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Review

Review of the Monitoring Applications Involved in the Underground Storage of Natural Gas and CO_2

Gabriele Fibbi *, Matteo Del Soldato and Riccardo Fanti

Earth Sciences Department, University of Florence, Via La Pira 4, 50121 Florence, Italy
* Correspondence: gabriele.fibbi@unifi.it; Tel.: +39-0552757551

Abstract: Natural gas is an indispensable resource not evenly distributed in the world. The gas supply chain is characterized by large imbalances between supply and demand, where the underground gas storage (UGS) application plays a key role for creating strategic reserves, taking advantage of geological structures. On the contrary, human activities will require clean energy with near-zero greenhouse gas emissions to be environmentally viable. A key element of this strategy is the carbon capture and storage (CCS) application useful for confining CO_2 into the geosphere to reduce anthropogenic emissions. The development of appropriate injection methods and long-term monitoring systems for leak detection of the underground storage of natural gas and CO_2 is important to prevent negative effects, such as ground deformations and micro seismic events. In this work, a variety of monitoring applications were gathered and critically analyzed for a total of 60 scientific contributions spanning the world. This bibliographic work shows an analytical and statistical overview of the most common use of UGS and CCS, representing the different goals of these two applications and analyzing the main monitoring techniques used in the gathered contributions. Currently, UGS monitoring requires further development, especially through multidisciplinary approaches useful for identifying possible effects on the surface and gas leaks at depth; meanwhile, CCS solutions are still at the experimental stage, also because of the high costs for large-scale applications that still need specific research. The state of the art of these two very different practices can improve the further development of new monitoring approaches or additional methods.

Keywords: gas storage; monitoring; UGS; CCS; reservoir displacement; leakage monitoring; ground deformation

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1. Introduction

Natural gas is an essential element for human activities that can be stored in underground geological structures during the summer season when the demand is lower, ready to be withdrawn and injected into the network to meet increased consumer demand in the winter season (Figure 1). Underground gas storage (UGS) applications play an important role in the management of the methane (CH_4) supply chain, covering demand and securing gas supply in case of international crises or for creating a strategic reserve. UGS has been used effectively for nearly a century to balance the mismatch in gas supply and demand [1]. At the end of 2020, there were 661 UGS facilities in operation in the world, with a working capacity of 423 billion m^3 [2].

There are three main types of UGS sites: depleted gas/oil fields, aquifers, and salt caverns. Each storage type has its own physical characteristics related to the geotechnical proprieties, e.g., porosity, permeability, retention capability, and economics features (i.e., site preparation and maintenance costs), which govern its suitability for particular applications [3]. The capability to hold natural gas and the injection and withdrawal rate are two relevant characteristics of the underground storage reservoir. The first two UGS types involve the gas in natural porous strata and tend to have a relatively large amount of storage capacity but a low rate of injection and withdrawal, while salt caverns involve the leaching of salt deposits underground to create a cavern that tends to have small amount of storage capacity but high rates of injection and extraction [4]. Most UGS facilities are constructed in depleted gas/oil fields. This is because their ability to contain the gas over a prolonged period of time has been proven [5].

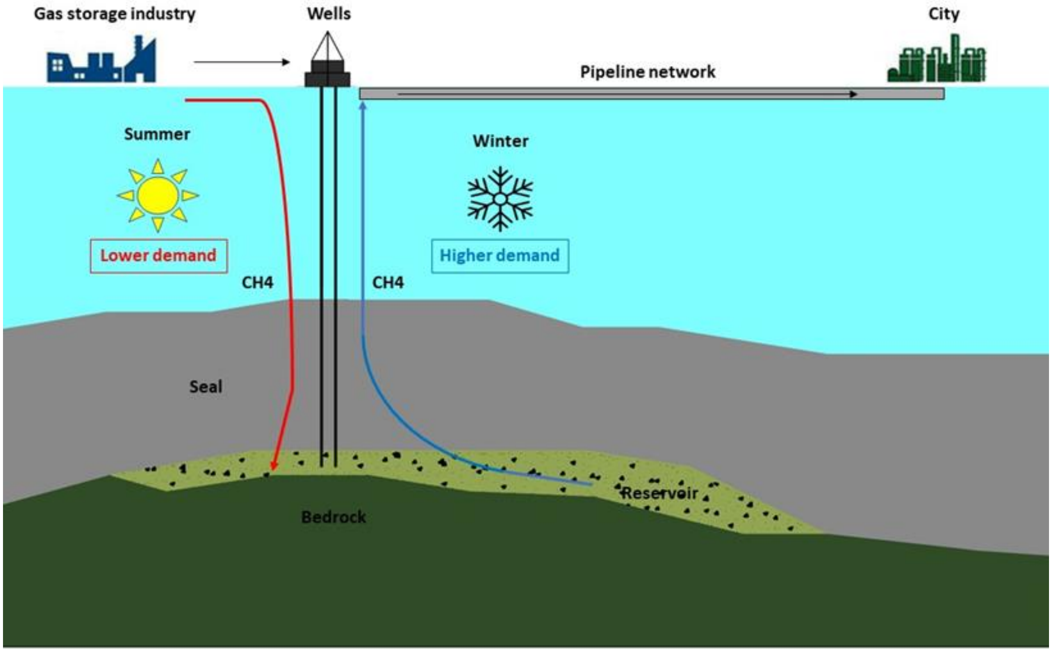

Figure 1. The underground gas storage useful for creating strategic reserves of natural gas. On the left (red color): the CH_4 injection during the summer when demand is lower; while on the right (blue color): the methane withdrawal to meet winter's increased consumer demand.

To combat global warming caused by constant human exploitation of fossil fuels, effective control of greenhouse gas emissions is likely to prove one of the most important scientific challenges of the 21st century. Human activities cause a 1.5 °C global warming and it will become an inevitable fact [6]. In December 2015, at COP 21 (Conference of Parties) in Paris, an international agreement was signed to set the target of limiting global warming by the end of this century to below 2 °C (preferably limiting it to 1.5 °C) compared with pre-industrial levels [7]. The concentrations of three greenhouse gases, carbon dioxide, methane, and nitrous oxide (N_2O), were in the last decade higher than those recorded for at least 800,000 years [8]. The continuous rise of these greenhouse gases creates a potential risk of breaching climate tipping points with devasting consequences, such as the collapse of ice sheets, abrupt changes in ocean circulation [9], complex extreme weather events [10], and far greater global warming than projected [11]. The long-term storage of carbon dioxide, which is the most-produced greenhouse gas (about 80%) emitted into the atmosphere by human activities [12], could be the solution for these effects. The carbon capture and storage (CCS) approach is the capture process of carbon dioxide (CO_2) before it enters the atmosphere by means of sequestration and storage in geological structures for centuries or thousands of years (Figure 2). The purpose of CCS is to achieve the goal of "zero emissions" as far as possible, without abandoning fossil fuels, which is not achievable in the short term. There are four main options for the permanent storage of CO_2: (i) depleted oil/gas reservoirs; (ii) saline aquifers, which offer high potential in terms of storable volumes of CO_2; (iii) salt caverns, characterized by high sequestration efficiency and a high fill rate; and (iv) deep coal fields, which are still being studied. Storage of CO_2 in salt caverns differs from natural gas storage in salt caverns because of the continuous cavern gas pressure build-up. Four main possible factors can influence the long-term pressurization of a CO_2 sequestration cavern: salt creep, compressibility of CO_2

as a supercritical fluid, leakage from caverns, and leakage along the wells [13]. Most formations suitable for carbon dioxide storage are found between 1000 m and 4000 m depth. Usually, the CO_2 is captured from wide sources, such as coal-fired, chemical, or biomass power plants, and then confined in an underground stable geological formation. When CO_2 is injected into underground formations it becomes a dense "supercritical" fluid at around 0.8 km depth. The supercritical fluid behavior is an intermediate condition between gas and liquid, taking advantage of gas's ability to spread rapidly in the porous spaces of the geological formation and liquid's possession of density and storable qualities [14]. Its volume is dramatically reduced from 1000 m^3 at the surface to 2.7 m^3 at 2 km depth. The injection with these characteristics is useful to provide an efficient utilization of underground storage space in the pores of sedimentary rocks [15] and to remove the fluids, e.g., phreatic water, from the reservoir rocks surrounding the input point, allowing CO_2 to enter and remain in the reservoir. It is essential that the geology should be characterized to determine that CO_2 will not return to the surface through faults, joints, or other pathways. The CO_2 after injection begins to dissolve in local formation waters and initiates various geochemical reactions. Some reactions can chemically contain CO_2 by the formation of new carbonate minerals, other chemical processes may cause mineral dissolution [16].

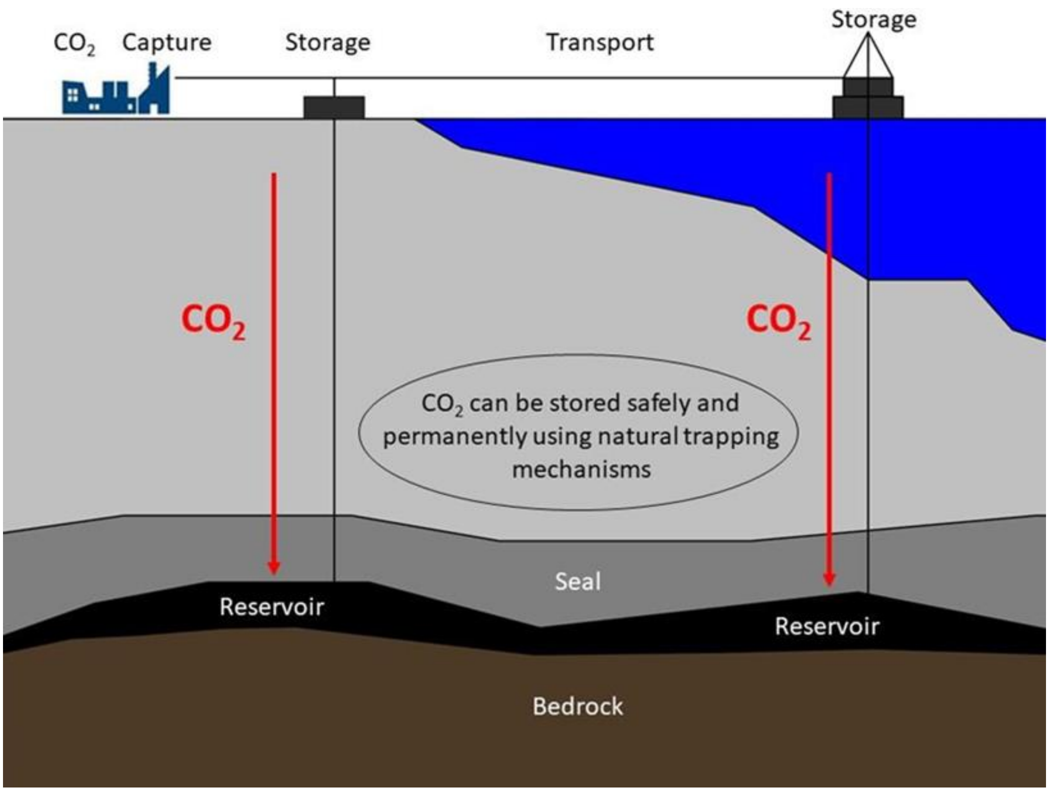

Figure 2. The carbon capture and storage technique. The capture and sequestration process of carbon dioxide before it enters the atmosphere in a geological structure is represented with the red color.

Since the 1990s, important CCS research projects were conducted in Europe, the US, Canada, and Australia. A lot of knowledge was gained from the observation of the first demonstration projects. The three main pioneering CCS sites are (i) Sleipner (Norway), with approximately 1 million tons of CO_2 injected per year since 1996, e.g., [17,18], (ii) Weyburn (Canada), involved in the Aquistore project, which injects about 1 million tons per year of CO_2 since 2000, e.g., [19], and (iii) In Salah (Algeria), injecting 1 million tons of CO_2 per year since 2004 until 2011 [20]. In addition, for the investigation of the CO_2 behavior, other interesting CCS projects and pilot sites involve Ketzin in Germany, e.g., [21], Lacq in France [22], Compostela in Spain [23], the CO2CRC Otway Project in Australia [24,25], Snøhvit in Norway [26], and Frio in the USA [27].

In the last decades, a new method for producing CH_4 by taking advantage of the storage of CO_2 has been under development. This method, even if still at an experimental stage, is called enhanced coalbed methane recovery (ECBM) [28,29], and it is an application made in coal fields that foresees the injection of CO_2 as a way to enhance the recovery of methane. Methane in coal seams exists in three different states: (i) adsorbed, (ii) free, and (III) dissolved. Unlike conventional gas reservoirs, CH_4 in coal is mainly adsorbed on the internal microporous surface area at near-liquid densities [28]. The highly volatile liquid CO_2 is injected into the coal seam and its volume rapidly expands hundreds of times in the gasification process, causing a pressure imbalance. The new fracture networks caused by CO_2 injection into coal seams cause many CH_4 spillovers [30]. The adsorption characteristic of carbon dioxide is much higher than that of methane, which makes CO_2 displace the CH_4 adsorbed on the surface of the coal pore structure. In addition, the injected CO_2 may react with the mineral composition in the pore structure of the coal rock mass, making the fracture more fully developed, which will lead to the release of CH_4. The driving force of the coalbed methane increases, and it flows to the wellbore [31]. In this regard, a large amount of methane is displaced from the pores of a coal seam, allowing an improvement in productivity and prolonging the stable production time of coalbed methane wells [32]. Two case studies of this new application are situated in the Sardinia Sulcis Basin (Italy), e.g., [33], and the Powder River Basin (USA) [34], where the possibility of using ECBM technology was tested.

Gas storage activities can induce ground deformation events characterized by considerable magnitude. Therefore, storage operations are carefully monitored to verify the integrity of the reservoir, the effectiveness of activities, and the respect of safety conditions. Typically, ground deformation effects have a rather slow temporal dynamics and extend spatially. In this regard, interferometric synthetic aperture radar (InSAR) technology, with its advantages of extensive coverage in surface deformation monitoring and all-weather traceability of injection processes, is becoming one of the promising monitoring technologies worldwide adopted in UGS and CCS projects [35–37]. InSAR and seismic data are two measurement approaches that can be analyzed for obtaining a more specific result about reservoir displacement and subsidence investigation [38]. Other useful techniques can be implemented for the integration of these analyses, e.g., unmanned aerial vehicles (UAV), e.g., [39], and global navigation satellite systems (GNSS), e.g., [35,37], allowing more specific studies of the area of interest.

UGS and CCS activities can induce different vertical ground movements over the reservoirs area, which are typically quite small, from millimeters to a few centimeters. The ground deformation caused by UGS reflects the operations of injection and withdrawal of gas into/from the reservoir [40], while displacements induced by CCS reflect the only injection activity useful to confine carbon dioxide in underground geological structures. The theoretical course of the injection and withdrawal cycle at an UGS site and an example of a CO_2 injection profile of a CCS activity are shown in Figure 3.

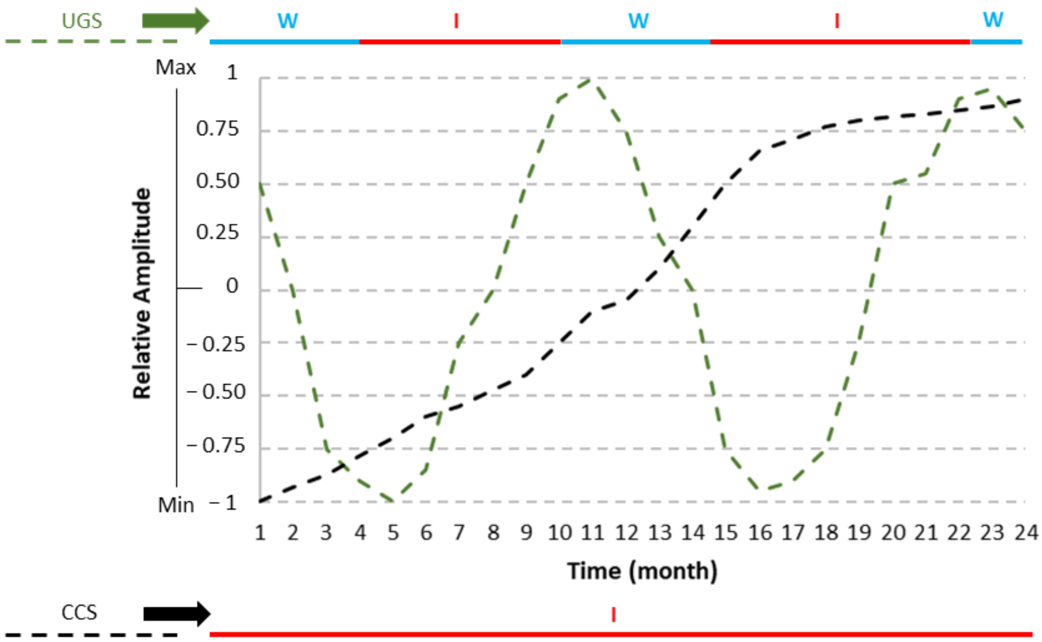

Figure 3. The theoretical course of the injection (red color) and withdrawal (blue color) cycle at an underground gas storage (green color) and the theoretical CO_2 injection profile of a CCS activity (black color).

For this review, the scientific contributions, different congressional proceedings, book chapters, or peer-reviewed articles focusing on ground deformation caused by underground storage of natural gas and CO_2 were collected and critically analyzed. An extensive bibliometric analysis that focuses on (i) the description of the criteria used to extract the data collection, (ii) the temporal analysis of the gathered papers, and (iii) the spatial-interest study of the gas storage topic is useful to explain the current development of UGS and CCS activities. The main limitation of this topic is that much useful data to localize and characterize gas storage projects are impossible to obtain because of copyright, which protects information about industries involved in gas storage operations, working gas volumes, and monitoring data. Gas storage is a main topic of the current times, especially for environmental issues. The interest in carbon capture and storage is increasing rapidly. In fact, CCS is considered a crucial strategy for meeting CO_2 emission reduction targets. This is evidenced by a fair number of papers about carbon dioxide geosequestration and reservoir characterization published in the last two decades.

2. Data Collection

All the scientific contributions, peer-reviewed books and articles, and congress proceedings about the reservoir monitoring for ground deformation caused by CO_2 or CH_4 storage activities were collected through the Web of Science (WoS)'s freely accessible web search engine for the natural sciences [41]. The advanced search option allows one to look for all types of contributions, combining several options for searching, e.g., by keywords in titles and in keyword lists and by study area locations.

The WoS search was based on the interaction of three keyword groups: (i) type of application; (ii) gas storage; and (iii) techniques of monitoring. For catching scientific contributions focusing on issues of interest for this review, the three keyword groups were taken into consideration for title contribution (TI) and list of author keywords (AK), combined by means of Boolean operators (Figure 4). For selecting the scientific contribution by the type of application, keywords such as "ground deformation", "monitoring", "site characterization", "reservoir monitoring", and "surface displacement" were used. To focus the research on articles about gas storage activities, two groups of topics were looked for: (i) the carbon capture and storage keywords, such as "CCS", "CO_2", "CO_2 storage", "carbon dioxide", and "carbon capture and storage"; and (ii) the underground gas storage keywords, such as "UGS", "CH_4", "CH_4 storage", "natural gas", "methane", and "underground gas storage". The scientific contributions were selected by also considering the monitoring techniques for the storage activities, using keywords such as "LiDAR" (light detection and ranging) and "InSAR", related ones such as "DInSAR" (differential interferometric synthetic aperture radar) and "A-DInSAR" (advanced differential SAR interferometry), or "PSI" (persistent scatterers interferometry) and related words such as "PS" or "PSInSAR", "SBAS" (small baseline subset) and "P-SBAS" (parallel-SBAS), "SqueeSAR", "UAV", "drone", "GPS" (global position system), "GNSS", "leveling", "tiltmeters", "assestmeter", and "interferometry". The number of scientific contributions selected using these keywords were finally refined by the use of their combination by Boolean operators: AND for considering articles that have at least one keyword of each group and OR for selecting contributions having keywords of at least one group. This approach allows the extraction of the contributions about the monitoring technologies involved in UGS and CCS activities useful for identifying ground deformation events.

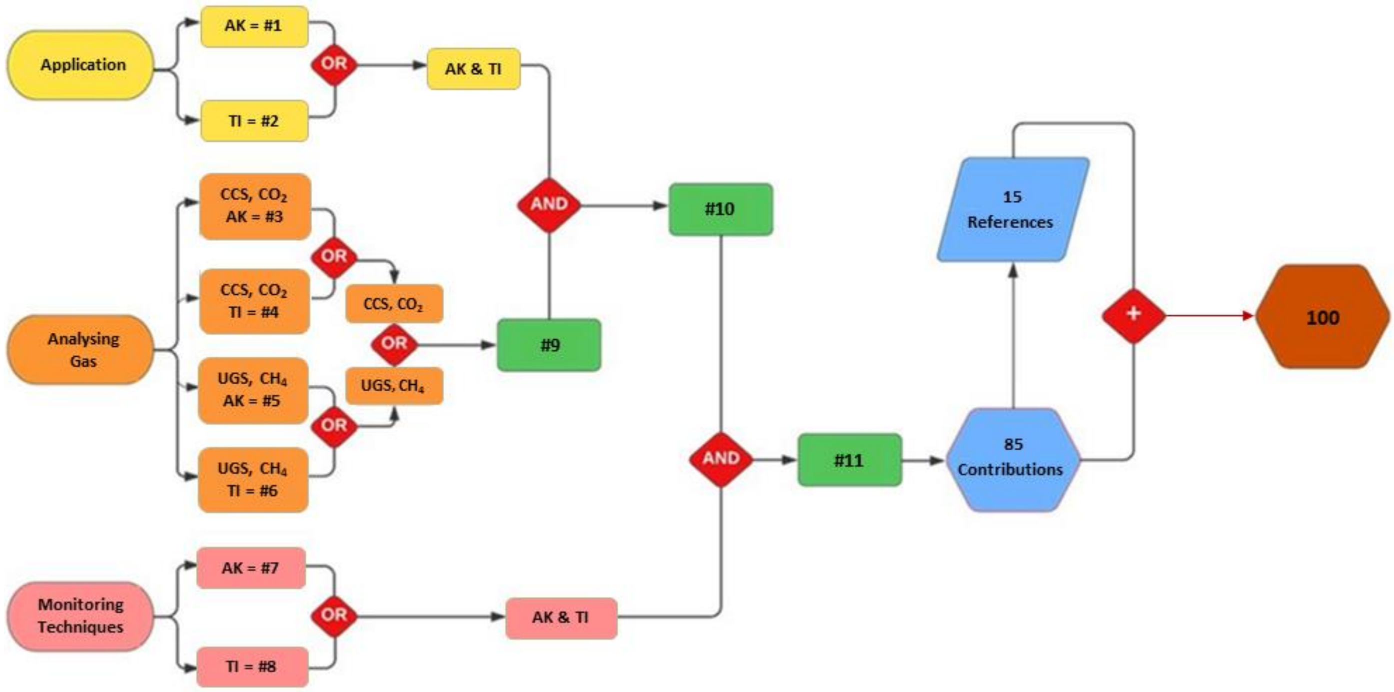

Figure 4. Structure of data collection criteria used to extract all the contributions about the research topic.

The data collection was conducted in early 2022 and a preliminary list of 85 scientific contributions was gathered. Then, during the first analysis of the automatically collected contributions, 15 further articles were added by their reference lists. This was a necessary step since some journals, though few, do not have author keywords and were not intercepted using the advances, but with the automatic approach described above. A total of 100 scientific contributions were collected. In this review, only the contributions about the reservoir monitoring of ground deformation caused by underground storage of CH_4 or CO_2 were considered. For this reason, 40 scientific contributions were removed from the list: (i) one article was written in Chinese, (ii) eight papers were related to fugitive gas, and (iii) another thirty-one publications focused on atmospheric gas concentration. In the end, 60 contributions between handbooks, scientific articles, proceeding papers, and reviews were collected. Each contribution was individually examined to catalogue the aim and the adopted procedure by general information fields automatically extracted from the WoS database and specifically features extracted by a critical analysis (Figure 5).

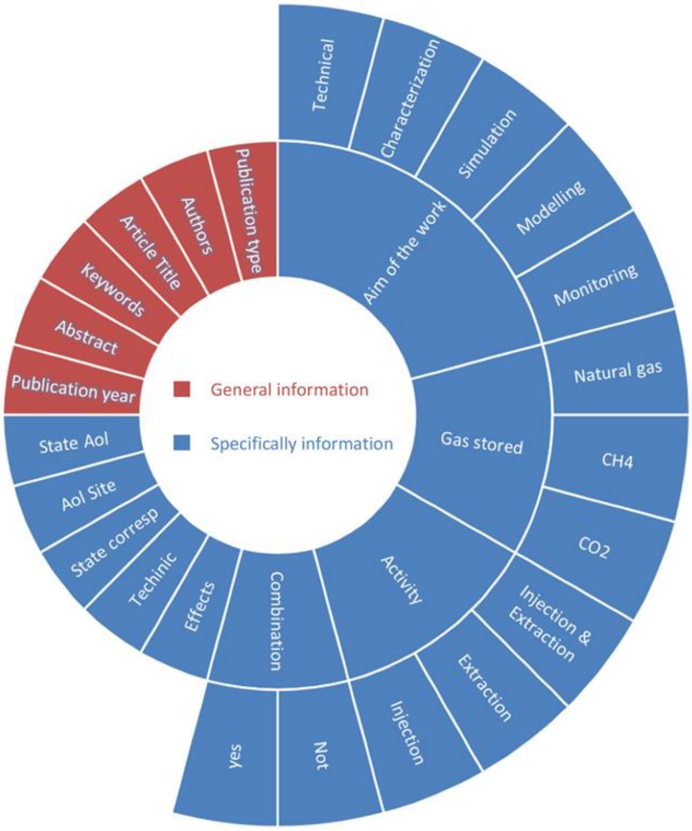

Figure 5. Head of the database used to classify the information of the 60 selected contributions. The general information is represented with the blue color while the detailed information is highlighted in red.

General information:

- Publication type—distinction between articles in journals (J), proceedings of conferences (C), or books (B);
- Authors;
- Article title;
- Author keywords;
- Abstract;
- Publication year;

Specific information:

- State AoI;
- AoI site;
- State corresponding;
- Activity—injection or extraction;
- Aim of the work—the type of research, the present work being categorized into five classes as (i) monitoring, (ii) modeling, (iii) simulation, (iv) characterization, and (v) technical;
- Gas stored;
- Investigation technique;
- Combination of more techniques—if the main monitoring technique is combined with another activity;
- Ground deformation effects.

These new fields allow detailed analysis of each contribution and categorize the contained information for statistically investigating the state of the art in these developing issues.

3. Temporal Evolution of the Scientific Production

The scientific contributions of the collection on CCS monitoring were published from 2009, e.g., [42], to early 2022 [43], while the first article on UGS monitoring was published in 2010 [44] and the last in 2020 [40], but it is strictly related to the date of the article collection (Figure 6).

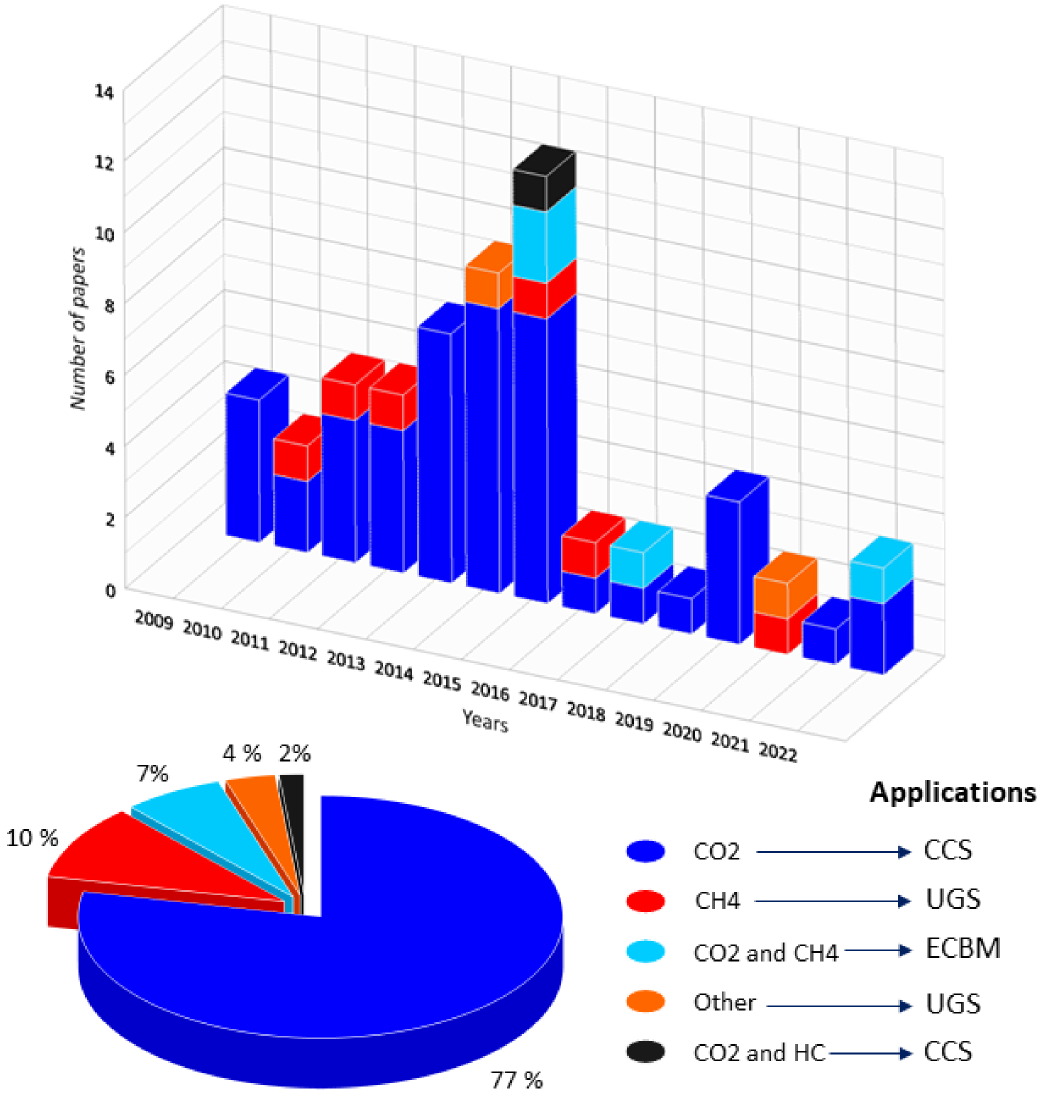

Figure 6. Scientific papers published from 2009 to 2022 subdivided for gas analysis and different storage activities. In the bottom left: the statistical percentage of gas used for different applications.

The first group of scientific contributions published, from 2009, presented the world-pioneering onshore CO_2 capture and storage project at the In Salah site, e.g., [45], which shows the InSAR approach for monitoring the storage-induced deformation since it is a well-suitable site for this technique. In fact, In Salah (Algeria) is an onshore site characterized by outcropping bare soil and no vegetation, e.g., [46]. This was the first site presented by the scientific community as a monitored site. The In Salah CCS project concerned the injection of 0.5–1.0 million tons of CO_2 per year into the Krechba Formation from 2004 to 2011 into a water-filled strata at 1800–1900 m depth [45]. The Krechba Formation had a relatively low level of rock permeability compared to oil reservoir rocks. Therefore, injection was carried out through three horizontal long-reach wells [45]. On this site in 2009, the SAR Envisat images covering the period July 2003–March 2007 were processed and analyzed to evaluate the potential of the InSAR approach for monitoring the effect of the

CO_2 injection [46]. The InSAR data showed that from 2004 very high uplift rates of +14 mm/year close to CO_2 injection well "KB-503" and +8 mm/year at "KB-501". The ground deformation rate showed a decrement in both injection sites around September 2005 [47], with values of approximately +5 mm/year [46]. Considering a longer period of the CCS activities, the average uplift rate around all the In Salah injection wells was about +7 mm/year. On the same site, the RADARSAT-2 data from January 2004 to March 2007 confirmed the uplift deformation around the injector wells, estimated at approximately +8–9 mm/year [42]. The results of this study are comparable with Vasco's [46] and Onuma's [47] works, despite the use of different SAR sensors. The KB501 injection data show continuous CO_2 injection at a constant well-head pressure from the start of the injection, and the injection rate averaged about 10–15 Mscfd (million standard cubic feet per day) [45]. The gradual vertical uplift with time, as observed by Rutqvist et al. [45], indicates that the uplift does not react instantaneously to injection pressure but rather appears to be correlated with the injected volume. However, the distribution of surface uplift data presented in Vasco et al. [46] already shows a clear uplift signature around KB501 after 24 days of injection. The injection and uplift responses at the KB503 injection well show similar behavior as at KB501. Time-lapse seismic and micro-seismic data also provided valuable new insights into the response of the formation to CO_2 injection. Monitoring data have been used to update and refine the geological, geomechanical, and flow dynamical models of the storage complex, e.g., [48,49]. The storage of CO_2 in the Krechba Formation gives valuable insight into how CO_2 can be stored in analogous carboniferous sandstone wells. The In Salah CCS project was suspended in 2011 because of concerns about the integrity of the seal. No leakage of CO_2 was reported during the lifetime of the project.

From 2010 to 2015, the gas storage monitoring topic was exploited to monitor ground deformation in 42 different scientific works, with an average contribution of seven articles/year. The maximum number of publications was recorded in 2015 with a peak of 12. In these 6 years, the CCS German pilot site of Ketzin resulted in an important case study for estimating ground deformation caused by the injection of carbon dioxide in a saline aquifer at a depth of 750–800 m. The Ketzin project started in June 2008 and remained active until August 2013, confining about 61,000 tons of CO_2 [50]. The first applications of passive and active seismic data to detect micro-seismicity and monitor CO_2 migration were proposed by Arts et al. [21] in 2013. The passive seismic data analysis conducted since September 2009 did not show events directly linked to the CO_2 injection. Two active seismic surveys were conducted after CO_2 injection started, the first one in October 2009 and the second in October 2011. Subtle changes were observed at the reservoir level, but no attempt has been made to further quantify the observed changes [21].

Another important site where seismic monitoring has been carried out is the CCS Aquistore project of Weyburn, situated in the Canadian province of Saskatchewan. After an alleged leakage of gas from the Weyburn site in January 2011, monitoring studies began to investigate this issue. It turned out that the gas leak was not due to the injected CO_2; rather, it was caused by naturally occurring biogenic CO_2 originating from biological processes in the soil [51]. Aquistore has an extensive seismic program composed of traditional 2D and 3D seismic, a unique permanent areal array composed of 630 geophones installed in March 2012 at a 30 m depth and a distributed acoustic sensing (DAS) fiberoptic line for seismic surveys. DAS technology uses fiberoptic cables as a linear array of acoustic sensors that records the acoustic field at high spatial and temporal resolution [52–54]. The characteristics of the acoustic noise generated along the borehole will change continuously during injection and withdrawal operations. Anomalies in the acoustic profile recorded in DAS signals can be identified and used as indicators of potentially early information of a loss of containment (LOC) incident in need of further investigation [55]. Comparisons of data can be used to model time-lapse imaging of CO_2 movement, allowing injected CO_2 to be tracked and traced as it moves laterally in the reservoir, e.g., [18,19,56]. Two projects at the Weyburn field are active: (i) the commercial enhanced oil recovery (EOR) project, where CO_2 plays an important role, as well, as an excellent solvent for hydrocarbons

[57,58], and (ii) the CO_2 storage-potential research project [19,59]. The injection of carbon dioxide into partially depleted oilfields to occupy the pores in which the hydrocarbons were trapped reduces oil viscosity and increases its volume, allowing the oil to flow through the reservoir rock to production wells more easily. As a consequence, the CO_2 is residually trapped and permanently stored. The EOR application was also analyzed in 2015 for monitoring the west Texas site through InSAR measurements extracted by an ALOS sensor from January 2007 to March 2011, where a total displacement of up to about 10 cm was detected [60,61].

In recent years, from 2016, the number of scientific contributions significantly decreases, while the beginning of 2022 shows a possible increase since three articles were published in a few months. These variations could be explained by considering the experimental activities developed in the period between 2004 and 2013. Several geological gas storage pilot sites were at the heart of a high number of studies that were published between 2009 and 2015. The percentage of published contributions about the monitoring of underground storage of natural gas and CO_2 shows as a higher number of contributions (77%) referring to carbon capture and storage, thus carbon dioxide sequestration, one of the most promising technologies for greenhouse gas management and environmental issues, e.g., [59].

A small percentage (10%) analyzes UGS activities for energy supply in winter or to ensure anomalous requests, e.g., [43]. The remaining 13% is divided between study sites that focus on both CO_2 and CH_4, e.g., [62,63]; CO_2 and hydrocarbon (HC) [61] or other natural gases, e.g., [40]. In the last decades, a new injection technique to decrease CO_2 emissions and produce methane known as ECBM has been studied concerning the injection of CO_2 into deep non-extractable coal seams for methane production and submitted for the northern Appalachian basin (USA) [62]. In the same year, the Sardinian Sulcis basin was studied to identify a reservoir for ECBM application [33,63], while in 2022, the ECBM activities of California (USA) were investigated [43].

4. Spatial Distribution of Underground CO_2 and Natural Gas Storage Projects

The spatial distribution of the scientific contributions collected shows that these practices are not yet widespread, but only in a few countries are there studies or pilot sites (Figure 7). It is worth noting that some articles showed multiple cases of studies in different countries. Spatially, sites of interest characterized by gas storage activities are localized in only 12 countries. The higher number of publications are focused on the In Salah CCS project (Algeria), nominated in 27 publications, 20 journal articles, e.g., [48,49,64–68], and 7 conference proceedings [47,69–74].

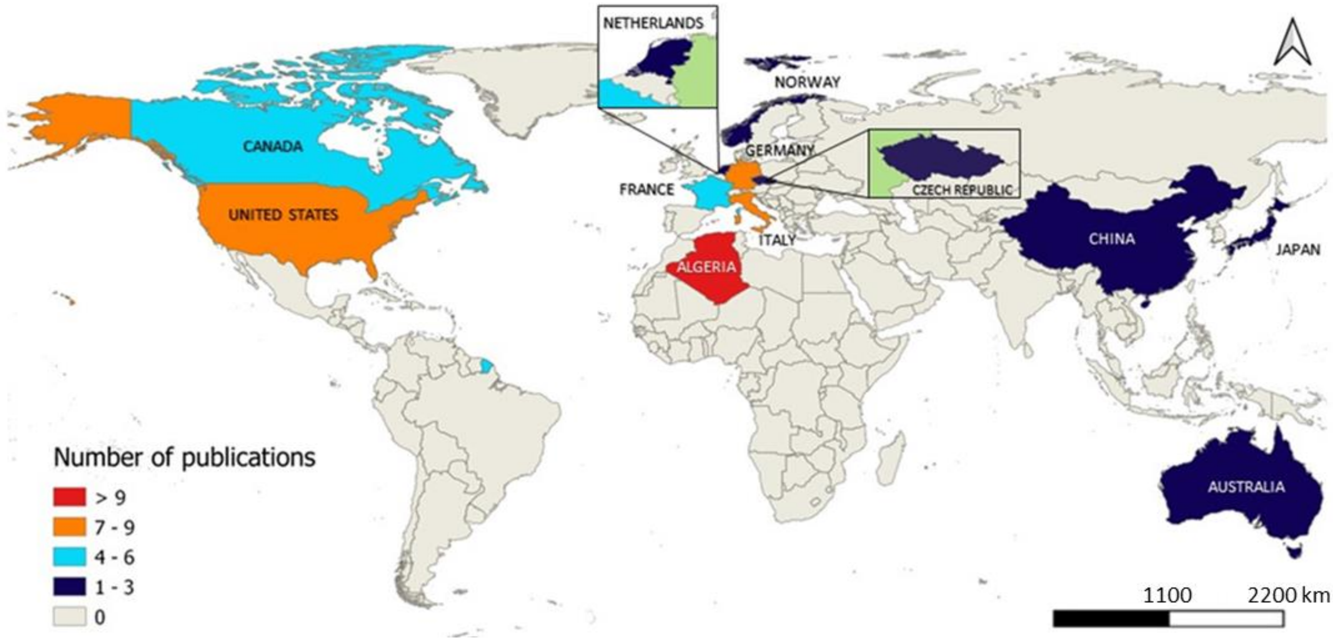

Figure 7. World spatial distribution of the scientific contributions.

This high number of contributions on the In Salah site, three times more than the others, is justified considering that this place was a world-pioneering onshore CO_2 capture and storage project [75], where very interesting results were produced by InSAR analyses. CCS applications in In Salah were well-adapted to InSAR monitoring because of the bare soil without vegetation that characterized this site.

The other gas storage projects most represented are located in Europe, with nine monitored sites distributed in six different nations, and in North America, with six sites located in the USA and Canada. Figure 8 presents a Europe-wide overview showing (i) the location of each gathered site, (ii) the type of application, and (iii) references to other existing UGS sites [76]. The second-ranking country is European; in fact, Italy is represented with eight total contributions focusing on two different main issues. The first topic gathered six articles focusing on underground gas storage operations located in the Po River basin, which present monitoring activities of practices for creating a strategic reserve of natural gas, e.g., [44,77–80]. In addition, two scientific publications on the monitoring and characterization of the Sardinia Sulcis basin test the possibility of using ECBM technology [33,63].

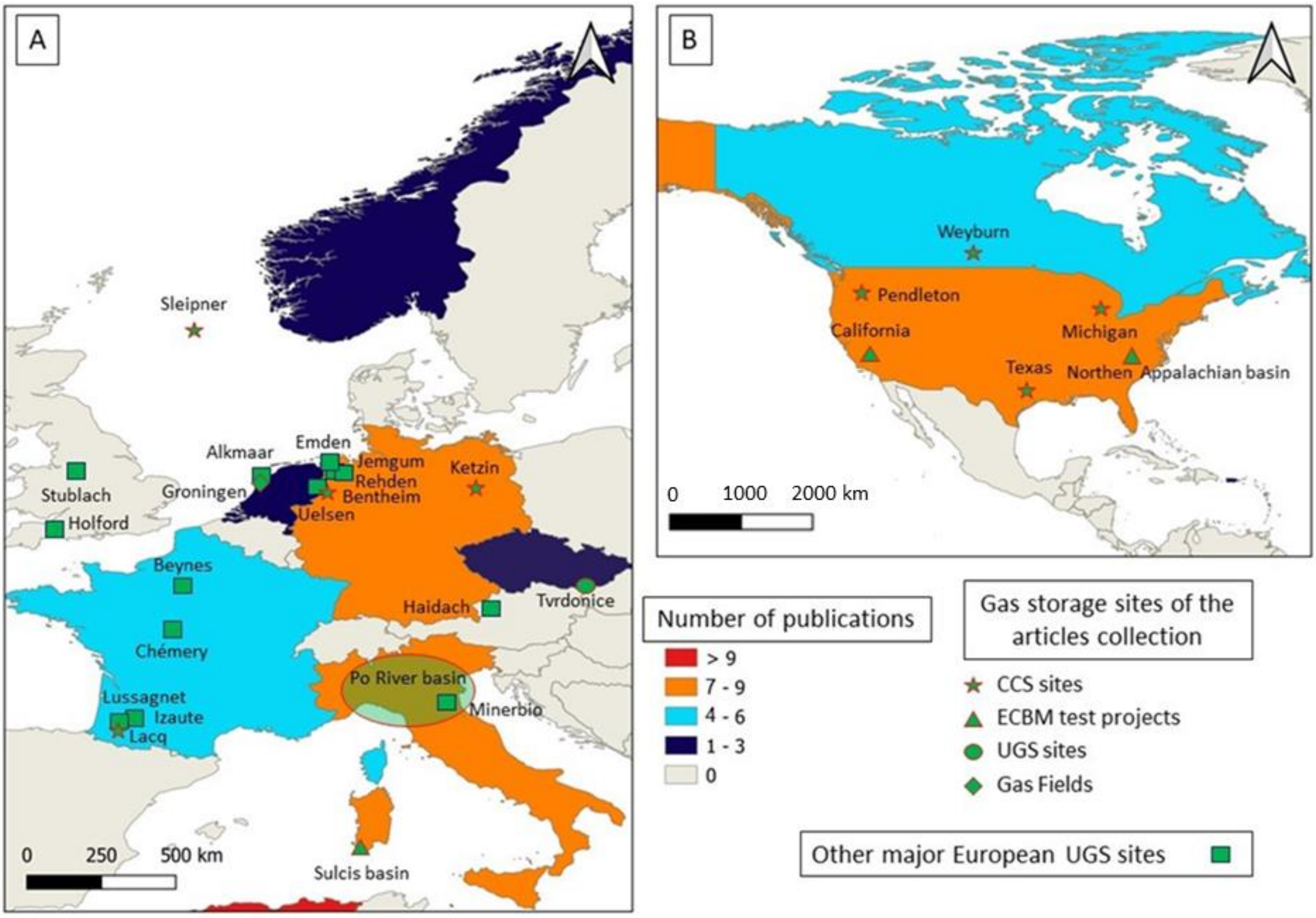

Figure 8. The enlargement of European (**A**) and North American (**B**) spatial distributions, highlighting the underground storage of CO_2 and natural gas sites selected by type of application. The most important European UGS sites, which were not gathered in the data collection, are also represented.

The other nations most represented are:

(i) Germany with seven scientific publications. Four journal articles focus on the Ketzin pilot site activities preventing greenhouse gas from entering the atmosphere [81,82], on a comparison of seismic interferometry techniques in carbon dioxide sequestration monitoring [83], and on a new concept of using ghost reflections (nonphysical reflection events) retrieved by seismic interferometry for monitoring carbon dioxide storage activities in Bentheim [14]. The other three scientific contributions are conference proceedings focusing on a permanent seismic monitoring system at the Ketzin CCS pilot site [21,50] and a study on monitoring carbon capture and storage areas using micro unmanned aerial vehicles [84];

(ii) The USA, with the same number of contributions, divided into six journal articles and only one conference proceedings. The journal articles refer to the monitoring of the west Texas EOR site [38,60,61], the storage and recovery operations in a confined aquifer located in Pendleton [85], the CO_2 storage in a depleted reservoir in Michigan [86], and the monitoring of natural gas storage in the California site [43]. The single conference proceeding focuses on the CCS project of the northern Appalachian basin [62];

(iii) Canada, with a total of six scientific contributions including four publications in international journals [18,19,38,87] and two conference proceedings [88,89]. All the contributions are focused on the monitoring and characterization of the Aquistore CO_2 storage project located in Saskatchewan near Weyburn;

(iv) France, with a total contribution of five: three journal articles and two conference proceedings. These articles propose to test the feasibility of long-term surface deformation monitoring by InSAR on carbon dioxide storage projects in European contexts, such as Lorraine, e.g., [90], where studies were conducted but CCS operations were not funded, and the monitoring of flux and soil–gas concentrations at the Lacq-Rousse CCS pilot site [22]. The congress proceedings show the preliminary studies for CO_2 injection in the PICOREF sector situated in the Paris basin [59] and a study on the use of persistent scatterers interferometry in highly vegetated/agricultural areas for long-term CO_2 storage monitoring [73].

The Jingbian (China) EOR site is recalled in two journal articles [38,91], while the CCS applications carried out in Shanxi province (China) with the case study of Shizhuang Town are represented with only one journal article [39], for a total of three Chinese contributions.

Norway and Australia were each presented in two scientific contributions: the offshore CCS site of Sleipner (Norway) in two journal articles [18,92], while the CCS pilot site of Otway Victoria (Australia) in an article journal [24] and a conference proceeding [25].

The site of Chiba prefecture (Japan) is represented with only one journal article [93], as is the gas fields of Groningen, which is located in the northeastern part of the Netherlands [94]. The latter is the largest natural gas field in Europe, with an estimated 2740 billion m^3 of recoverable natural gas 3 km deep in a sandstone layer, and it is a relevant case of study for the monitoring of subsidence and seismicity phenomena induced by natural gas production [95,96]. Since 1991, induced earthquakes have occurred in the province of Groningen that are linked to gas production from the gas field. In 1995, a regional monitoring network became operational to study the induced seismicity in the north of the Netherlands [97]. The Groningen gas field remained at a low activity rate until 2003; further seismic activity was increased, coinciding with an increase in production of the field. Long-term monitoring of induced seismicity in the north of the Netherlands and the recent expansion of the network in Groningen form the basis for understanding the processes responsible for the generation of earthquakes. An accurate estimate of the seismic hazard is essential for risk assessment and the subsequent hazard-mitigation planning. Since induced seismicity is a nonstationary process, understanding temporal and spatial variations in seismicity patterns and their relation to changes in production is essential. However, due to the relatively small number of events recorded, it takes time to detect statistically significant changes [98].

Finally, the underground gas storage site of Tvrdonice (Czech Republic) has only one journal article focusing on radar interferometry as a comprehensive tool for monitoring the fault activity [40].

5. Critical Analysis

5.1. Aim of the Work and Techniques Used

The gathered contributions were critically analyzed to categorize and statistically investigate them. The aims of the collected scientific contributions were divided into five classes, as follow:

- Monitoring: activities focusing on LOC detection, ground deformation, reservoir displacement, and subsidence/uplift studies. The monitoring studies were carried out through different techniques, such as InSAR, e.g., [89], seismic reflection and ambient seismic noise, e.g., [82], GPS/GNSS, e.g., [60], pressure analysis, e.g., [66,74,86], tiltmeter, e.g., [19], and geological data, e.g., [33,63];
- Modeling: studies analyzing all the available data to obtain a reservoir system model for understanding the physical, chemical, and geotechnical parameters, such as fluid pressure, permeability, angle of internal friction, porosity, acidity, and temperature, e.g., [46,99];

- Simulation: researchers simulating the geological conditions and their changes by the exposition of the areas to specific activities. This type of study is very important to learn the possible effects and prevent damage caused by gas storage activities, e.g., [90,100];
- Characterization: contributions aimed at the geological, geotechnical, geochemical, and geophysical detailed characterization of the potential reservoir system analyzed in the study area, e.g., [33,63];
- Technical: research works focusing on the description of innovative techniques or applications of reservoir monitoring, e.g., [64,75].

Many contributions present works related to multiple classes, as different data exploitation methodologies were applied. Figure 9 shows the percentages of publications for each category. The higher number of papers shows monitoring studies of reservoir systems dedicated to gas storage activities (46.2% of the total), e.g., [14,73]. The most-used technique for continuous reservoir monitoring is InSAR, e.g., [68,70,87–89], with 36 papers (83.7% of all monitoring contributions). Just few monitoring contributions focus on other techniques, such as seismic reflection and ambient seismic noise (9.4%), mainly used to monitor the pilot site of Ketzin located in Germany, e.g., [21,50], and the Aquistore CCS project of Weyburn (Canada), e.g., [52–55], and GPS/GNSS (6.9%), e.g., [60]. UGS activities can be dangerous because of the potential for gas leaks from pipelines, which could provoke fires or flammable clouds (flash fires) [101] and ground deformation caused by a high rate of gas injection or gas pressure [39]. In fact, methane is highly flammable when mixed with air at certain concentrations, making gas leakage at the ground surface a severe safety hazard and threat to surface infrastructure [102]. Gas leakage risk is high because of the high pressure of the stored gas and the repeated injection and withdrawal cycles that stress the well-formation storage system. The most dangerous effect is a large-scale surface blowout, such as the one that occurred at the Aliso Canyon UGS facility in California in October 2015 [103–105]. In addition, periodic injection and withdrawal of natural gas could cause vertical deformations of the terrain surface; for this reason, the continuous monitoring of UGS activities plays a key role. Radar interferometry is a commonly used method for tracking ground deformations that allows the registration of even relatively small changes (mm/year). The results of Rapant et al.'s [40] studies show a high correlation between periodic injection and withdrawal of natural gas into/from the reservoir and periodic ground deformations above it.

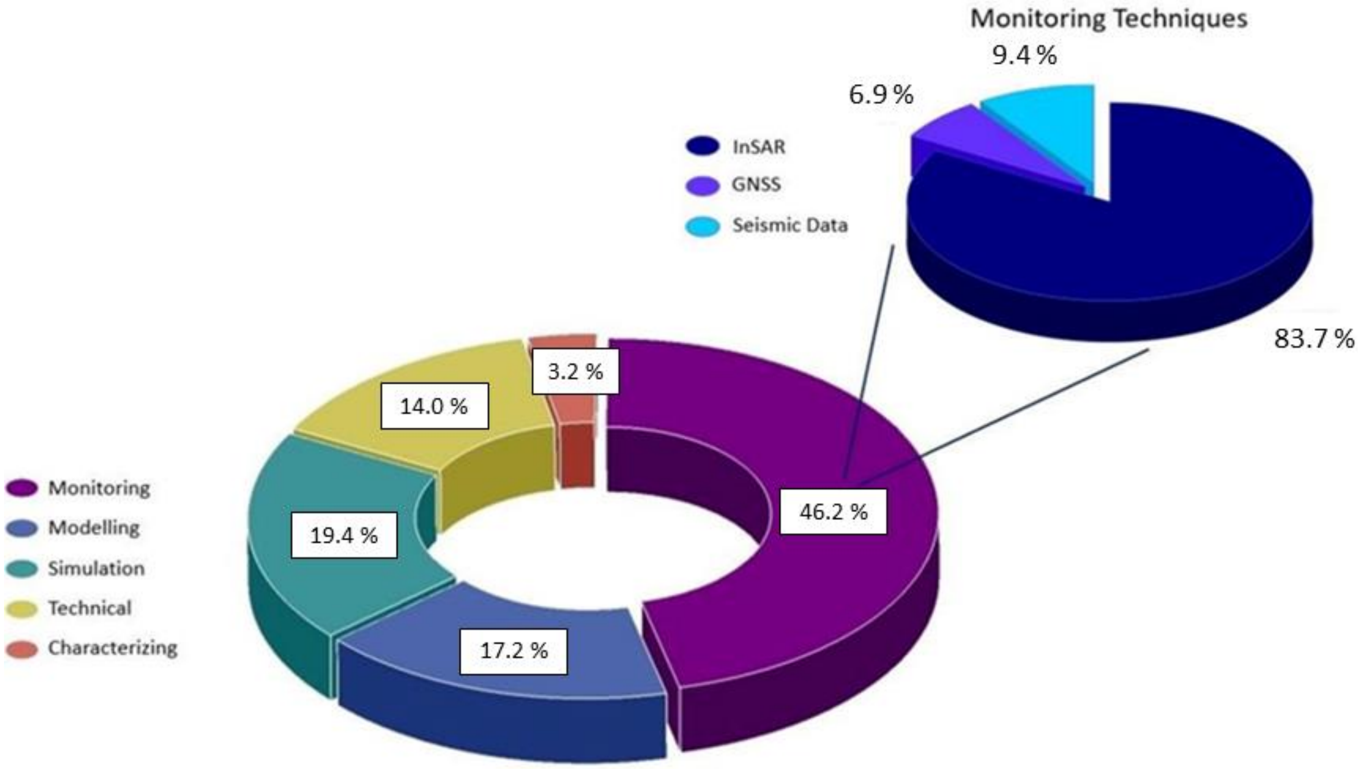

Figure 9. Statistical distribution of the research topics. In the top right: the percentage of main monitoring techniques used in data collection.

In the CCS process, the migration pathway of CO_2 after the underground injection phase becomes very important information for judging the possible storage status, as well as one of the essential references for evaluating possible environmental effects. Once CO_2 leakage occurs, it will not only lead to the failure of the sequestration project and a lot of economic losses, but it can also cause irreversible damage to humans and the environment. For this reason, the topic of the security of the sequestration area has received wide attention over the last decades. InSAR technology, with its advantages of extensive coverage in surface deformation monitoring and all-weather traceability of injection processes, has become one of the promising technologies frequently adopted worldwide in CCS projects.

Zhang et al. [38] show a UAV photography measurement technology with a 3D surface model for extracting the high-resolution digital elevation model of the CCS sequestration area in Shizhuang Town, Shanxi Province (China). With these data, they combine the InSAR technology to display the results of surface deformation monitoring of the CO_2 injection area more clearly.

Modeling class is represented by 17.2% of the total. There are four models considered essential for managing gas storage risks [55]: (i) the reservoir model useful for assessing and predicting the response of reservoir pressure in space and time during injection and withdrawal operations under various risk mitigation scenarios; (ii) the geomechanical model used to simulate stress changes and deformation in the reservoir; (iii) the wellbore model used to simulate the injection, withdrawal, and leakage processes in the well, and (iv) the geohazard model useful for probabilistic seismic analysis, displacement analysis, and earthquake-induced analysis. Unlike the previous three models, the geohazard model is distinct in that it takes a probabilistic approach [55]. Computational modeling is a powerful tool for the study of gas storage activities and it can be used to complement experiments. The aim of these models is the analysis, representation, and handling of geometric information. The need for more structured models with higher descriptive capabilities grows with the morphological complexity of the represented objects. Raziperchikolaee et al. [86] used a combined monitoring-and-modeling approach to assess surface uplift associated with CO_2 injection into a depleted carbonate reef of the Michigan basin. The works of these categories present multidisciplinary methodologies to evaluate the environmental impact of gas storage activities from a geomechanical point of view in connection with the ground surface displacement that may cause effects on existing structures and infrastructure [44]. Many times, calibrated reservoir models were useful for forecasting injection rates and designing effective strategies for improved oil and gas recovery, e.g., [77,79,84].

The analysis of the acquired millimetric-scale movements combined with the detailed geological analysis, both at reservoir and regional scale, represents the focal point for understanding the investigated phenomena. Based on this information, a fully integrated and multidisciplinary geological, fluid-flow, and geomechanical numerical modeling approach is useful to reproduce the main geometrical and structural features of the involved formations combined with the poromechanic processes induced by the storage operations. The main achievement of the fully integrated and multidisciplinary methodology is a deep knowledge of the system and the involved processes, a mandatory stage for the creation of the CO_2 and natural gas storage simulation, e.g., [37,85]. The contributions that simulate the real conditions that can occur in the reservoir systems with gas storage activities are 19.4% of the total. These simulations can be achieved by using a large amount of data and they are used to analyze complex situations that could present risk. Some articles with this aim propose the feasibility test of long-term surface deformation monitoring based on SAR interferometry of carbon dioxide storage sites, e.g., [66,90,99].

The technical contributions (14.0%) focus on (i) monitoring fault activity in the proximity of UGS facilities, e.g., the Vienna basin [40], where the tectonic fault structure of this area caused special behavior, (ii) InSAR data interpretation and impact assessment for monitoring the evolution of CCS activities though time and the detection of surface deformation induced by reservoir exploitation, e.g., [64,70], (iii) the combination of different monitoring traditional and remote-sensed data, e.g., that used to analyze In Salah CCS activities, e.g., [48], and (iv) approaches for assessing the most suitable areas to be monitored by remote-sensing data [39]. The Vienna basin [40] is particularly interesting because the area adjacent to the underground gas storage activities shows exactly the opposite phase of typical UGS vertical movements, i.e., the terrain above the underground reservoirs subsides with the injection of natural gas. The results of Rapant et al. [40], which were based on the analysis of geological condition and fault activity by the radar interferometry technique, show that this behavior is conditioned by the tectonic fault structure of the area. In fact, the vertical movement follows UGS activity in the phase of injection/withdrawal of natural gas to the west, while to the east, in the hanging wall block of the Tvrdonice fault, the movement is manifested in a counter-phase. This behavior can be explained by the fact that the rocks above the UGS behave as a cantilevered beam on the western side, while on the eastern side it is free because of the anticipated slip on the fault plane [40].

The characterizing works focus on GNSS, Dem/Lidar and geological and geotechnical studies, e.g., [25], to analyze the limitations and strengths in gas storage sites, such as the reservoir depth, the geological setting, the working gas capacity, i.e., the volume of gas that can be stored and withdrawn, and the cushion gas, i.e., the necessary pressure to allow the working gas to be withdrawn from the storage at high rates. Works about these approaches are less represented with 3.2% of total contributions. One of the most cost-effective ways to increase deliverability and working gas capacity in gas storage reservoirs is to operate at higher pressure [106]. Maximum safe operating pressures for a reservoir depend on several geomechanical factors, including in situ stresses, stresses induced by local and global pressure changes in the reservoir, and the mechanical properties of reservoir and overburden material. The typical practice is to operate gas storage reservoirs at levels at or below original reservoir pressure because of concerns about caprock integrity, fracturing, faulting, and gas losses [107]. However, current approaches for choosing maximum operating pressure limits, considering the initial discovery pressure, are often overly conservative. This leads to underutilization of existing storage resources and consequent competitive restrictions on particular projects. In many instances, the pressure in a gas storage reservoir can be safely increased if the geomechanical behavior of the reservoir and overburden is well-characterized. Characterization of reservoir properties like porosity and permeability in reservoir models typically relies on the historical matching of data, well pressure data, and possibly other fluid-dynamical data. Fais et al. [63] presented a methodology suitable for identifying a caprock-reservoir system for CO_2 storage in the Sulcis coal basin (Sardinia, Italy). The petrophysical and geophysical characterizations indicate that the potential carbonate reservoir located at the base of the Eocene stratigraphic sequence in the mining district is heterogeneous but presents suitable reservoir zones for the storage of CO_2.

5.2. Satellite SAR Constellations

InSAR time-series analysis has been developed as a technique for mapping surface changes through space and time [108]. This technology uses satellites to measure millimetric-scale changes in the satellite-to-surface distance, which can be translated into surface deformation over spans of days to years. Ground deformations may be due to many causes, such as gas storage or withdrawal. Well leaks, reservoir leaks, and fault motion can also produce detectable surface movements [46]. The measured surface deformation can then be transformed to infer the volume changes within the reservoir associated with pressure changes caused by natural gas storage operations. The latter approach is useful to estimate the reservoir volume change and observed range changes in order to identify anomalous events [55]. The advantages of InSAR are that the cost is low and the data collection process is nonintrusive. The data are often freely available for noncommercial use, providing cost-effective long-term monitoring. The main drawbacks of the InSAR technique are geometric and temporal decorrelation, as well as atmospheric disturbances that affect the radar signal [109,110]. Therefore, InSAR data must be processed to remove atmospheric effects, orbital errors, and the influence of topography [111].

The satellite constellation used in the collected work was analyzed by both considering the sensors bands, thus the wavelength, and the constellation name (Figure 10). Considering the satellite wavelength of the whole database, 47 C-band datasets were implemented, as well as 8 X-band datasets, and only 1 L-band dataset. The number of datasets does not correspond with the number of contributions since some researchers used more than one SAR dataset over one site to cover a larger time span. In fact, eight contributions present the combination of different satellite SAR sensors, e.g., [37,43], of which four articles combine the C- and X-bands, e.g., [49,68]. Instead, no scientific studies show the combined use of X- and L-bands.

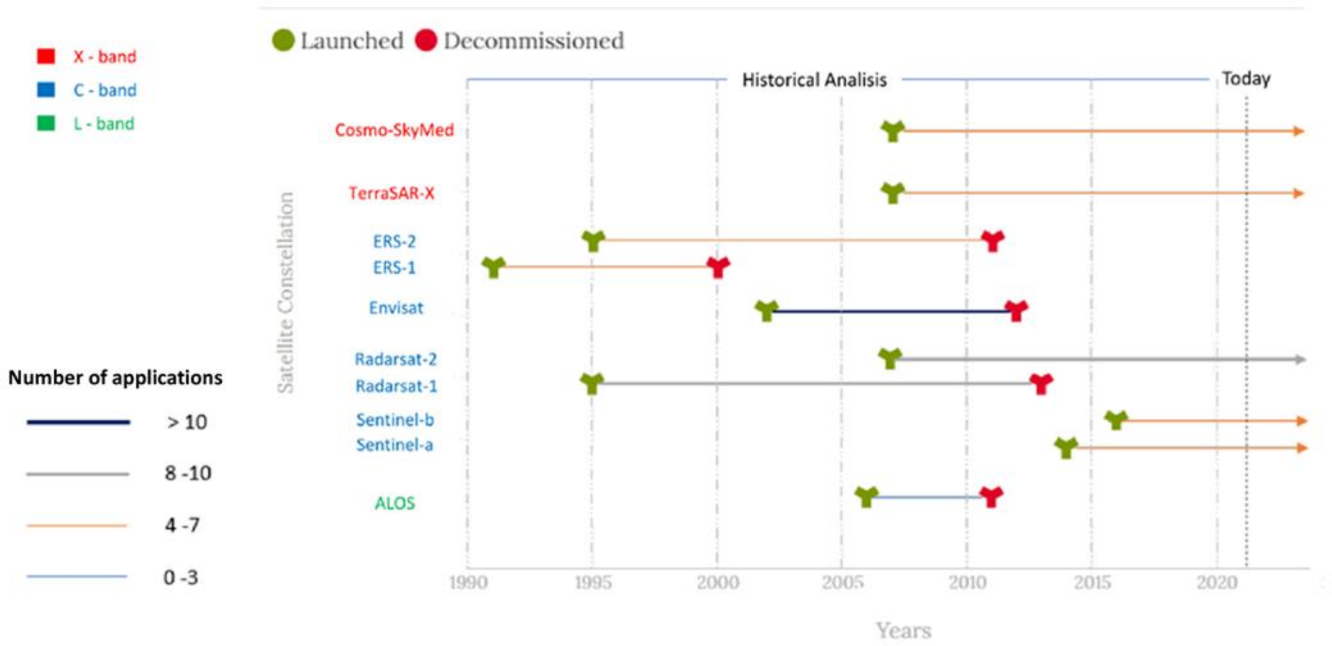

Figure 10. Satellite SAR constellation usage considering all the applicative contributions.

The most-used SAR satellite constellation is Envisat (2002–2010), launched by the European Space Agency (ESA), which compares in 27 applications, e.g., [67,73,74], followed by the RADARSAT constellation, launched by the Canadian Space Agency (CSA) with 10 applications, e.g., [44,85]. The more recent and freely available dataset of the Sentinel-1 constellation [100,112,113], launched in 2014 by the ESA, was used to study underground gas storage activities in six applications, e.g., [38,91]. The less-used C-band dataset is the ERS constellation (the oldest 1992–2011), which was used in four applications, e.g., [61,94]. The higher number of datasets were collected in the C-band (5.6 cm wavelength) since it is a good compromise for urban and nonurbanized areas. The same number of ERS applications was recorded by contributions using SAR datasets in the X-band (3.1 cm wavelength), as TerraSAR-X (launched in June 2007 by the DLR, the German Aerospace Center) and COSMO-SkyMed, an Italian Earth-imaging constellation consisting of four identical satellites launched between 2007 and 2010, with four applications, respectively, e.g., [66,81], while ALOS (L-band) was used in only one application [40].

InSAR technology is the most typical near-surface monitoring approach. Remote sensing with its unique monitoring advantages for gas leakage monitoring in detecting and locating the leakage point in real time with wide observational scope has been used for a complete migration process by using its long time-series monitoring capacity and noninterference with the drilling and injection/withdrawal process for the long term. However, there is no mature evaluation system to determine whether InSAR technology is suitable for each UGS or CCS site. Zhang et al. [39] propose eight factors that may affect gas storage monitoring using the InSAR technique: (i) vegetation coverage; (ii) topographic factor; (iii) reservoir location; (iv) land use/land cover; (v) injection/withdrawal rate; (vi) injection/withdrawal quantity; (vii) reservoir depth (theoretically, the shallower the reservoir, the better the surface deformation effect); and (viii) monitoring duration. InSAR technology is a potential monitoring method for UGS and CCS sites, but it still has limitations, especially in heavily vegetated and complex mountainous areas, e.g., [39].

5.3. Monitoring Techniques

In addition to InSAR monitoring, high-precision GPS measurements are also used to analyze surface deformation associated with gas injection at a geological reservoir [60]. GPS and InSAR are highly complementary methods for measuring surface deformation and can be combined to increase available data [114]. Both approaches enable the collection of information about ground deformation caused by the differences of two consequent acquisitions. Their variable applications, even if strictly related to ground deformation, have encouraged the authors to combine the GNSS and InSAR data, as testified by 14 contributions, e.g., [27,63]. As with InSAR technology, GPS measurements show better results when the reservoir depth is low. With shallow strata, a small overburden pressure and a fast deformation response allow an easy realization of InSAR and GPS observations. Oil and gas fields at depths between 1.5–2.5 km are the areas devoted to commercial injection, while the minimum depth for supercritical CO_2 is 800 m, but a caprock thickness is also required. Nowadays, most of the storage thickness ranges are between 0.8 and 5 km [115]. During injection and withdrawal processes, the change in the formation pressure makes the surface deformation obvious, which can be clearly observed using InSAR and GPS technology. When reservoir depth is greater than 2.5 km, it is no longer easy to cause surface deformation, so ground deformation evidence decreases with depth [39]. These techniques were evaluated on an active CCS and recovery project located in Pendleton (USA) [85], where 1.9 million m^3 of CO_2 per year were injected into basalt aquifers to about a 150 m depth. In this site, significant gravity anomalies and vertical deformation of the ground surface were localized to the immediate surroundings of the injection wells by GPS measurements. A similar result was detected by InSAR monitoring analysis between 2011 and 2013 recording sub-centimetric deformation in the western part of the city.

Geophysics is a fundamental part of subsurface observation, change detection and reservoir analysis. The seismic analyses are used to detect possible way of gas leakage and to monitor gas storage activities characterizing the reservoir structures with geotechnical and hydrodynamic parameters. Elastic wave-based geophysical methods are sensitive to a subsurface elastic module, which can be used to determine, among other properties, porosity, density, and fractures geometries. Seismic methods are dependent on effective stress and pressure, elastic properties, and density of solid and fluid components of rock material [116]. Seismic applications can be of different types, such as (i) 3D seismic data, e.g., [37], (ii) seismic reflection, e.g., [14], (iii) ambient seismic noise, e.g., [44], (iv) ambient seismic data, e.g., [18], and (v) 2D seismic data, e.g., [83]. Depending on the application, seismic data are processed in specific ways to interpretate the geometry of the subsurface and characterize it in terms of spatial distributions and selected properties, such as saturation distributions and reservoir volume change. Seismic reflection data in CO_2 monitoring studies are processed to generate amplitude versus offset data for each subsurface location. When it is combined with appropriate rock physics models, these attributes constitute a very useful input to learn about fluid saturation [117]. The advantage of passive seismic analysis, such as ambient seismic noise, compared to active seismic analyses is that the cost is low and data results are continuous, e.g., [44]. Moreover, a drawback of the latter technique is the need to average correlations over a long time period to obtain a sufficient signal-to-noise ratio (SNR) for the phase fluctuations to be measured accurately. Seismic analyses are often used as a deepening of the InSAR monitoring to improve the knowledge of site characterization. In addition, the seismic analyses are among the main monitoring techniques of CCS activities, above all where the InSAR approach required the installation of permanent reflectors or for offshore sites, e.g., Sleipner and Snøhvit, e.g., [17,26]. The study of seismic waves in the data collection was mainly used to monitor the Ketzin pilot site (Germany) and Aquistore CCS project of Weyburn (Canada), for a total of 17 contributions (Table 1).

Table 1. Summary of the reference papers for each gas storage monitoring techniques.

Technique	Number of Applications	Type of Analysis
GPS-GNSS	14	Combined with InSAR or Geological Data, e.g., [39,64,85]
Seismic	17	3D Seismic, e.g., [37] Seismic Reflection, e.g., [14] Ambient Seismic Noise, e.g., [44] Ambient Seismic Data, e.g., [18] 2D Seismic Data, e.g., [83]
Pressure Analysis	12	Well-Head Pressure, e.g., [66] Bottom-Hole Pressure, e.g., [44,74,79] Flowing Bottom-Hole Pressure, e.g., [86]
UAV	5	Drone gas leak monitoring, e.g., [25,80]
GWL	4	Comparison of GWL with Seismic Velocity, e.g., [78]
Tiltmeter	3	Ground Deformation Monitoring, e.g., [52]
Wireless Sensor Networks	1	Monitoring CO_2 Storage and Leakage [92]
Geochemical Baseline	1	Geological Characterization [33]

The standard monitoring program employed at UGS or CCS sites includes wellhead pressure, temperature analyses, surface leakage detection, and well-logging inspections, e.g., [44]. Well-based logging tools provide highly detailed measurements directly within the formations of interest. Log-based measurements include conductivity, pressure, temperature, acoustic velocity, electrical responses, borehole images, and formation fluid composition [118]. A widely used practice for reservoir pressure monitoring is to detect well-head pressure (WHP), e.g., [66], and then compute the corresponding bottom-hole pressure (BHP) using gas thermodynamic models, e.g., [55]. The problem with this approach is that variable or unknown temperatures of gas in the wellbore lead to a significant uncertainty in the density of the fluid, which then gets carried over into the estimate of the BHP [44,74]. These uncertain pressure values may lead to erroneous estimates of gas data, which may disguise detection of even moderate leaks [77–79]. In addition to WHP and BHP, flowing bottom-hole pressure (FBHP), e.g., [86], is an accurate method to predict gas pressure in petroleum engineering applications, such as production optimization [119]. The latter practice is useful for monitoring fluid movements inside the wellbore and its nearby regions. CO_2 migration is the primary concern in CCS projects. Pressure monitoring and analysis is useful to warn of any possible CO_2 leakage by taking control of the pressure change at the upper layer of storage reservoirs within injection wells. However, this causes incomplete monitoring distribution and leaves the migration path undetermined [120]. This technique is used in 12 different contributions of the data collection, e.g., [44,72].

UAV drone surveys can be used to monitor gas atmospheric concentrations at various elevations for surface LOC detection [55]. The latter technique allows the delineation of CH_4 or CO_2 plumes above the reservoir and can be implemented with the installation of permanent sensors at certain locations, such as wireless sensor networks (WSN) [92], useful to estimate leakage fluxes and source locations [121].

Additional techniques used to monitor gas storage activities are (i) groundwater level (GWL) analyses used to compare annual seismic velocity changes in four applications, e.g., [82], (ii) tiltmeter installation for ground deformation monitoring, with three applications, e.g., [19], and (iii) geochemical baselines to obtain a geological characterization [33], represented by only one application respectively.

Geochemical monitoring provides insight into both reservoir containment and active geochemical processes that could impact injection efficiency. Geochemical tracer techniques provide a direct measure of subsurface connectivity between the points of tracer injection and measurement of subsurface. Seismic monitoring analyses are more accurately understood when constrained by the geochemistry of the subsurface systems [122].

6. Conclusions

Geological gas storage is an increasingly important issue that includes two different main topics: underground gas storage, referring to the storage of imported CH_4 from foreign countries or regions to create a strategic reserve for energy supply fluctuation, and carbon capture and storage, useful for confining carbon dioxide and avoiding its dispersion in the atmosphere.

UGS is a widespread practice in Europe, e.g., [40,44,77–80], where depleted natural gas fields, aquifers, and salt caverns were used to store methane in underground formations to secure a gas supply in case of energy crises or for daily and seasonal fluctuations. There are over 150 active underground gas storage sites in Europe, of which 42% are located in Germany. Major active underground gas storage sites of Europe are in Germany, such as Rehden, Emden, Uelsen, and Jemgum, and in Italy, with Minerbio as the major active UGS site in the country. France is the third highest country in Europe with Chemery, Lussagnet, and Izaute being the most active gas storage sites [123]. The UGS activities are dangerous because of the potential occurrence of gas leaks from pipelines, which could provoke fires or flammable clouds (flash fire) [101] and ground deformation because of the high rate of gas injection or gas pressure, e.g., [39,69].

The CCS activity, instead, has received extensive attention as an effective method to reduce greenhouse gas in the atmosphere [6]. In fact, carbon neutrality is a goal that the world is striving to achieve in the context of global warming [6,12]. The CCS onshore sites more represented in the data collection are the In Salah region (Algeria), e.g., [48,49,64–74], and the Ketzin pilot site in Germany, e.g., [14,81–83]. Both CCS and UGS applications require subsurface characterization and monitoring to prevent micro seismic events, e.g., [74], ground deformation, i.e., subsidence or uplift, e.g., [64,74], changes in reservoir volume, e.g., [48], and CO_2 upwelling, e.g., [18].

It is important to understand the goals of monitoring, e.g., performance assurance, regulatory requirements, and an overarching desire for project risk reduction, to identify the most appropriate monitoring techniques. Minimizing monitoring cost will also be an overarching goal [116].

The temporal sampling of monitoring results has to be an important consideration. Monitoring tools can be separated into essentially continuous and into discrete time periods between measurements. For those tools with discrete time intervals, the goals of monitoring determine the decision of how often to monitor. In addition, subsurface measurements can be considered: i) direct measurements monitoring, thus tools include determination of pressure and temperature, measured at a specific in situ location of the subsurface, such as well logging data; and ii) indirect measurements, typically observing a proxy, such as seismic velocity, which is physically related to the subsurface property of interest. For gas storage performance assessment, the reservoir depth zone (the top of the permeable/porous storage zone) is a value to be considered. The choice of the monitoring approach to be used should consider the depth and areal extent of the reservoir to improve the monitoring result. The monitoring activities of the gathered scientific contributions focus short- and long-term migration pathways of gas through the response of the surface after injection. Monitoring techniques that provide real-time information on ground deformation and gas leakage, short-term migration in strata, such as seismic reflection, ambient seismic noise, and pressure analyses are appropriate to study phenomena occurring during the injection process. On the contrary, InSAR and remote sensing techniques provide a detailed analysis of the long-term migration pathway of gas through ground deformation monitoring after the injection. A multidisciplinary approach is essential for identifying a suitable gas storage reservoir and characterizing the system from geological, geotechnical, geophysical, and geochemical points of view.

InSAR technology, with its advantages of extensive covering and all-weather traceability, is becoming one of the promising technologies adopted worldwide in CCS and UGS projects because of the good compromise cost benefits with respect to traditional approaches [39,124], but it is still in its infancy in this field of study. In fact, InSAR technology still has technical drawbacks for monitoring ground deformation. Due to safety considerations, gas storage projects are often built far away from cities, including in mountains and deserts. These places are inevitably faced with foreshortening and other incoherence phenomena, resulting in the absence and inaccuracy of results, e.g., [39]. However, InSAR technology has extensive application prospects in the field of gas storage monitoring in the future. For example, the In Salah CCS project demonstrated that satellite data offers a nice opportunity to monitor onshore injection activities. Combined with geomechanical modeling, such measurements give reliable and very useful monitoring data. Geophysical methods related to safe storage of CO_2 are important, both in ensuring that carbon dioxide is actually stored in the reservoir and in detecting potential leakage or pressure build-ups. Seismic tools are often used to improve the structural and geological model and validate the monitoring data. An initial 3D reflection seismic survey can also serve as a structural framework for the spatial location of other monitoring data, as well as a baseline for determining temporal changes in seismic properties [116].

Seismic analyses are among the main monitoring techniques of gas storage activities, above all where the InSAR results are not successful. The Aquistore project of Weyburn (Canada) is an example of a geophysical listening acquisition system useful for this respect. The correlation between the data obtained from these two techniques allows a detailed analysis of both surface and reservoir effects.

Wellhead analyses provide highly detailed measurements directly within the formations of interest and are useful to create geotechnical models of gas storage reservoirs. On the other hand, the variable or unknown temperature of gas in the wellbore leads to a significant uncertainty in the density of the fluid, which then gets carried over into the estimate of the pression [44,74]. These uncertain pressure values may lead to erroneous estimates of gas data, which may disguise detection of even moderate leaks.

The flowing bottom-hole pressure is an accurate method to predict gas pressure in reservoir applications [119]. Pressure monitoring and analysis is useful to warn of any possible CO_2 leakage by taking control of the pressure changes at the upper layer of storage reservoirs within injection wells. However, this causes incomplete monitoring distribution and leaves the migration path undetermined.

The International Energy Agency greenhouse gas (IEAGHG) program has developed an online selection process that can be a first useful step to identify the most appropriate techniques to design a program for monitoring a CCS project [125].

A monitoring network consisting of many different sensors provides a large amount of data, which can be used for simulating activities of initial gas production and of the decades of gas storage. The simulation can be carried out for detecting the critical points of an injection site to avoid stressing the reservoir system. For this reason, a multidisciplinary approach, the combining of multiple monitoring techniques and data collection methods is the most accurate system for the analysis of complex effects caused by gas storage practices.

7. Future Perspective

Oil and gas applications in geological formations, for example, taking advantage of depleted reservoirs, are widespread practices that need further studies to improve monitoring methods. While UGS activity can be already considered an established approach, the CCS is an innovative technology that emerged in the last decades. Since 1996, carbon capture and storage pilot projects have been significantly increasing worldwide.

In 2020, the CCS technique confined 40 million tons of CO_2 in underground reservoirs spread worldwide, with the American sites as major exponents [126]. The great interest of oil companies in the carbon capture and storage topic is allowing the development of new methods and specific applications, such as ECBM, for the storage of CO_2 for environmental purposes but, at the same time, provide economic returns by extracting methane. The Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) that are meeting such aggressive climate targets will require the large-scale deployment of CO_2 capture, transport, and geological storage. The main problem is that the progress is slow, mainly because of cost issues related to the capture process and subsequent extensive monitoring. From the scientific point of view, underground sequestration of carbon dioxide is feasible, and we can verify that it is stored safely through monitoring. The Sleipner CCS site is an example of an economically feasible project, given that the carbon dioxide is captured directly from the methane gas produced at the field. Pipeline specifications preclude high concentrations of CO_2 in the natural gas stream, so the natural gas must be processed first to remove most of the CO_2 entrained in the gas stream [116]. In addition, the Canadian site of Weyburn provides the technological information for the continued development of the processes mentioned. In fact, the Aquistore project is fully integrated with carbon-dioxide-capture plants.

At present, CCS solutions are still at the experimental stage, also because of the high costs for large-scale applications, and they still need further and specific research. The next years will reveal if the CCS methods will be among the leading techniques in the race for energy transition.

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