-privileged position capable of safely capturing these emissions within Europe using eco-friendly technologies. Particular emphasis in the present study was placed both on the knowledge level regarding the critical issue of CO_2 capture and storage and exactly how a representative sample of 300 European citizens perceive it. An additional scope of this paper was to investigate how informed European citizens are regarding CO_2 issues, as well as whether they agree to CO_2 capture, storage, and utilization technologies to be carried out in their countries in order to solve CO_2 environmental problems. The representative sample examined was strategically selected so that it was possible to safely attribute the relevant conclusions and propose the corresponding corrective actions that will lead Europe to a better future.

2. Research Methods

This review mainly summarizes researchers' findings regarding the current situation of CCUS processes in Europe. Emphasis was given to CO_2 mineralization. We further explored the current developments in CCUS technologies in Europe and the use of pathways based on the number of published articles, their authors, keywords, affiliations, etc.

In order to investigate how informed the European citizens are about CO_2 capture, storage, and utilization issues, as well as whether they agree with such solutions for reducing CO_2 emissions, a number of questions were given to a variety of European citizens. For this reason, in order to obtain a representative statistical sample, 300 European citizens deriving from various European countries were chosen from 25 May to 25 June of 2022 (Figure 2). The questions were shared/given in a hotel located in Kefalonia Island, which constitutes one of the most famous European tourist destinations and now has

an air connection with almost all European countries. Moreover, this hotel was chosen as it contains a geological stand where geological information is given and also because people of different educational backgrounds can be observed (Figure 2). The island of Kefalonia was strategically chosen, as in 2021, it was included in the UNESCO Geoparks, as a result of which it attracts many European citizens who visit the island to discover the natural beauty of the geopark. All the answers were statistically analyzed in order to draw important conclusions.

Figure 2. (**a**–**g**): European citizens completing the questionnaires regarding CO_2 issues at the geological stand of the hotel.

3. Strategies and Mechanisms of CO_2 Storage in Europe

Contingent upon reservoir conditions, CO_2 can be sufficiently stored in the form of compressed gas, liquid, or at supercritical state. The most common trapping mechanisms of CO_2 storage are (1) stratigraphic/structural or hydrodynamic, (2) residual storage, (3) geologic solubility storage, and (4) mineral sequestration [41]. Once CO_2 is injected, the subsurface will spread laterally while synchronously rising until it meets, by chance, a caprock that possesses a capillary entry pressure higher than the buoyancy or hydrodynamic force (buoyancy effect). This trapping, namely, structural or stratigraphic trapping, or what is often called hydrodynamic trapping, is favored because of the low permeability of the caprock. This mechanism is the most valuable because it is necessary for most storage sites, as this prevents CO_2 leakage [42]. Structural and/or stratigraphic trapping is determined by the rock's characteristics, the pore volume, and reservoir permeability.

Residual trapping happens when the injected CO_2 expels formation fluid as it flows through the rock formation. As a result of the capillary force, the remaining CO_2 is trapped by the expelled fluid within the pores of the rocks, so that it becomes immobile [43].

In solubility trapping, CO_2 dissolves into the formation fluid. The density of the brine will slightly increase by the dissolution of the CO_2. That slight density difference is enough to benefit the transmission flow, which is likewise a mechanism of CO_2 trapping [44]. CO_2 solubility within groundwater is influenced by temperature and salinity. When the temperature and salinity rise, then solubility decreases.

Mineral trapping is related to the formation of new stable mineral phases via geochemical reactions in the reservoir [45]. As time passes, the injected CO_2 will dissolve into the brine and set up an important number of geochemical reactions, many of which could promote mineral trapping. This mechanism depends on the structure, mineralogy, and hydrology of the surrounding formations, while the reaction rate of mineral forming depends on the temperature, pressure, pH, and the contact lithotypes with the CO_2 bearing brine. Natural mineral trapping is a very slow process and, without human intervention, would only be able to occur through many thousands of years.

Geological storage comprises injecting CO_2 within rock formations that can safely absorb and store it for many thousands of years. Formations that have been considered as suitable for storing CO_2 are found in sedimentary basins, were sediments have accumulated and gone through diagenetic processes through the geological periods. Sedimentary basins usually have an extent of thousands of kilometers [46]. According to the CO_2StoP project (CO_2 Storage Potential in Europe), which began in January of the year 2012 and concluded in October of 2014, by including information from 27 countries (Figure 3), a database was created as part of the project that contains the information required to evaluate potential CO_2 storage locations. A data analysis system was formed to analyze the database's complex data, as well as a Geographical Information System (GIS) capable of displaying the locations of suitable geological storage formation sites, the individual assessment units, and other subdivisions (daughter units that include hydrocarbon reservoirs or structural saline aquifer traps).
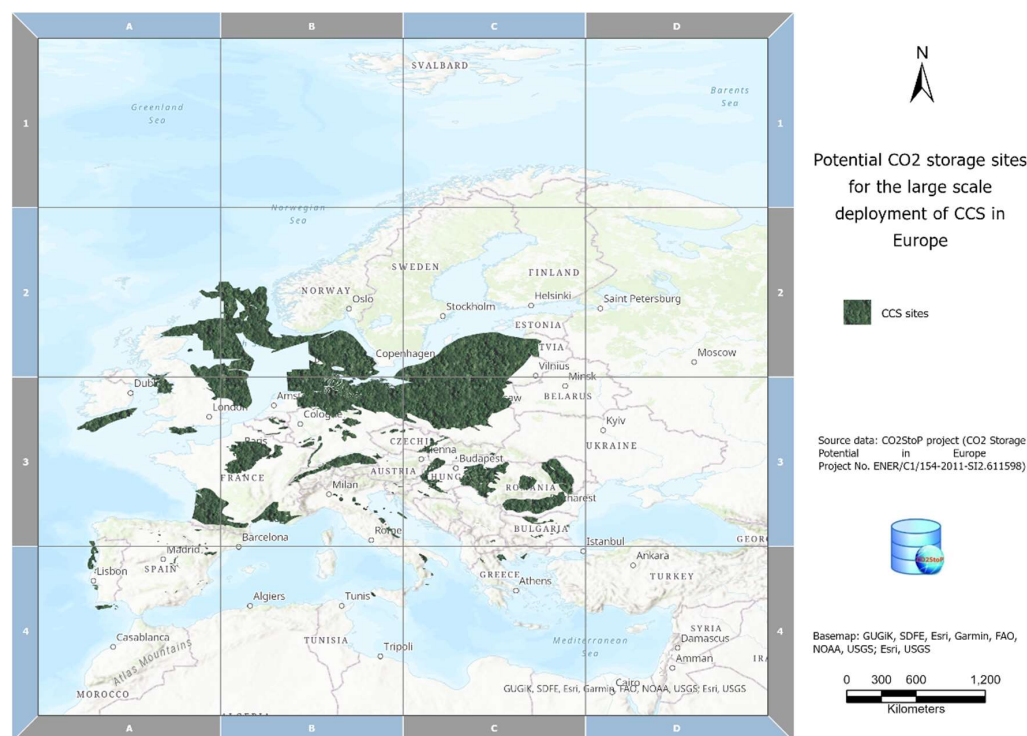

Figure 3. Representation of potential European CCS storage sites. Green color depicts the CCS sites. Data were retrieved and modified from CO_2StoP project (CO_2 Storage Potential in Europe. Project No. ENER/C1/154-2011-SI2.611598).

Un-mineable coal seams have been proposed as suitable for CO_2 storage purposes. Lately, the possibility of storing CO_2 in basalt formations is being considered. Aquifers and oil reservoirs involve storing CO_2 within the pore volumes of subsurface rocks. The injected CO_2 is restrained on the coal matrix as a result of adsorption into the coal seams. Carbon mineralization (i.e., a chemical reaction) is the storage mechanism in basalt. Geological storage is not possible to accomplish globally as Earth's geology differs. Summarizing, four options appear to predominate for storing CO_2 in geological formations, including saline aquifers, depleted oil reservoirs, coal seams, and silica-undersaturated basaltic rock formations. Nowadays, around the Europe Union, there are Commercial- and Pilot/Demonstration-scale CCS Facilities. These CCS Facilities, both active and those in the implantation stage, are assembled in Table 1, Figure 4.

Table 1. Commercial- and Pilot/Demonstration-scale CCS Facilities around Europe. Adapted from: https://co2re.co/FacilityData.

Project	Location	Category	Status/Started	Operational	Facility Industry	Storage
Hafslund Oslo Celsio-Klemetsrud Waste to Energy Plant	Norway	Commercial CCS Facility	In Construction	2025	Waste Incineration	Yes
Acorn	UK	Commercial CCS Facility	Early Development	Mid 2020s	Oil Refining	Yes
Acorn (Minimum Viable CCS Development)	UK	Pilot and Demonstration CCS Facility	Advanced Development	2021–2022	Various	Yes
Acorn Direct Air Capture Facility	UK	Commercial CCS Facility	Early Development	2026	N/A	No
Acorn	UK	Commercial CCS Facility	Early Development	2025	Hydrogen Production	Yes
Adriatic Blue-ENI Hydrogen CCS	Italy	Commercial CCS Facility	Early Development	2026	Hydrogen Production	Yes
Adriatic Blue-ENI Power CCS	Italy	Commercial CCS Facility	Early Development	2026	Power Generation	Yes
Air Liquide Refinery Rotterdam CCS	The Netherlands	Commercial CCS Facility	Advanced Development	2024	Hydrogen Production	Yes
Air Products Refinery Rotterdam CCS	The Netherlands	Commercial CCS Facility	Advanced Development	2024	Hydrogen Production	Yes
Antwerp@C-BASF Antwerp CCS	Belgium	Commercial CCS Facility	Advanced Development	2030	Chemical Production	-
Antwerp@C-Borealis Antwerp CCS	Belgium	Commercial CCS Facility	Early Development	2030	Chemical Production	-
Antwerp@C-Exxonmobil Antwerp CCS	Belgium	Commercial CCS Facility	Early Development	2030	Chemical Production	-
Antwerp@C-Ineos Antwerp CCS	Belgium	Commercial CCS Facility	Early Development	2030	Chemical Production	No
Barents Blue	Norway	Commercial CCS Facility	Early Development	Mid 2020s	Fertilizer Production	No
Borg CO_2	Norway	Pilot and Demonstration CCS Facility	Early Development		Various	Yes
Caledonia Clean Energy	UK	Commercial CCS Facility	Early Development	2024	Power Generation	Yes
Carbfix Project	Iceland	Pilot and Demonstration CCS Facility	Operational	2012	Power Generation	Yes
Cinfracap–Pipeline	Sweden	Pilot and Demonstration CCS Facility	Early Development		Various	No
Cinfracap–Shipping Pipeline	Sweden	Pilot and Demonstration CCS Facility	Early Development		Various	No
CIUDEN: CO_2 Storage Technology Development Plant	Spain	Pilot and Demonstration CCS Facility	Operational	2015	N/A	Yes
CODA Shipping	Iceland	Commercial CCS Facility	Advanced Development	2026	Various	No
CODA Terminal Onshore Infrastructure	Iceland	Commercial CCS Facility	Advanced Development	2026	Various	No

Table 1. *Cont.*

Project	Location	Category	Status/Started	Operational	Facility Industry	Storage
CODA Terminal Pipeline	Iceland	Commercial CCS Facility	Advanced Development	2026		No
CODA Terminal Storage	Iceland	Commercial CCS Facility	Advanced Development	2026		Yes
Copenhill (Amager Bakker) Waste to Energy CCS	Denmark	Commercial CCS Facility	Advanced Development	2025	Waste Incineration	No
DMX^{TM} Demonstration in Dunkirk	France	Pilot and Demonstration CCS Facility	Advanced Development	2022	Iron and Steel Production	No
Drax BECCS Project	UK	Commercial CCS Facility	Early Development	2027	Power Generation	Yes
Drax bioenergy carbon capture pilot plant	UK	Pilot and Demonstration CCS Facility	Operational	2019	Power Generation	No
Ervia Cork CCS	Ireland	Commercial CCS Facility	Early Development	2028	Power Generation Refining	Yes
ExxonMobil Benelux Refinery CCS	The Netherlands	Commercial CCS Facility	Advanced Development	2024	Hydrogen Production	Yes
Fortum Oslo Varme–Shipping Route	Norway	Pilot and Demonstration CCS Facility	Early Development	2025	Waste Incineration	Yes
Fortum Oslo Varme–Truck Route	Norway	Commercial CCS Facility	Advanced Development	2025	Waste Incineration	Yes
Geothermal Plant with CO_2 Re-injection	Croatia	Pilot and Demonstration CCS Facility	Operational	2018	Power Generation	Yes
Humber Zero–Phillips 66 Humber Refinery CCS	UK	Commercial CCS Facility	Advanced Development	2028	Hydrogen Production	Yes
Humber Zero–VPI Immingham Power Plant CCS	UK	Commercial CCS Facility	Advanced Development	2027	Power Generation	Yes
Hydrogen 2 Magnum (H2M)	The Netherlands	Commercial CCS Facility	Early Development	2024	Power Generation	No
Hydrogen to Humber Saltend	UK	Commercial CCS Facility	Early Development	2026–2027	Hydrogen Production	No
HyNet North West	UK	Commercial CCS Facility	Early Development	Mid 2020s	Hydrogen Production	Yes
HyNet North West–Hanson Cement CCS	UK	Commercial CCS Facility	Early Development	2026	Cement Production	Yes
LEILAC	Belgium	Pilot and Demonstration CCS Facility	In Construction	2020′s	Cement Production	No
MOL Szank field CO_2 EOR	Hungary	Commercial CCS Facility	Operational	1992	Natural Gas Processing	Yes
Net Zero Teesside–BP H2Teesside	UK	Commercial CCS Facility	Early Development	2027	Hydrogen Production	Yes
Net Zero Teesside-CCGT Facility	UK	Commercial CCS Facility	Early Development	2025	Power Generation	Yes
Net Zero Teesside-Net Power Plant	UK	Commercial CCS Facility	Early Development	Late 2020s	Power Generation	Yes
Net Zero Teesside-Suez Waste to Energy CCS	UK	Commercial CCS Facility	Early Development	2027	Waste Incineration	Yes
Norcem Brevik–Cement Plant	Norway	Commercial CCS Facility	In Construction	2024	Cement Production	No
Norcem Brevik- Shipping Route	Norway	Commercial CCS Facility	In Construction	2024	Cement Production	Yes
Northern Gas Network H21 North of England	UK	Commercial CCS Facility	Early Development	2026	Hydrogen Production	Yes
Nothern Lights–Pipeline	Norway	Pilot and Demonstration CCS Facility	Early Development	2024	Various	No
Nothern Lights–Storage	Norway	Pilot and Demonstration CCS Facility	Early Development	2024	Various	Yes
Orca	Iceland	Commercial CCS Facility	Operational	2021	Direct Air Capture	Yes
Polaris Carbon Storage	Norway	Commercial CCS Facility	Advanced Development	2024	Hydrogen Production	Yes
Porthos–Compressor Station	The Netherlands	Commercial CCS Facility	Advanced Development	2024	Various	No

Table 1. *Cont.*

| Project	Location	Category	Status/Started	Operational	Facility Industry	Storage
Porthos–Offshore Pipeline	The Netherlands	Commercial CCS Facility	Advanced Development	2024	Various	No
Porthos–Onshore Pipeline	The Netherlands	Commercial CCS Facility	Advanced Development	2024	Various	No
Porthos–Storage	The Netherlands	Commercial CCS Facility	Advanced Development	2024	Various	Yes
Preem Refinery CCS	Sweden	Commercial CCS Facility	Early Development	2025	Hydrogen Production	No
Shell Refinery Rotterdam CCS	The Netherlands	Commercial CCS Facility	Advanced Development	2024	Hydrogen Production	No
Sleipner CO_2 Storage	Norway	Commercial CCS Facility	Operational	1996	Natural Gas Processing	Yes
Snohvit CO_2 Storage	Norway	Commercial CCS Facility	Operational	2008	Natural Gas Processing	Yes
STEPWISE Pilot of SEWGS Technology at Swerea/Mefos	Sweden	Pilot and Demonstration CCS Facility	Operational	2017	Iron and Steel Production	No
Stockholm Exergi BECCS	Sweden	Commercial CCS Facility	Advanced Development	2025	Bioenergy	-
Stockholm Exergi BECCS–Shipping Route	Sweden	Commercial CCS Facility	Advanced Development	2025	Bioenergy	-
Technology Centre Mongstad (TCM)	Norway	Pilot and Demonstration CCS Facility	Operational	2012	Oil Refining	No
UKCCSRC Pilot-scale Advanced Capture Technology (PACT)	UK	Pilot and Demonstration CCS Facility	Operational		Power Generation	No
ZERO Carbon Humber–Keady 3 CCS Power Station	UK	Commercial CCS Facility	Early Development	2027	Power Generation	No
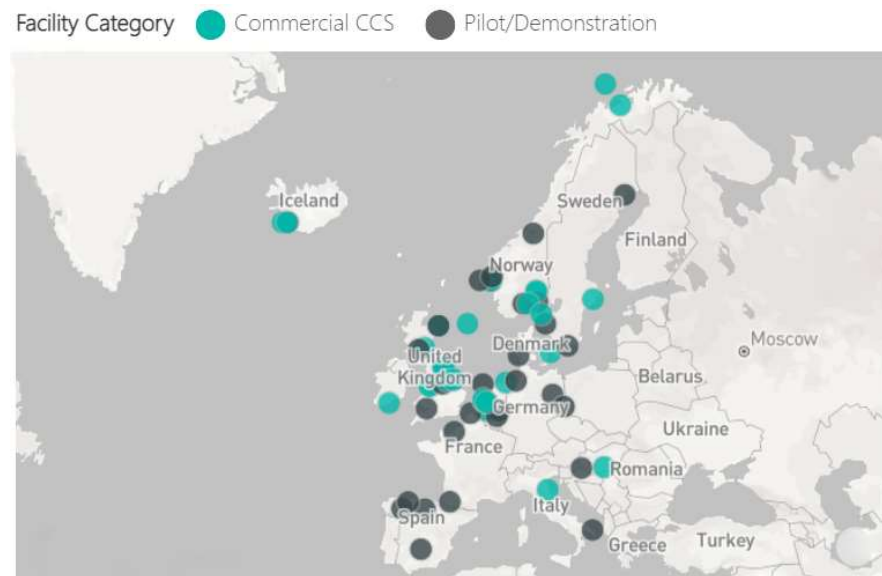
Figure 4. Representation of the Commercial-scale CCS Facilities around Europe. Map adapted from https://co2re.co/FacilityData.

3.1. CO_2 Storage in Saline Aquifers

Saline aquifers include geological formations consisting of water-permeable rock formations that are saturated with brine. The amount of CO_2 that can be stored in saline aquifers is large. Saline formation trapping mechanisms include solubility trapping, mineral trapping, structural trapping, and residual trapping. There are vital properties an aquifer must meet to be considered suitable for CO_2 storage. These properties are the following: sufficient porosity, permeability, thickness, adequate depth, and an impermeable

caprock [47]. Potential storage sites must be geologically stable regarding their tectonic activity, which may form pathways for CO_2 to migrate from the reservoir through the caprock and even to the surface. In contrast to other types of storage sites, saline aquifers often hold vast trading and large territorial coverage. Accordingly, it is more likely to be placed close to CO_2 emission sources, and therefore, the cost of transporting the CO_2 decreases [48,49]. The most urgent challenge regarding CO_2 sequestration within saline aquifers is potential pressure gathering and CO_2 mobilization in the formation, which could possibly cause the fracture of the formation, reactivate any faults, and finally lead to CO_2 leakage [50].

In the European Union, there are chiefly two commercial-scale CCS deployed projects in saline aquifers, which are the Sleipner project (country) and the Snøhvit project (country). Besides the aforementioned large-scale CCS projects, there is also a small-scale project, the Ketzin pilot site in Germany.

Considering the Sleipner Project, the injected CO_2 came from its separation from methane formed at the Sleipner land at the North Sea. The injection took place at the Utsira Sand aquifer formation; from 1996 when it was initiated until 2018, an amount of 18 million tons were injected [51]. With regard to the Snøhvit project, the operation started in 2008. With knowledge from the Sleipner project, in the Snøhvit CCS project, CO_2 was separated from the liquefied natural gas (LNG) project and injected within the deeper Tubåen Formation, which is in the Barents Sea. By 2012, an amount of 1600 ktons of CO_2 had been injected, and it is estimated that ~23 million tons of CO_2 can be safely stored based upon the project's estimated lifetime period [52,53]. The Ketzin pilot site has been developed since 2004; by 2012, an amount of 61,400 tons of CO_2 were safely stored into 630 m to 650 m deep sandstone formations (U. Triassic Stuttgart) at an anticlinal structure of the Northeast German Basin [54]. This enhances public acceptance of such pilot projects to be developed under such detailed modeling and monitoring operations.

3.2. CO_2 Storage within Depleted Oil and Gas Reservoirs

Oil and natural gas reservoirs are considered optimum geologic storage sites since they have stored hydrocarbons for even millions of years, displaying properties appropriate for CO_2 storage. Once oil and natural gas have been removed from an underground formation, it leaves permeable and porous volume pores that could be filled with CO_2. Injecting CO_2 could further enhance oil production through mobilizing fluids towards producing wells by a process called enhanced oil recovery (EOR). Moreover, oil and gas reservoirs have an abundance of existing equipment established on the surface and underground that can be reused for CO_2 storage with small-scale conversions. There are many large, abandoned, and mature oil-gas offshore fields in Europe (despite their cumulative CO_2 storage capacity falling below what is possible within saline aquifers). Fine examples are the onshore and offshore gas fields in N. Germany and in the Netherlands, as well as in the south parts of the North Sea. The CO_2 amount that could be stored within depleted gas fields depends highly on the quantity of gas that was produced and also on the depletion grade of the field.

3.3. CO_2 Storage in Coal Beds

Un-mineable coal is coal that, because of geological, technological, and economic factors, cannot be mined but could be a potential storage site for CO_2. To be considered for CO_2 storage, the ideal coal seam should display proper permeability and also be regarded as un-mineable. Coal seams could also store methane (CH_4), which could be developed in conjunction with CO_2 injection; this process is known as "enhanced coal bed methane (ECBM) recovery". As previously mentioned, the injected CO_2 is restrained on the coal matrix as a result of adsorption into the coal seams, whereas CH_4 is also released and produced. This entrapment mechanism is considered everlasting. Coal beds are beneficial because of their position, which is usually nearby to an existing or planned coal-fired power plant. As a result, transportation costs may be reduced.

3.4. CO$_2$ Storage in Deep Ocean

The CO$_2$ could be directly injected within the deep ocean at water depths exceeding 2700 m [55,56], where liquid CO$_2$ could sink into the seafloor; this occurs because the CO$_2$ is denser than seawater under relatively high pressure and at low temperature conditions [56,57]. The storage capacity is very high because of the enormous volume of the ocean. On the other hand, this CCS mechanism is not easily applied since it can influence the marine environment.

3.5. CO$_2$ Storage in Deep-Sea Sediments

The choice of injecting CO$_2$ into deep-sea sediments combines the advantages of geologic storage as well as ocean storage, preventing many shortcomings [58–61]. To explain in more detail, there are no potential harms posed to oceanic ecosystems, and this happens because the CO$_2$ targets deep sediments rather than the oceanic water. The storage mechanisms are similar to terrestrial sequestration mechanisms, such as dissolution trapping, residual trapping, as well as mineral trapping, which still constitute a critical factor. It should also be noted that innovative storage mechanisms, such as gravitational and hydrate trapping, are also applicable in the sequestration. Gravitational trapping is enhanced by the higher density that leads CO$_2$ in the sea [57] to the widely mentioned negative buoyancy zone (NBZ). The optimum depth for the salinity and temperature-dependent density of seawater is exactly 2700 m [62]. Hydrate trapping acts due to CO$_2$ hydrate development at high pressure and low temperature conditions [59]. We would like to point out that, in the first injection stage, a small number of hydrates develop at the lower parts of the hydrate formation zone (HFZ), promoting limitation of the caprock's permeability. The area of the hydrate caprock increases with larger amounts of CO$_2$ and, as a result, reaches the bottom of the HFZ and limits the CO$_2$ underneath it. At the same time, CO$_2$-saturated fluids are expected to sink downwards as a result of buoyancy-driven advection. At the end, the hydrated CO$_2$ and also the CO$_2$ liquid are expected to dissolve in seawater and turn into CO$_2$ aqueous solution via diffusion and permanent storage mechanisms. Despite the large capacity and feasibility of this technology, it remains at the readiness level of formulation technology. Furthermore, CO$_2$ storage in deep-sea sediments is much more costly than onshore methods. Additionally, it requires a great deal of time to increase the method's acceptance by society [60,63].

CO$_2$ Storage in Basalt Rock Formation in Europe

The physicochemical properties of basaltoid rocks, but also of other rock formations within basaltic layers, are considered proper candidates for CO$_2$ storage. The mineralogy of basalts can allow injected CO$_2$ to interact with Ca and Mg to develop stable and safe carbonate calcite and dolomite. This process represents a valuable tool for CCS since mineralization permanently stores carbon in a solid mineral structure, which allows CO$_2$ to be captured within its structure. Carbon mineralization can be implemented through the following methods: (1) in situ, in which CO$_2$-enriched fluids move through the rock pores; (2) ex situ, in which an alkalinity source is moved to a CO$_2$ capture site at relatively high temperature and pressure conditions in a vessel reactor; (3) surficial mechanisms by which CO$_2$ reacts with the alkalinity source above the surface [64]. Carbon mineralization costs depend on available CO$_2$ and the alkalinity conditions of the reaction [64].

Basalts are Ca, Mg, and Fe-rich volcanic rocks that can be used for CO$_2$ storage via mineralization purposes. CO$_2$ mineralization in basaltic rocks is achieved through the reaction between Ca-Mg-Fe-rich minerals and carbonic acid. The latter comes from injected CO$_2$ dissolution and the subsequent increase in water reactivity due to H$^+$ release. Some of the most common carbonate minerals that can be formed include calcite, magnesite, dolomite, and siderite, as it is described by the following mineralogical reaction [34,65]:

$$(Ca,Mg,Fe)^{2+} + H_2CO_3 \rightarrow (Ca,Mg,Fe)CO_3 + 2H^+ \tag{1}$$
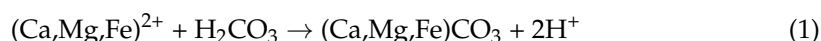
Selection of the appropriate basaltic types for CO_2 mineralization depends on a series of physicochemical criteria that include: (a) an abundance of Ca, Mg, and Fe-rich minerals, (b) a low silica saturation of the basalt, (c) a high porosity–permeability, and (d) the alteration degree [65]. In addition, the total volume of the basaltic outcrops, as well as their proximity to water sources, are two important factors that should be considered before application of in situ CO_2 mineralization. Thus, despite the wide distribution of basaltic rocks on Earth [34,66,67], only a few types can be considered for CO_2 storage based on the above-mentioned criteria.

Mineralogical reactions

Basalts are predominantly composed of glass and, to a lesser extent, magmatic minerals such as olivine, clinopyroxene, orthopyroxene, spinel, and plagioclase. Hence, the efficiency of CO_2 mineralization in basalts is closely linked with the carbonation rate of the distinct magmatic components (minerals and glass). Carbonation of olivine (reaction-2) is a natural process that develops slowly, which should be enhanced in large-scale storage projects [23,68,69]:

$$Ol + 2CO_2 \rightarrow 2Mgs + SiO_2(s) \tag{2}$$
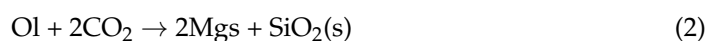
Results from experiments suggest that olivine dissolves at higher degrees under more acidic conditions, from 10^{-11} to $10^{-8.5}$ mol/m^2/s for a pH range of 13 to 1.5 [34,70]. Regarding the temperature conditions, Kelemen et al. [71] suggest that olivine exhibits an optimal carbonation rate at ~185 °C.

Dissolution of clinopyroxene is controlled by the mineral (3). Experimental results suggest that, after the injection of the water-dissolved CO_2, the subsequent pH decrease will lead to increasing dissolution rates of clinopyroxene-rich basalts [70]. In particular, the dissolution rate of augite ranges from 10^{-12} to 10^{-8} for mol/m^2/s for a pH range between 7.3 and 2 [70]. Experimental results of the carbonation rate of diopside also indicate that alkaline conditions (increasing pH values) reduce the diopside dissolution [72].

$$Cpx + 4H^+ \rightarrow Mg^{2+} + Ca^{2+} + 2H_2O + 2SiO_2(aq) \tag{3}$$
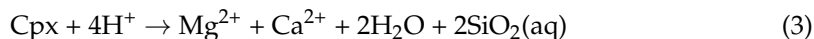
Another important parameter that must be considered for the dissolution rates of diopside and glass in basalts is the carbonation coating phenomenon [73]. Experimental results reveal that carbonate coatings can decrease the dissolution rates of SiO_2, CaO, and MgO in diopside and in the glass of basalts, when the liquid solution is saturated in calcite at pH: 8 and 70 °C [73], consequently affecting the cation release from the dissolved basalt to the liquid phase.

Orthopyroxene appears as an accessory mineral phase in basaltic rocks. However, its dissolution can contribute additional amounts of Mg^{2+} according to the mineral reaction-4:

$$Opx + 2H^+ \rightarrow Mg^{2+} + SiO_2 + H_2O \tag{4}$$
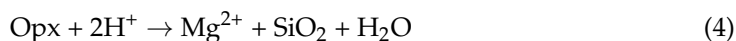
The formation of calcite during the mineral carbonation of basalts is linked with the available Ca^{2+} cations in the solution, which are mostly derived after dissolution of calc-silicate minerals including anorthite and clinopyroxene, as well as from the dissolution of the glass-rich groundmass. The reaction for dissolution of anorthite and precipitation of calcite [34] are given below:

$$An + 8H^+ \rightarrow Ca^{2+} + 2Al^{3+} + 4H_2O + 2SiO_2(aq) \tag{5}$$

$$Ca^{2+} + CO_2 \rightarrow CaCO_3 + 2H^+ \tag{6}$$
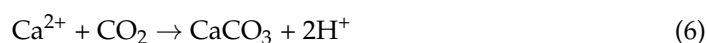
The glass matrix is an important factor that substantially affects the carbonation rate of basalts during the injection of CO_2. Experimental results have shown that, for a pH range of ~12 to ~6, the glass-enriched basalts are dissolved at considerably lower rates compared to clinopyroxene- and forsterite-rich basalts [74,75]. However, further pH decreases from ~7 to ~3 will lead to rapidly increasing dissolution rates of the basaltic glass [74,75].

Mineralization storage in Basalt Rock Formation Projects in Europe
CarbFix (Iceland)

CCS has been included in the EU agenda since 2007, whereas the first EU directive on CCS was published in 2009 [76]. At the current stage, only two large-scale field projects of in situ CO_2 mineralization in basalts have been deployed, whereas some of the recent projects were cancelled mostly due to financial and/or regulation issues (e.g., Jänschenwalde project in Germany and Porto Tolle project in Italy [76]). The CarbFix project in Iceland (Hellisheiði Geothermal Power Plant) aimed to create a technology for the removal of CO_2 from the atmosphere and its subsequent storage into basalts [77]. CarbFix was aligned with Directive 2009/31/EC for the geological storage of CO_2 in basalts [77]. It was a pioneering and comprehensive scientific project, whose results give important insights and unravel key parameters for the successful implementation of CO_2 storage in basalts worldwide. Estimations of the CO_2 sequestration into the basalts of the CarbFix site indicate a 0.33 Gt storage capacity, whereas the estimated CO_2 storage potential in the active rift zone of Iceland is 6100 Gt [78]. The CarbFix program in Iceland has now progressed from a pilot (original CarbFix) [79] to the industrial scale (CarbFix2) [80]. The project conducted detailed geological and hydrological characterization of the region, including hydrochemical modeling [77]. The following regulations were applied during the initiation of CarbFix [65]: (a) planning actions, (b) environmental impact assessment (EIA) studies including groundwater contamination, (c) health regulations, (d) safety regulations, and (e) regulations associated with greenhouse effects and radiation.

Considering the technical parameters of the project, the concept was based on two major pillars. The first was the injection of water-dissolved CO_2 into basalts because of its higher density compared to common fresh water, which renders it more difficult to return to the surface [77]. The second characteristic is related to the acidic nature of the CO_2-charged water, which makes it appropriate for the development of dissolution reactions that release high amounts of cations such as Ca^{2+} and Mg^{2+}. The CO_2 injection was based on the Manhattan Project [81], in which CO_2 was injected into a pipe reaching 350 m depth, and it was released into groundwater in the form of bubbles. It should be mentioned that the CO_2 that was dissolved with water is afterwards injected within the basaltic-bearing aquifers in proximity to the Hellisheidi geothermal power plant. Another critical issue that was considered was the injection depth, which is highly linked with high injection pressures [77]. Thus, CO_2 was injected into local groundwater in order to achieve better dissolution of the CO_2 and, consequently, better performance for mineral reactions. The monitoring of the dissolved CO_2 was based on variable tracers [77,82,83]. However, significant concerns were raised during the implementation of CarbFix, which were recorded and assessed for the improvement of the method. In summary, the major issues were the following [77]: (a) problems associated with the separation of CO_2 and H_2S; (b) pore-clogging issues of the sparger, which were solved by re-designing and constructing the sparger; (c) problems associated with the low permeability of the injection wells due to discontinuous gas injections that caused pH changes; (d) pore-clogging of the subsurface aquifer due to the presence of Fe-oxidizing bacteria [77,84,85]; and (e) explosion issues. The evolution of CarbFix is the EU-funded CarbFix2 project, which aims to store CO_2 into submarine basalts based on the advantage of inexhaustible seawater supplies [77,86]. The injection is developed in the Húsmúli re-injection region, and the project seeks to provide cost-effective and technically mature capture and storage of CO_2 and H_2S [87]. Following the major principles of CarbFix, the captured and dissolved CO_2 and H_2S react with basalts, allowing the release of cations such as Ca^{2+} and causing subsequent pH decrease, leading afterwards to the precipitation of carbonate and sulfide minerals [88].

Basalt that includes about 10 wt% CaO [89], as well as MgO and FeO in sufficient amounts, is highly reactive. Through this, carbonates precipitate at great depths due to carbon sourced from CO_2 injection, as well as from Ca, Mg, and Fe sourced out of basalt alteration. At a pilot scale, carbonate precipitated in two years' time with injection temperatures of 20–50 °C and only a few months between 60 and 260 °C [79,80,90]. This

technique poses the advantage of carbon stored in the form of carbonate minerals, a highly robust substrate compared to supercritical CO_2 being stored via other CCS techniques, and this technique allows stable storage for a prolonged period of time [79,91].

The CarbFix project focuses on CO_2 crystallization within alkali basalts for permanent storage. CO_2 injection within basalts provides many advantages over other methods since it can achieve fast mineralization with its large potential storage volume [67,91–93]. Through this method, CO_2 is dissolved within water before injection into highly porous basalts [35,79,91]. Basalts are enriched with CaO, MgO, and FeO. After being dissolved, CO_2 is no longer buoyant, and the acidic CO_2-charged fluid promotes the release of these elements via basalt dissolution, allowing calcite, magnesite, siderite, and carbonate solid-solution formation [34,91], thus achieving CO_2 storage.

The CarbFix project has been mentioned in many papers [89,90,94]. It is deployed in SW-Iceland, ~30 km eastwards of Reykjavik and ~3 km SW of the Hellisheidi geothermal power plant. This power plant annually produces ~40,000 tonnes CO_2 and 12,000 tonnes of H_2S as byproducts of geothermal energy production; the gases are of magmatic origin.

The Case of Orca (Iceland)

Carbfix was initiated with the injection of CO_2 that was previously captured by the plant of Climeworks' Orca (Iceland), which is the first commercial chain of direct-air capture and storage worldwide [8]. The Orca chain will combine underground CO_2 storage in the form of minerals with direct-air capture at a rate of 4000 tons of CO_2 per year [20]. Climeworks increases the CO_2 capture per module, leading to the maximum capture and storage capabilities worldwide [27].

The Case of Grundartangi Plant (Iceland)

The Norwegian Aker Carbon Capture is collaborating with Carbfix and Elkem Iceland to reduce the produced CO_2 emissions by the ferrosilicon plant of Elkem in Iceland via the implementation of CCS technologies within basalts [30].

The Case of Carbfix Coda Terminal (Iceland)

Potential geological storage "reservoirs" for mineralized CO_2 also comprise sedimentary rock formations, such as sandstones. Sandstones have been suggested mainly because of their high permeability, their great geographical distribution, and their physicochemical features [95–99]. Sandstones possess the appropriate properties for energy storage due to their compositional (e.g., CaO- and SiO_2-rich), textural, and structural features, as well as their low alteration degrees [19,100,101].

Mafic- and basalt-derived sandstones in Europe are relatively frequent occurrences. The intra-basaltic sandstones in the Faroe-Shetland Basin in the UK are a good example of such rock types [4,102,103]. Despite the fact that the mineralogical composition of basalt-derived sandstones is characterized by high Ca^{2+}, Mg^{2+}, and Fe^{2+} contents (rendering them appropriate for carbon sequestration), there are several issues that should be resolved regarding their suitability for CO_2 storage, such as their storage capacity and their distance from CO_2 sources [4].

Calcite- or dolomite-rich sandstones, in which carbonate minerals are cement materials (reaching up to ~11% of the rock mass), have different physicochemical and mechanical properties compared to the low-carbonate cement types; hence, the dissolution of the carbonate cement close to the injection site can lead to the formation of more acidic water solutions, rendering them more reactive in terms of mineral dissolution and leading to subsequent increases in permeability and porosity [4]. In addition, the combination of the ions results in re-precipitation phenomena and the formation of second-generation carbonates [4,104,105].
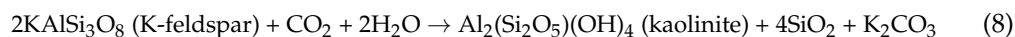
Greywackes include sand grains within fine-grained clayey matrix, in which the clay fraction is higher than 15%. The sand-sized grains usually contain rock fragments with diverse mineralogical composition (e.g., pyroxene, amphibole, quartz, and feldspars), whereas clayey parts are usually rich in chlorite and biotite [4]. Despite the suitability of their mineralogical composition for CO_2 storage, the clay-rich matrix of greywackes lowers their porosity and permeability, leading to decreased injectivities [4,105].

Redbeds and glauconitic sandstones are Fe-rich sandstones that contain high hematite quantities and iron-rich micas, respectively, which can supply Fe^{2+} during the addition of SO_2 or H_2S in the injection stream [4]. Thus, hematite can lead to the formation of siderite ($FeCO_3$) or ankerite ($CaCO_3$, $MgCO_3$, and $FeCO_3$) during Fe reduction [4].

Arkosic sandstones include feldspars, and they can also be deployed for CO_2 storage purposes due to their relatively high quantities of anorthite, whose carbonation is described by the following reaction [4]:

$$CaAlSi_2O_8 + H_2CO_3 + H_2O \rightarrow CaCO_3 + Al_2Si_2O_5(OH)_4 \tag{7}$$
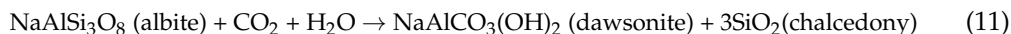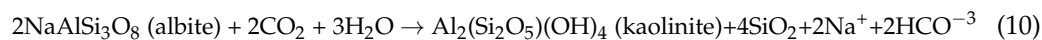
The mineralogical composition of arkosic sandstones, such as those of the Klepa Nafpaktias (Greece) [97], promotes their CO_2 storage capacity since K-feldspar can react with the injected supercritical CO_2 according to the following reactions (8) and (9):

$$2KAlSi_3O_8 \text{ (K-feldspar)} + CO_2 + 2H_2O \rightarrow Al_2(Si_2O_5)(OH)_4 \text{ (kaolinite)} + 4SiO_2 + K_2CO_3 \tag{8}$$

$$3KAlSi_3O_8 \text{ (K-feldspar)} + H_2O + CO_2 \rightarrow KAl_3Si_3O_{10}(OH)_2 \text{ (illite)} + 6SiO_2 + K_2CO_3 \tag{9}$$

Thus, the dissolution of alkali feldspars is expected to enhance clay mineral formation and quartz crystallization. This case presents many similarities with that described for the Mesohellenic Trough (NW Greece), which investigated the potential of CO_2 storage within porous sandstones that are overlaid be a less permeable caprock formation [23,96,99,106].

Based on Hangx and Spiers [107], plagioclase of basic chemistry is expected to develop both types of secondary minerals, although clay precipitation may likely precede that of carbonate. Moreover, the presence of albitic plagioclase is expected to lead to kaolinite and dawsonite crystallization, depending on the rock/water/CO_2 proportions through these reactions [95,108]:

$$2NaAlSi_3O_8 \text{ (albite)} + 2CO_2 + 3H_2O \rightarrow Al_2(Si_2O_5)(OH)_4 \text{ (kaolinite)} + 4SiO_2 + 2Na^+ + 2HCO^{-3} \tag{10}$$

$$NaAlSi_3O_8 \text{ (albite)} + CO_2 + H_2O \rightarrow NaAlCO_3(OH)_2 \text{ (dawsonite)} + 3SiO_2(\text{chalcedony}) \tag{11}$$

According to Christopoulou et al. [99], the mineralogical compositions of sandstones are highly associated with successfully achieved CO_2 sequestration. They suggested that specific mineral phases are considered critical in relation to the capacity of a rock to sequestrate CO_2. The minerals that likely develop a positive effect on sequestration are serpentine, epidote, K-feldspar, plagioclase, and mica-group minerals. On the contrary, quartz, the matrix (given the fact that it is not composed of clay minerals), dolomite, and calcite are reported as inhibitory components. Based on the above petrographic and mineralogical indications, they proposed the following index:

$$PrP = (Serp + Ep + Kfs + Pl + Mica)/(Qtz + Cment + Cc + Dol), \tag{12}$$

The petrographic results of the PrP index (Potential reactive Phases) demonstrate a clear correlation per sandstones and, therefore, per lithological formation. When the index tends to the unit of "1", the rock becomes more suitable to retain CO_2 within its structure.

4. Carbon Capture and Utilization Pathways in Europe

Several technologies related to the utilization of CO_2 are available, some of which include the use of CO_2 in chemicals, fuels, and durable materials and the use of CO_2 in mineral carbonation and construction materials, along with the use of CO_2 in biological algae cultivation and enzymatic conversion, especially attracting technologies at higher levels of maturity. Among others, CO_2 can be naturally converted into materials through photosynthesis, ultimately producing biomass, but it is also being used in applications such as the extraction of compounds with supercritical CO_2, dry cleaning, and uses in the food industry. Europe, through projects and industrial initiatives, is making a strong contribution to science, research, and innovation in the CCU field.

4.1. CO₂ in Chemicals, Fuels, and Durable Materials

CO_2 can be converted into various useful chemical products and synthesized fuels that can replace current chemical feedstock in the chemical, pharmaceutical, and polymer industries. The most important applications are urea (~160 Mtyear^{-1}), inorganic carbonates (~60 Mtyear^{-1}), polyurethane (~18 Mtyear^{-1}), acrylic acid and acrylates (10 Mtyear^{-1}), polycarbonates (4 Mtyear^{-1}), and alkylene carbonates (a few ktyear^{-1}). Many applications that concern pharmaceuticals, agrochemicals, polymers, lubricants, coating, and catalytic reactions are another category of chemicals that can be produced from captured CO_2.

Formic acid is another important chemical that could be formed through CO_2 utilization. Hydrogenation of CO_2 into formic acid has been gaining interest mainly due to the mild reaction conditions, the lack of formation of byproducts, the ability to store hydrogen in liquid form, and the easy decomposition of formic acid into hydrogen and CO_2. CO_2 hydrogenation is a promising method, as the inherent chemical energy of hydrogen carriers is used to support the CO_2 conversion, even though the source of hydrogen is critical since 96% is produced out of fossil fuels, leading to higher CO_2 emissions.

It should be noted that the use of CO_2 in energy storage is accomplished taking into consideration power-to-fuel technology (including power-to-gas and power-to-liquid), using renewable hydrogen [109]. Methanol constitutes one of the most effective commercial-scale ways to transform CO_2 nowadays. This constitutes a tool for producing several industrial chemicals that comprise formaldehyde, acetic acid, methyl tertiary-butyl ether (MTBE), and dimethyl ether (DME) [110]. Dimethyl carbonate (DMC) can also be formed from CO_2 and methanol. This can be used as a solvent in transportation fuel [111]. Methane production, through the Sabatier reaction, is a crucial catalytic conversion process [112]. The methane produced in the reaction is commonly referred to as synthetic natural gas (SNG). It also enables the storage of large amounts of renewable energy in existing natural gas grid storage systems and can be directly used in most endothermic engines and other known natural gas facilities [113].

In addition to CO_2 hydrogenation, another process that has attracted interest is the electrochemical transformation of CO_2 [114–116]. The materials of electrodes and catalysts, the pressure and concentration of CO_2, reaction medium, temperature, pH, buffer strength, and electrolyte solution play crucial roles in the electrochemical transformation's products, such as formic acid and/or formate, carbon monoxide, ethylene, and ethanol. Dry re-forming of methane that acts as the intermediate product, which could be converted into added-value fuels or chemicals, through the confirmed Fischer–Tropsch process are responsible for Syngas production [117]. CO_2 may react with various organic compounds (alcohols and amines) for producing useful chemicals in the pharmaceutical and agrochemical fields (open and cyclic carbonates and carbamates) [111]. Furthermore, some available pathways can also utilize CO_2 as a feedstock for producing carbon-based materials, such as polymers, [118] carbon fibers, and composites, as well as fine chemicals [111,119].

4.2. CO₂ for Mineral Carbonation and for Construction Materials

Mineral carbonation of CO_2 constitutes a new tool for CO_2 storage. There are various ways to accomplish carbon mineralization, regarding mineral ore use [64]. In situ mineral carbonation leads to CO_2 injection into rocks. It circulates through subsurface porosity and reacts with different minerals, mainly calcium or magnesium silicates, which form solid precipitates [37,120]. Such alteration is thermodynamically favored despite the slow kinetics. At the surface, the concentrated CO_2 is reacted with the alkalinity source on-site. On the other hand, in ex situ mineral carbonation, the process is chemically performed at industrial scale. The alkalinity source is further transported for CO_2 capture; combined with CO_2 at high temperatures and pressures, this leads to stable mineral carbonates, such as sodium carbonate and bicarbonate, calcium, and magnesium carbonate [29].

In order to capture one ton of CO_2, an amount of three to four tons of mineral ore is needed [121]. For CO_2 mineralization, slow kinetics are presented as crucial. Waste byproducts, such as cement dust and steel slag, as well as air pollution control residues

and biomass waste, are presented as important alkalinity resources [25]. Even though there are numerous studies regarding CO_2 in mineral carbonation, and the potential of in situ mineralization is considered critical, the discussion in the following is constrained to ex situ mineralization since in situ mineralization is a component of the CCS strategy. This type of work has been performed by Azdarpour et al. [122]. Wang et al. [123] reviewed CO_2 sequestration by mineral carbonation, combining mineral carbonation and the recovery of valuable metals from ore deposits and, at the same time, decreasing the total costs by cost shares for mineral recovery. CO_2 also has another construction application (building materials). Two basic technologies for the injection of CO_2 into concrete material have been observed: carbon curing and carbon conditioning. In the first one, unlike the weathering carbonation that is naturally observed in hardened concrete, CO_2 gas may act as a curing agent, yielding a bonding matrix by improving the CO_2-based material's performance. Zhang et al. [124], when summarizing mechanisms, processing, and material performance associated with the carbonation curing of cement-based materials, highlights that it is conducive to a more sustainable stance for the concrete industry, while at the same time, it also allows the perpetual fixation of CO_2 and a closing of the CO_2 circle. Carbon conditioning is the injection of CO_2 into recycled aggregate; the final product is referred to as CO_2 concrete [125]. Tam et al. [126] made a comparison between CO_2 injection within concrete and recycled aggregate concrete, concluding that carbonation of recycled aggregate is generally quicker and easier than that of concrete. On the other hand, the use of CO_2 in cement-based materials was also examined by Jang et al. [127], showing that the capacity of maximum CO_2 uptake by a cement-based material is approximately 0.5 ton CO_2 per ton material, even though experimental CO_2 uptake capacity ranges from 0.07 to 0.24 ton CO_2 per ton material. It should be noted, at this point, that CO_2 can be taken directly from flue gas emissions (with a CO_2 concentration higher than 10%), [128] and CO_2 mineralization could be succeeded by the aqueous accelerated carbonation reaction of calcium and magnesium silicates in alkaline solid wastes [129]. This direct flue gas carbonation has also been studied by He et al. [130], where the CO_2 contained within the cement kiln flue gas was used to precast concrete plants for the manufacture of building products. In this process, expensive concentration or purification steps are unnecessary, while direct flue gas carbonation is likely profitable in the short term.

4.3. CO_2 in Biological Algae Cultivation as Well as Enzymatic Conversion

Various algae can be used for converting CO_2 into a variety of compounds, including different hydrocarbons, lipids, and other complex oils, resulting in alternative pathways in order to produce biodiesel and other biomass derivative products [131]. Velea et al. [132] selected thirty-five various microalgal strains and examined their growth rate and potential for CO_2 bio-fixation using the emissions from a typical coal-fired power plant. Most algae species contain oil ranging between 20 and 50% (dry weight of biomass); the lipid and fatty acid ingredients vary based on culture conditions. Algae biomass can efficiently absorb about 1.83 tons CO_2 per ton biomass [133]. Algae cultivation is conducted in an open or closed system. This could be carried out using various methods, including open raceway ponds and photobioreactors. In addition, there are a variety of factors that may play critical roles in algae growth, including light (quantity and quality), temperature, oxygen, salinity, nutrient availability, pH, CO_2, and biotic elements such as bacteria [134]. Biofuel development generally involves the processes of settling, flocculation, filtration, flotation, centrifugal sedimentation, extraction, and purification. Zhang [135] studied current demonstration projects by using flue gas in order to grow algae. The status and applications of algae biofuels were also discussed by Adeniyi et al. [136]. Mustafa et al. [117] reviewed the enzymatic conversion of CO_2 by oxidoreductases, lyases, and microbes. Cyanobacteria give great potential as they are naturally convertible, require simple nutrients, exhibit rapid cell growth, and can be used for biofuel generation [117]. Enzymatic and microbial electrolyzes also have good potential and are currently under development [137,138]. Yaashikaa et al. [115] also reported a list of bio-products obtained from CO_2 and microbial

species, including isobutanol, isopropanol, lipids, and methyl ketone. The optimal selection of microbes, physiological parameters, and design of the bioreactor can enhance biological and biochemical processes. The use of microbes has vastly increased to transform CO_2 into high-value products. Many microbial species have been found to enhance the conversion process. In addition, various microorganisms can be genetically modified while at the same time increasing the yield and efficiency [117]. In order to recycle CO_2 into organic products via microbial electrosynthesis, this may be considered an attractive option, especially in the context of circular bioeconomy and biofuel production. By following Bian et al. [139], the problems of lipid extraction in algae-based processes or unstable catalysts in CO_2 electro reduction to generate CO_2-based products with a relatively short carbon-chain are not encountered by microbial electrosynthesis, and this mainly happens because of the long-term stability of reactors as well as the high efficiency of CO_2 reduction.

5. Social Aspect and Statistical Analysis

Social acceptance plays a crucial role in every conceivable implementation strategy. The introduction of CO_2 storage technologies in countries such as France, Belgium, and Germany has resulted in great resistance to the concept itself among stakeholders and the public [140]. Despite the increasing research, as well as investment efforts, CCS deployment is usually followed by negative perceptions of CO_2 transport and storage. Several projects regarding storage applications have been cancelled [141]. In contrast to CO_2 storage, CO_2 utilization seems to be more acceptable to most people. This may happen as CO_2 is considered as waste recycling. Jones et al. [142] have studied public perception in the UK. They noticed limited awareness among many of the participants in the research, and they also noticed the need for further information about the issue. However, te interest has increased because of national and international legislation related to CO_2 and other GHG emissions (e.g., EU ETS), leading to the innovation and development of CCU technologies as well. The important studies conducted on emerging perceptions of CO_2 and product options (up to 2017) were summarized by Jones et al. [140]. Arning et al. [143] examined the social acceptance of CO_2-derived foam mattresses, enhancing the lack of awareness of technical knowledge while at the same time having a positive perception of CCU. Moreover, these studies dealt with health and environmental issues regarding the use of CO_2-based products (e.g., fear of allergies, soil concentration, and potential air pollution). Furthermore, Arning et al. [144] also mentioned the awareness of society concerning the sustainability and the end-of-life of CO_2-based products. It was also concluded from the variety of the research that, as the sustainability of these products remains questionable, social acceptance remains limited.

The trust in stakeholders and researchers who deal with CO_2 utilization constitutes a critical factor that generally influences research development. For this reason, local authorities play a significant role in informing society about CO_2 storage and utilization, as well as about their opportunities [145]. In Barendrecht in the Netherlands, the local government rejected a project concerning CO_2 utilization because they were aware of negative impacts on public health and environment [146]. Satisfactory efforts have been carried out [147] in some industries in order to limit the perceived risks while at the same time gaining wider acceptance of CO_2 utilization methods/strategies from the community. To increase the level of trust of society in stakeholders and researchers, an information campaign regarding the opportunities of CO_2 storage and utilization should be organized throughout Europe. It should be noted that there is a lack of studies concerning information on the current state of public perception and knowledge of CCS technologies. However, the results of certain studies [147] show that public awareness of CCS still remains low in various countries, such as Canada, the Netherlands, Norway, the UK, and the US. For public acceptance, the level of knowledge plays a crucial role [148]. Stakeholders interviewed by [149] in the ELEGANCY project rated public knowledge concerning CCS as rather low and believed that those CCS technologies are still not present in current public discussion due to low market penetration. The results of [150] in the context of an experiment indicate that CCS was observed more positively by those who claim to have more knowledge

about CCS and that they were also likely to display a greater interest in the technology. It should also be mentioned that the evaluation of CO_2 capture–storage–utilization options can change after an increase in information levels [151].

6. Questionnaire

As has already been mentioned in the methodology part, a questionnaire was given to 300 European citizens from various European countries regarding CO_2 issues. The questionnaire is listed below in Figure 5, while the answers for it are presented in Figures 6 and 7. As can be seen from the questionnaire, European citizens were called to answer how informed they are about CO_2 issues, how optimistic they are regarding the solving of CO_2 issues, as well as how much they agree to new methodologies being performed in their countries to solve CO_2 environmental problems. As shown in Figures 6 and 7, there was quite a low percentage of high educational level in the tested European citizens (23% had obtained an M.Sc. or Ph.D.), and the majority of them were from West and Central European countries (60%). Most of them were informed (mainly from media and internet) about CO_2 and about the European strategy for solving CO_2 problems, but they did not have knowledge regarding the used or proposed methods and technologies. Furthermore, they were not informed in-depth about the aforementioned technologies, not even about their advantages both for the environment and for society. They also seemed to be negative and hesitant about the adoption of these technologies in their countries.

Carbon capture, storage and utilization (CCUS) is a process that captures carbon dioxide (CO_2) emissions from sources such as coal-fired power plants and either reuses or stores energy so that it does not enter the atmosphere

Questions	*Answers*			
1. What is your educational level?	Sch. graduated	BSc	MSc	PhD
2. From what part of Europe do you come from?	N Europe	C Europe	S Europe	W Europe
3. Do you know what CO_2 is?		YES	NO	
4. Have you heard about the strategy of E.U regarding the reduction policy of CO_2 emissions?		YES	NO	
5. Do you think that you have sufficient information regarding CO_2?		YES	NO	
6. Do you know the term of CO_2 mineralization?		YES	NO	
7. What is your information source for carbon dioxide capture issues?	Internet	Media	Other	
8. Do you know the main benefits of CO_2 capture and storage?		YES	NO	
9. Are you optimistic about the future of the EU's strategy about CO_2 capture and storage with the knowledge you have so far?		YES	NO	
10. Do you think that carbon dioxide capture, recovery and storage (CCUS) technologies are effective in reducing climate change?		YES	NO	
11. Do you think that there are risks from adopting carbon capture (CCU) technologies and carbon capture and storage (CCS) technologies in Europe?		YES	NO	
12. Do you agree with the development of carbon capture, recovery and storage projects (CCUS) in your country?		YES	NO	
13. Do you think that the adoption of carbon capture, recovery and storage technologies (CCUS) in Europe is acceptable?		YES	NO	
14. Do you think that that the development of CO_2 capture and storage contributes to creating new jobs?		YES	NO	
15. Do you believe that project developers / industry in the area are able to work out the technical and coordination challenges of adopting carbon capture, recovery and storage (CCUS) technologies?		YES	NO	
16. Do you think that there are alternatives choices to CCUS technology that you think are best suited for your country, in order to significantly reduce CO_2 emissions?		YES	NO	

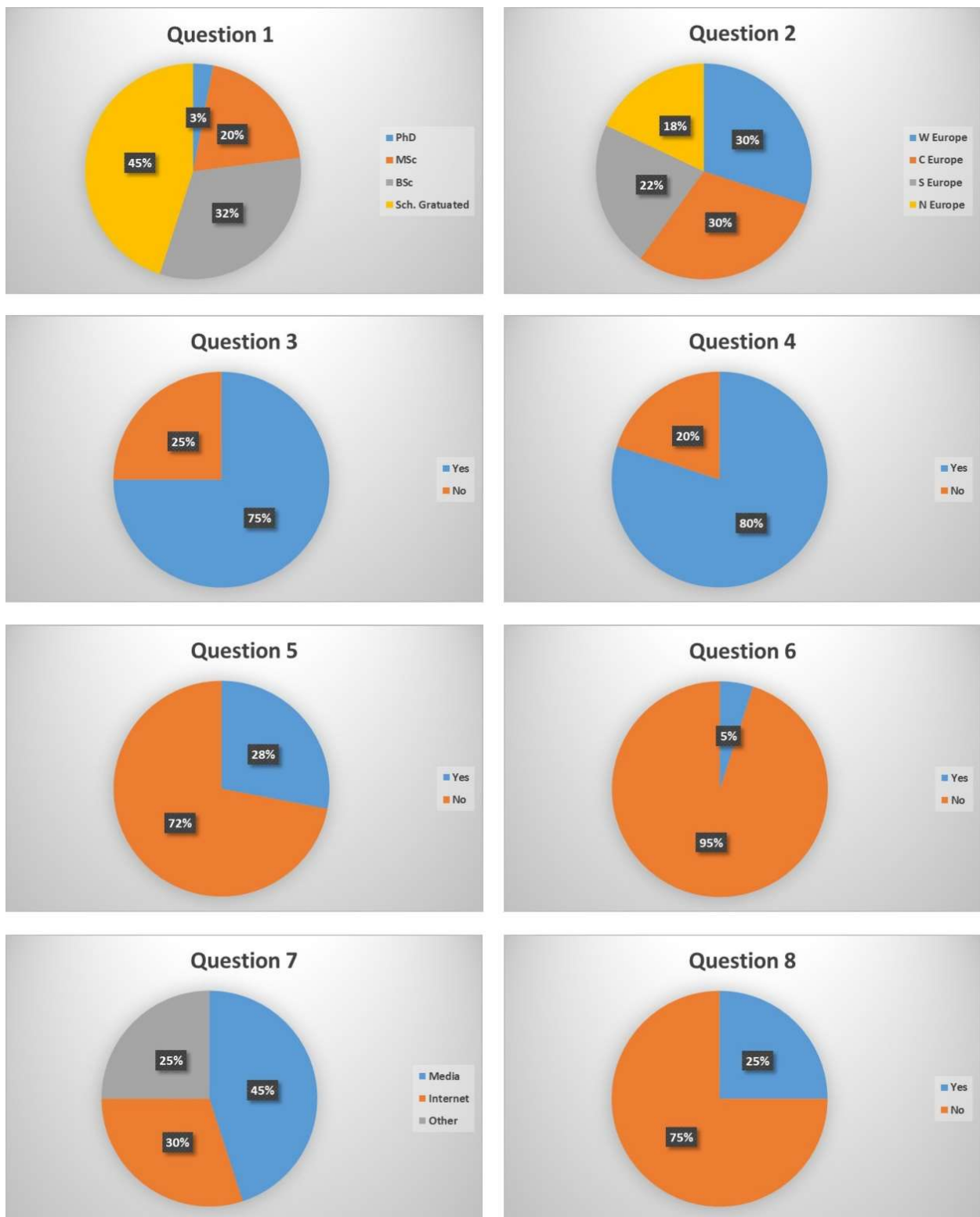**Figure 5.** Questionnaire shared and completed by European citizens.

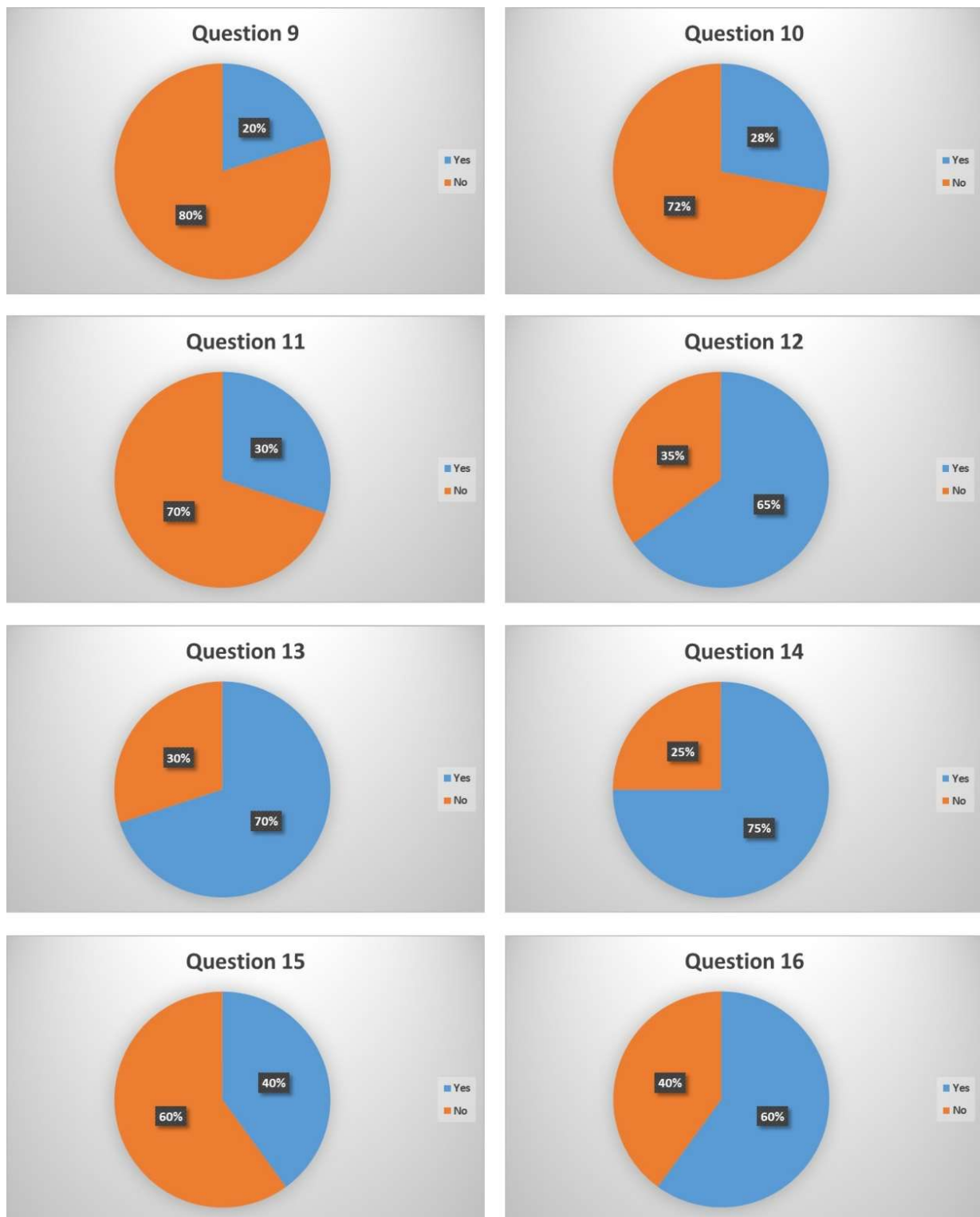**Figure 6.** Excel pie charts showing the answers from the questionnaires (answers to questions 1 to 8).

Figure 7. Excel pie charts showing the answers from the questionnaires (answers to questions 9 to 16).

7. Discussion and Suggestions for Future Research

In 2022, Europe is roughly halfway between the EU's environmental policy innovation as it was established in 1980 and the EU's 2040 vision of "prosperity within the planet". At the heart of this vision is the recognition that Europe's economic prosperity and well-being is inherently linked to its natural environment—from fertile soil to clean air and water. In the present study, studying the strategy of the last 40 years, the implementation of

environmental and climate policies has provided significant benefits for the functioning of Europe's ecosystems and also for the health and well-being standards of European citizens. In several regions of Europe, the local environment is reasonably good nowadays, as it has been since the beginning of industrialization, but this does not seem to happen in all of Europe. However, as shown in Figures 1 and 3, although Europe presents high concentrations of CO_2 in the atmosphere, it also has potential in the areas of high concentrations of CO_2 where CO_2 capture and storage can take place. This is a very encouraging event for the future of Europe and for the planet in general. Reducing pollution, nature's protection, as well as better waste management have contributed to this. Environmental policies also create economic opportunities and therefore contribute to the Europe 2020 strategy, which aims to transform the EU into a smart, sustainable, and inclusive economy by 2030. Carbon-capture technology is considered as a source of hope for reducing global greenhouse gas emissions, mainly reflected in the climate plans of European countries, as well as in the respective strategies of some of the world's largest oil and gas companies based in Europe. The issue, however, is still divisive, as researchers and environmental groups argue that carbon-capture technology is not a safe solution. However, as mentioned above, carbon capture and storage refer to a number of technologies designed to capture carbon dioxide from high-emission activities, such as power generation or industrial plants that use either fuels or biomass. European researchers who are working on the above capture and storage technologies believe that they can play a key role in achieving global energy and climate goals. The projects that appear to be currently underway in Europe as outlined above allow CO_2 capture and storage or the production of clean energy from renewable sources, thus helping to achieve emission reduction targets by 2030, if implemented before that date. However, their main goal is to demonstrate the commercial potential of the selected technologies and to contribute more broadly and in the long run to a low-carbon economy after 2030, if they are applied in other parts of Europe and the world. The support of Europe's pioneers in this field is expected to contribute to the realization of the EU's ambition to become a leader in the development of renewable energy technologies worldwide.

The carbon sequestration and mineralization method can actually help to reduce carbon dioxide emissions and Europe's sustainability and technological development. The effect of efficiency improvement on the emissions of CO_2 from a coal-fired plant is shown in Figure 8. At 50% efficiency, a power plant will emit up to 40% less CO_2 than the plant with a thermal efficiency of 30%. It should be noted here that the average global efficiency of coal-fired plants is currently 33% [152]. The addition of CCS will further reduce the emissions of CO_2 by more than 85% in comparison with the reference plant without CCS. However, to achieve this reduction, the CO_2 capture unit will consume up to 30% of the energy produced by the plant, which means more fuel must be burnt in order to generate the same amount of energy as the plant without CCS.

The greatest environmental risk associated with CCS relates to the long-term storage of the captured CO_2. Leakage of CO_2, either gradual or in a catastrophic leakage, could negate the initial environmental benefits of capturing and storing CO_2 emissions and may also have harmful effects on human health. On the other hand, CCS has the long-term potential to make a substantial positive impact on the amount of CO_2 emitted into the atmosphere by the stationary energy sector. Therefore, the potential risks need to be weighed against the potential benefits, as well as the possible consequences of inactivity.

Mineralization, according to the studies and research available now, promotes permanent and safe storage and could be the key to resolving the carbon dioxide crisis we face in our days. It is therefore proposed to launch new research and pilot projects across Europe so that we have more knowledge available and possibly more storage space.

At this point, it is proposed to create, in the long run, a database containing all the rocks of the European area, and mainly the basalts and sandstones that occupy a significant part of Europe. This database can be created through detailed petrographic mapping. In addition, tests should then be performed on an autoclaved carbon dioxide injection

system to test the ability of the European rocks to be used for CO_2 capture, storage, and further utilization.
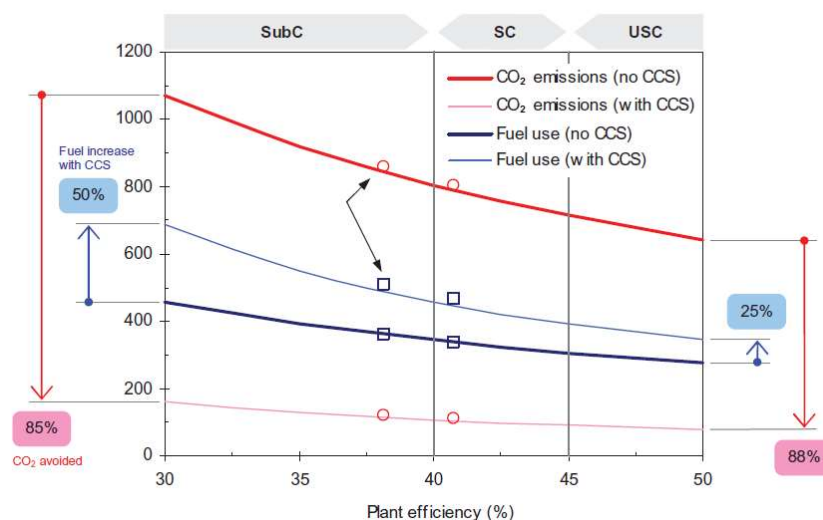

Figure 8. CO_2 emissions vs. efficiency (y-axis: specific CO_2 emissions and fuel consumption in kg/MWh). Calculation was made for a PC plant firing bituminous coal with an LHV of ~26.2 MJ/kg and carbon content of 0.64. CO_2 capture rate of 90% and efficiency penalty of 10% points were assumed when CCS was added [153].

Based on the questionnaire survey conducted in collaboration with a geo-friendly hotel in Kefalonia on a representative sample of 300 people in low-stress conditions for respondents and in a beautiful and natural environment, we identified important points that should be considered in any future research and/or pilot work that is carried out concerning the issue of CO_2 capture and storage. The most important finding of the present study focuses on the fact that the majority of European citizens who participated in the survey, regardless of their educational level, have heard from some means of communication what CO_2 is and what its effects are, and those who have a deeper knowledge have heard of capture methodologies; yet many consider them as unsafe methods. At this point, the greatest knowledge gap in the ordinary European citizen perhaps is observed. At this point, it seems that the European plan so far has failed, in part, as proper communication between European politics and society has not been achieved. In addition, perhaps a point that needs to be studied is the answers given to question 6, where the vast majority did not seem to have ever heard the term mineralization, which indicates that the scientific community, where it deals with the issue, should make efforts to make it well-known to a wider audience so that there is a holistic approach of science in society. The same conclusions are drawn from the answers to questions 8–11, where most of the citizens, on the one hand, do not know the benefits of such technology and, on the other hand, appeared to be pessimistic about the future of these technologies, which shows that European scientific and political strategy must still take several steps in the right direction. Exactly by following the same philosophy, the citizens answered the rest of the questions, regardless of their geographical destination. In order to ensure the desired social acceptance of the energy transition based on the experience gained in the design and implementation stages, it is proposed that all stakeholders improve the following elements: process independence, information quality and accessibility, freedom and participation diversity, clarity of arrangements, accountability and consideration of participation in decision making, transparency, and monitoring from the beginning to the completion of a project. The EU should make much greater effort to promote equal distribution and production–consumption through financial incentives, as this is the factor that has the greatest impact on the local acceptance of CO_2 capture and storage, while the main goal should be to put citizens at the heart of politics and ensure that they can benefit from new technologies that need to be implemented

at a much faster rate than they have been to date. In general, social acceptance by the community requires contact with citizens and stakeholders, as well as ensuring mutual trust through open communication and the opportunity to participate as early as possible in the development of actions and projects related to CO_2 capture and storage, at all appropriate levels of government, from the local to the international.

8. Conclusions

The conclusions of this study seem to be double. The first one is related to the technologies used in Europe for CO_2 capture and storage nowadays, while the second is related to the social acceptance of these technologies. Firstly, CO_2 mineralization in various rock formations, such as basalts and sandstones, seems to be a useful, hopeful, and environmentally safe solution among other proposed solutions. The second conclusion focuses on the social acceptance by European citizens of such methods/technologies for solving CO_2 issues in these days and, more specifically, the lack of information regarding the advantages of CO_2 capture and storage technologies used in several countries in Europe. It should be mentioned that there should be an organized project in all countries in Europe in order to popularize and communicate the scientific knowledge to a wider European audience, with the ultimate goal being the consolidation of sustainable development in Europe.

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