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Carbon capture and storage (CCS)

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Summary. — Carbon Capture and Storage (CCS) is an important tool for the decarbonization of the energy system to achieve the mid-century global climate change targets. CO_2 is captured using different industrial processes that involve membrane filtering or enhanced combustion. The CO_2 is then transported, preferably by pipeline, to a storage site where it is injected into a permeable reservoir. Sealing capacity of the storage site is of paramount importance for safe CO_2 sequestration, to avoid any geological leakage. Each CCS project must have a dedicated MMV (Measurement, Monitoring and Verification) programme to ensure conformance with the expected evolution of the CO_2 plume and its containment within the storage site. Eni is committed to the implementation of CCS, with several ongoing projects.

1. – Introduction (CCS defined)

Carbon capture and storage (CCS) or carbon capture and sequestration is the process of capturing carbon dioxide (CO_2) before it enters the atmosphere, transporting it, and storing it (carbon sequestration) for centuries or millennia([1]), normally in an underground geological formation (fig. 1). Alternatively, after capturing, the CO_2 can be used([2]) to produce other substances through chemical transformation. In both cases its dispersion in the atmosphere is avoided.

([1]) Excerpt from Wikipedia `https://en.wikipedia.org/wiki/Carbon_capture_and_storage`
([2]) If CO_2 is utilized in the sequestration process, the term CCUS is used instead of CCS.

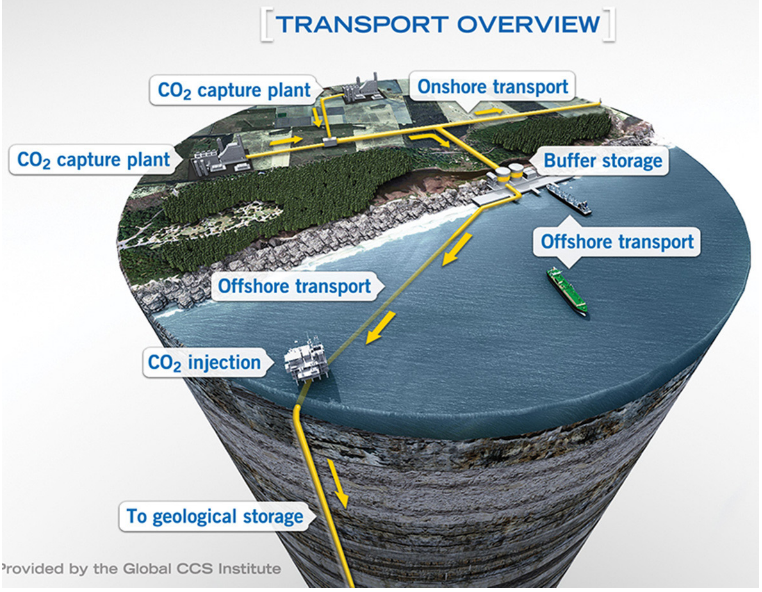

Fig. 1. – Schematic representation of a Carbon Capture and Storage project.

2. – Why CC(U)S is important

Internationally, CCUS is considered as an important tool for the decarbonization of the energy system. The International Energy Agency (IEA) stated in a recent report (CCUS in Clean Energy Transitions) that the capture, utilization, and storage of carbon dioxide must be a fundamental pillar of the efforts required to eliminate net greenhouse gas emissions within this century (fig. 2). CCUS is critical to address process emissions from cement, natural gas-based hydrogen, and biofuel production, to produce synthetic fuels, and to reach negative emissions from bioenergy with carbon capture and storage and direct air capture with storage.

CC(U)S is vital to reduce emissions to net-zero by mid-century and achieve global climate change targets.

3. – CCS in the world

CCS technologies are tried and tested as they have been in operation since the '70s. More than 260 Mt of anthropogenic CO_2 have been captured and stored to date, but there remains a massive gap between current CCS capacity and what is required to reduce global emissions to net zero. The global CCS industry must grow by more than a factor of 100 by the year 2050, to achieve the Paris Agreement climate targets. This means building 70 to 100 facilities a year. Most of the operational and planned facilities are located in USA, the rest is fragmented between 21 different countries (fig. 3).

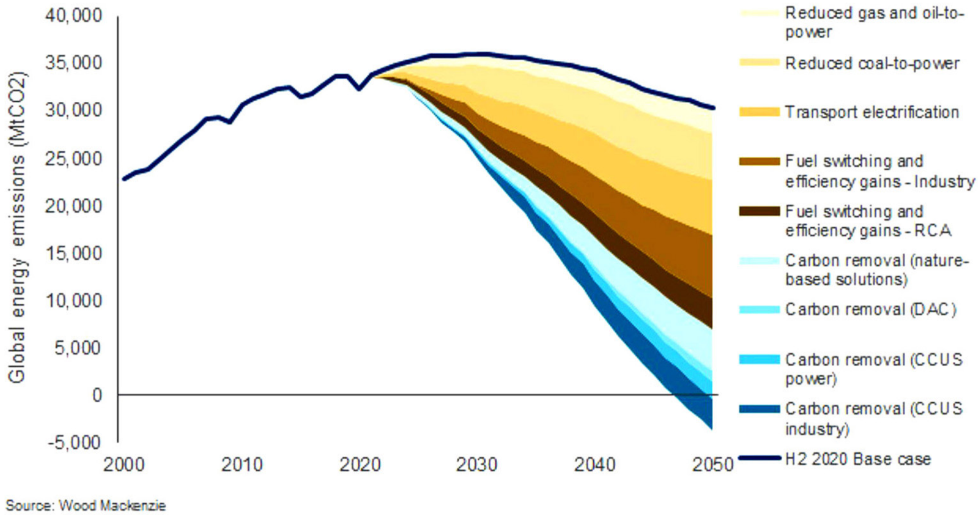

Fig. 2. – Change in global CO_2 emissions needed to reach net zero by 2050 [1].

Fig. 3. – World map of CCS facilities at various stages of development [2].

The current operational capacity today is around 55 Mtpa([3]) (@July 2021), but the number of CCS projects is growing on a weekly basis (fig. 4).

The planned capacity has reached almost 300 Mtpa (@June 2021), up from 100 Mtpa at the turn of 2021 (fig. 5). Over 50 projects have been added in the first half of 2021, with a strong input from multi-user, multi-industry hubs, which makes up over half of the capacity of the planned projects.

([3]) Mtpa = Million Tons per Annum = Mt/y.

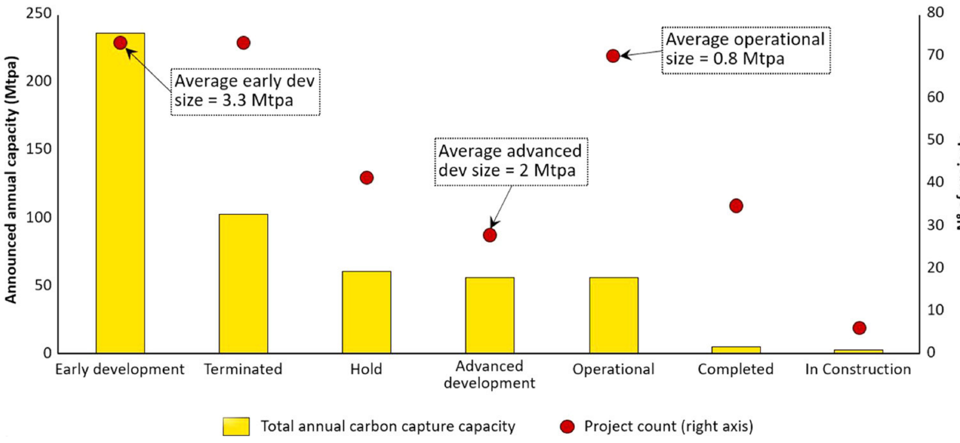

Fig. 4. – CCS projects development status in terms of capacity (left axis) and number (right axis). Please note the increase of average size per project moving from "Operational" to "Early development" [1].

The source of CO_2 to be reinjected comes for different industrial sectors, and it is evolving over the years (fig. 6). In the early stages of CCS, natural gas processing was one of the most important CO_2 sources, while for the future the "hard-to-abate" emissions will replace it.

The worldwide theoretical CO_2 storage capacity is huge and quite well distributed in most of the sedimentary basins (fig. 7). However, the screening for proper locations should take into consideration many local factors, both geological and logistical. In

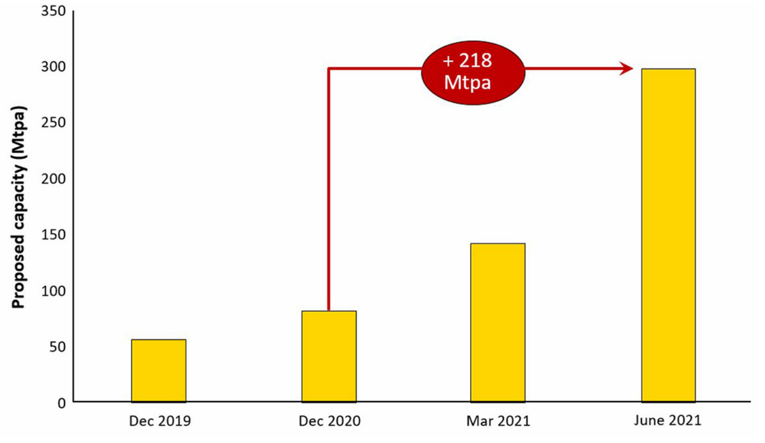

Fig. 5. – Total proposed CO_2 storage capacity in CCS projects [1].

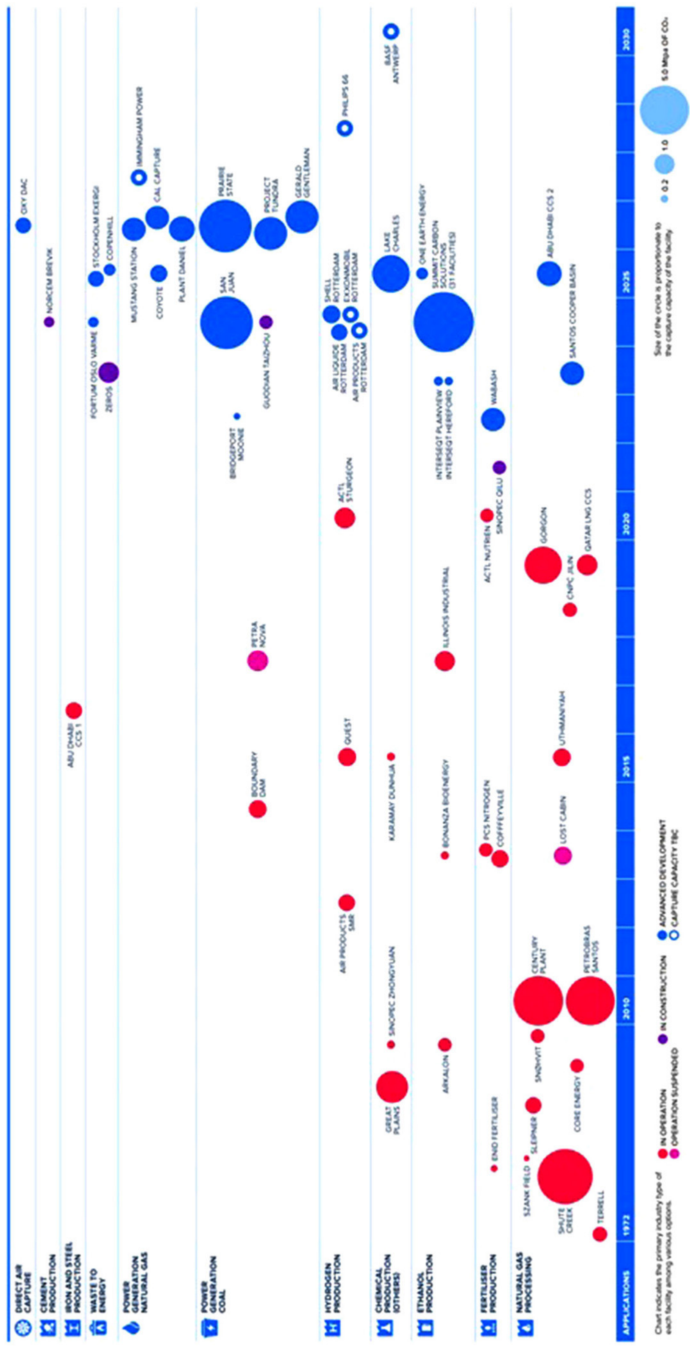

Fig. 6. – CCS projects by sector and scale over time [2].

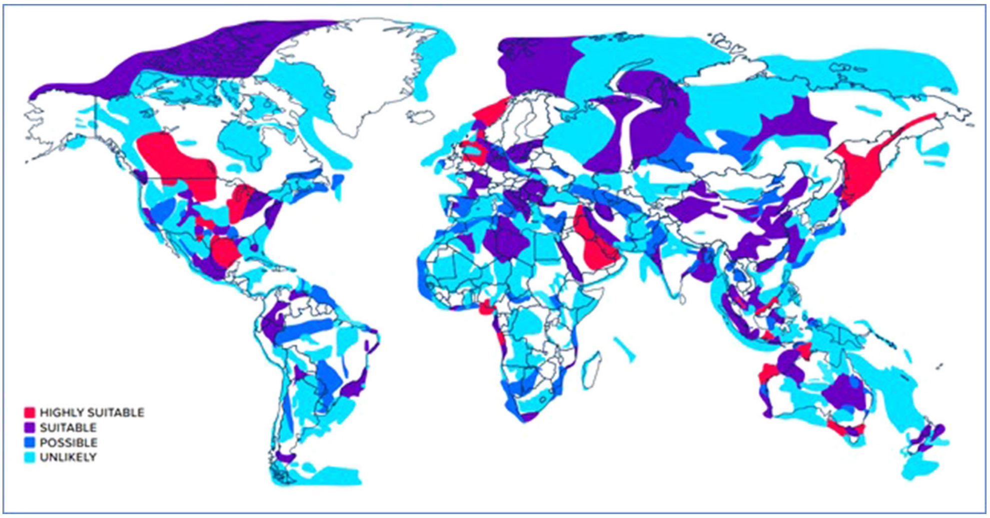

Fig. 7. – Suitable storage regions of the world based on the Global CCS Institute's storage basin assessment database [2].

particular, CO_2 sources should be close to the injection sites in order for the project to be economic/feasible. The carbon removal capacity should increase far beyond the current scenarios to meet climate targets (figs. 8, 9 and 10).

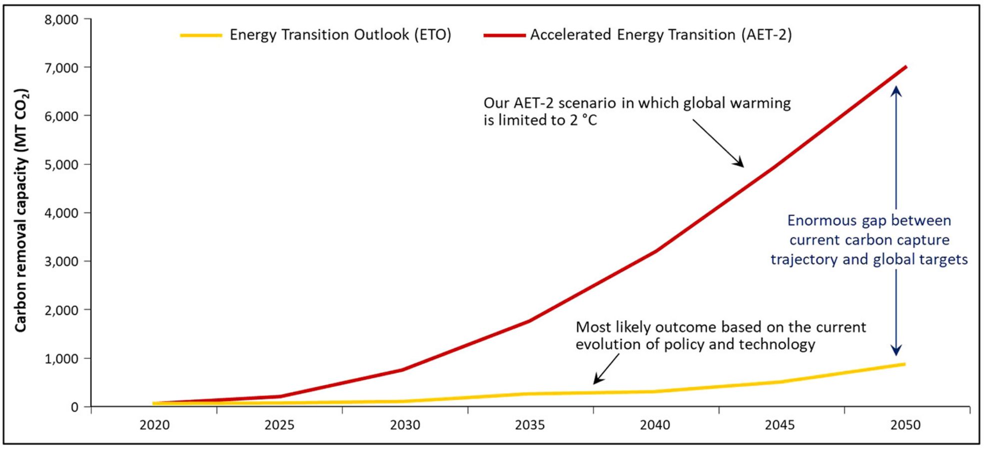

Fig. 8. – Comparison between carbon removal capacity needed for global targets and the current most likely scenario [1].

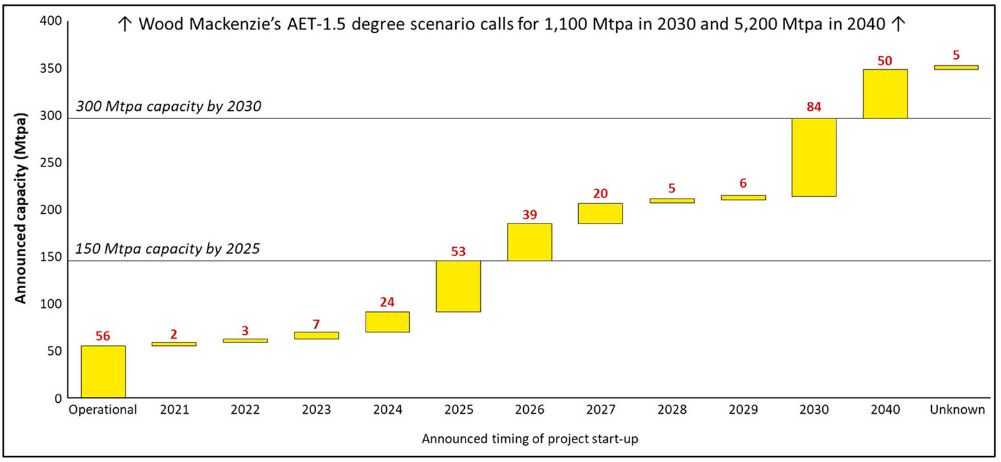

Fig. 9. – Planned carbon capture capacity additions by year of announced start-up [1].

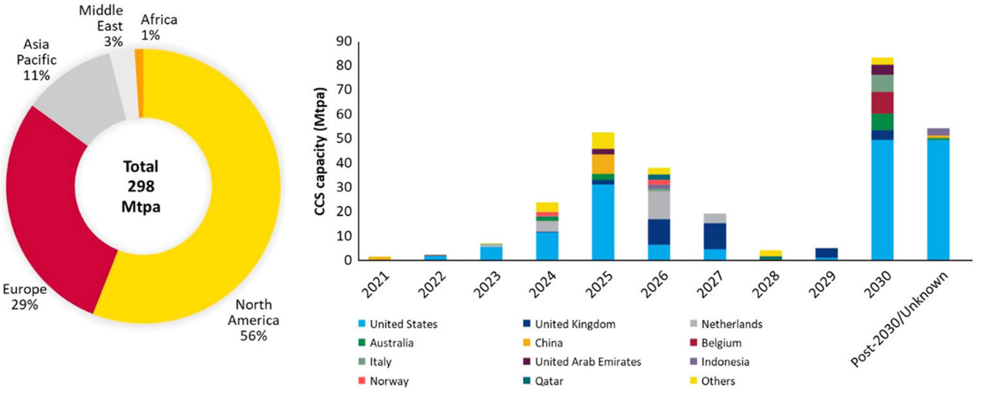

Fig. 10. – Geographical and time distribution of CCS capacity [1].

4. – CO_2 properties

CO_2 is a gas at standard temperature and pressure, and a solid if cooled and pressured sufficiently (fig. 11). If the temperature and pressure are both increased above the critical point for carbon dioxide (31 °C and 1070 psi, 73.8 bar), it can adopt properties midway between a gas and a liquid. More specifically, it behaves as a supercritical fluid above its critical temperature and pressure expanding in a container like a gas but with a density like that of a liquid.

CO_2 at deep reservoir depth is in a supercritical state, and to avoid phase changes the reservoir should be deeper than ≈ 800 m. Phase changes generate abrupt temperature

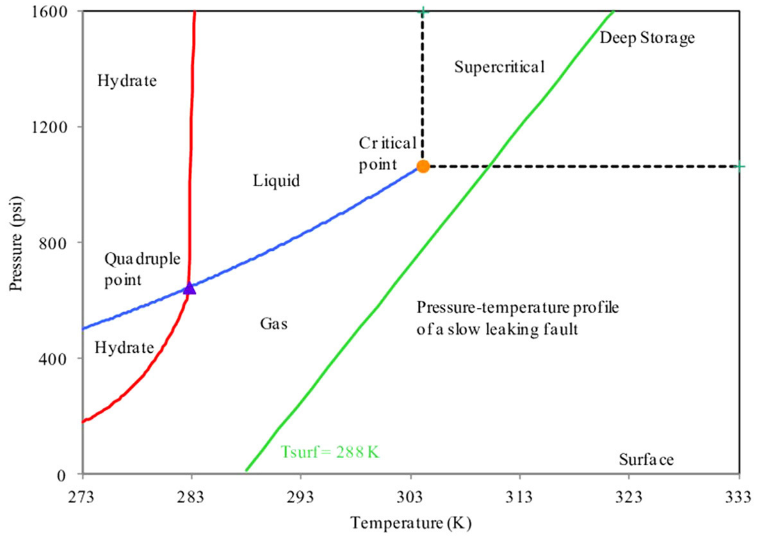

Fig. 11. – CO_2 phase diagram. The green line is a possible path of a CO_2 molecule moving from the reservoir up to the surface along a leaking fault. Depending on the temperature and thermal gradient, phase changes may occur [3].

variations, hence a proper planning of the processing design (*i.e.*, compressors, heaters) is needed. At supercritical state CO_2 is lighter than water, around 700 kg/m^3 at 300 bar and 90 °C.

CO_2 is not inert; it reacts with water and rocks leading to the acidification of the brines. A common reaction between CO_2 and water leads to carbonic acid formation.

5. – Carbon capture

Carbon capture is the process of extracting CO_2 from an industrial process. The following main types of capture processes are distinguished (fig. 12):

- Post-combustion: CO_2 captured from the exhaust gases is absorbed in a suitable chemical solvent. The CO_2 is then separated from the solvent and compressed in order to be transported and stored. Other post-combustion separation methods are by high-pressure membrane filtration or cryogenic separation.

- Pre-combustion: the fuel is converted into a mixture of H_2 and CO_2 before combustion using a process called gasification. CO_2 can then be transported and stored, while hydrogen can be used as a clean fuel.

- Oxy-combustion: this process involves the use of pure oxygen, or highly enriched air, in the combustion chamber. This type of combustion mainly produces steam and concentrated carbon dioxide, which is easier to process, to transport and store.

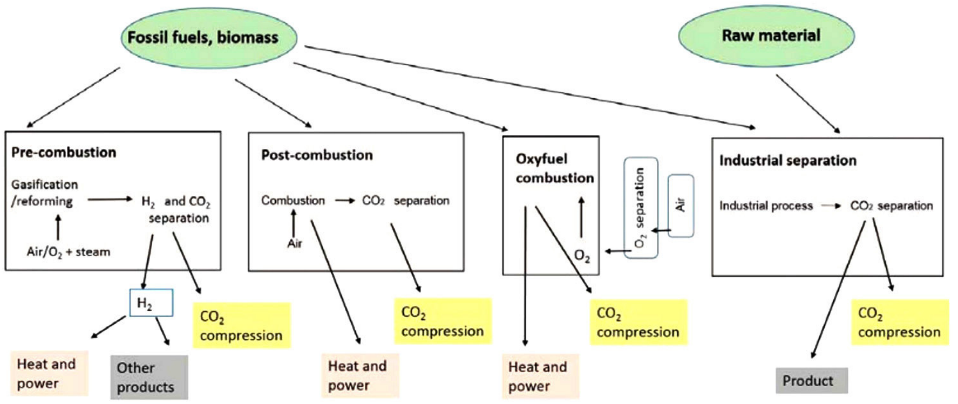

Fig. 12. – Schematic representation of carbon capture systems [4].

– Industrial separation: unwanted CO_2 from raw material is separated in different industry processes, such as natural gas sweetening, production of hydrogen and ammonia, etc.

6. – Carbon transport

Pipelines are by far the most used transport medium for CO_2. Special design considerations need to be implemented when constructing facilities for pipelining CO_2. The phase behaviour must be controlled during transportation, even in the case of multiphase flows. The best way of transporting CO_2 in the pipes is at ambient temperature and with a pressure above the supercritical one. Corrosion and fracture control should also be implemented, especially if CO_2 is transported together with water, which may lead to acidification. The pipes should be also kept at a safe distance from other infrastructure.

CO_2 is not flammable and inert at atmospheric conditions, but a sudden drop in pressure due to a pipe break could generate a similarly sudden drop in temperature around the broken area that could be dangerous and possibly mortal: a CO_2 pipe failure may lead to asphyxiation due to the very high CO_2 concentration around the break point. Since CO_2 is heavier than air, it stays on the ground for a longer time. CO_2 can also be transported using ships, in the solid phase at low temperature ($-35/-55\,°C$) and pressure ($7/20\,bar$). Ships need to have heaters and compressors, which are heavy and add to the transportation cost, and CO_2 is not a valuable cargo at the moment. Therefore, there is no easy way of increasing the number of CO_2 cargo ships if the CO_2 pricing or governments incentives do not change.

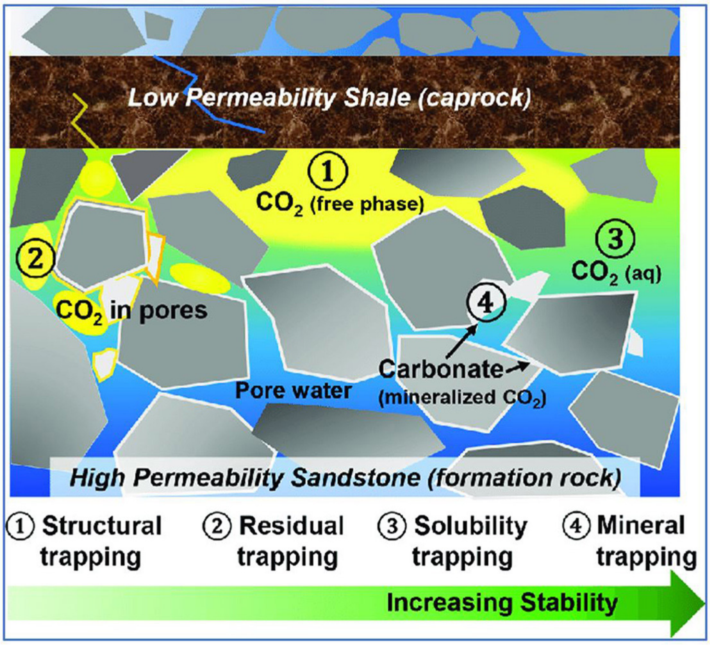

Fig. 13. – CO_2 trapping mechanisms [5].

7. – Carbon storage

The permanent storage of CO_2 can be done by injection in geological reservoirs. Deep saline aquifers and depleted oil/gas fields are most common, but other geological containments have been studied, such as coal beds and fractured basalts. CO_2 migrates inside the pore spaces driven by the balance between buoyancy and capillary threshold pressure. Different CO_2 trapping mechanisms contribute to the permanent sequestration of the CO_2 (fig. 13).

In depleted reservoirs the main trapping mechanism is structural trapping, where CO_2 replaces existing pore fluids (brine, residual hydrocarbons) filling the trap that previously contained hydrocarbons. Each trapping mechanism is associated with a time-dependent stability, with the mineral trapping (*in situ* carbonatation) as best option. Next to geological requirements, a CO_2 reservoir has to fulfil additional requirements, to be suitable for CO_2 storage:

Depth

The depth of the reservoir is usually larger than $\approx 800\,\mathrm{m}$. In such conditions, CO_2 always remains in the supercritical phase.

Capacity

The reservoir must be able to accommodate the total planned CO_2 injected volumes. The capacity can be computed with simple formulas; one of the most common is the one introduced by [6] and it refers to depleted hydrocarbons (HC) reservoirs:

$$m_{\mathrm{CO}_2} = \mathrm{HOIP} \ * \ \mathrm{URF} \ * \ \mathrm{FVF}(T_{\mathrm{res}}; pi) \ * \ \rho_{\mathrm{CO}_2}(T_{\mathrm{res}}; pi) \ * \ E,$$

where HOIP (Sm^3) is the hydrocarbon originally in place at standard conditions, URF is the ultimate recovery factor, FVF ($\mathrm{rm}^3/\mathrm{Sm}^3$) is the HC formation volume factor at initial reservoir conditions, ρ_{CO_2} ($\mathrm{kg/m}^3$) is the CO_2 density at initial reservoir conditions, E is the efficiency factor accounting for the non-ideality of the process (aquifer strength, compressibility during re-pressurization, compartmentalization, mixing with the residual gas).

A robust estimation of the efficiency factor is very difficult to obtain, due to the geological uncertainties that characterize natural reservoirs, especially deep saline aquifers. Moreover, this is a "static" approach, since all the dynamics of the process (pressurization, CO_2 migration, dissolution, etc.) are not considered.

Seal

The reservoir must be isolated from the surface, without leakage of CO_2. Shales and evaporites are well-known to be seal rocks. A good seal is usually thick, not fractured and extremely impervious.

Transport & injectivity

A CCS project can only work if CO_2 is available and can be transported at economically sustainable costs. Therefore, the best storage locations are close to CO_2 emitters. In addition, the reservoir porosity/permeability should be able to accept the planned CO_2 flows to avoid project failure but, also and most importantly, it should withstand the required pressure ramp-ups that could lead to unwanted fracturing.

Monitoring & remediation

CO_2 movements in the subsurface must be monitored and remedial actions should be possible: not all storage sites can be properly monitored due to logistical/regulatory/ environmental constraints. If a proper monitoring cannot be implemented, the storage site should be given up.

Stakeholders

Before starting any operations on an identified storage site, agreement among all involved parties (authorities, local communities, CO_2 providers, scientific advisors, etc.) should be reached.

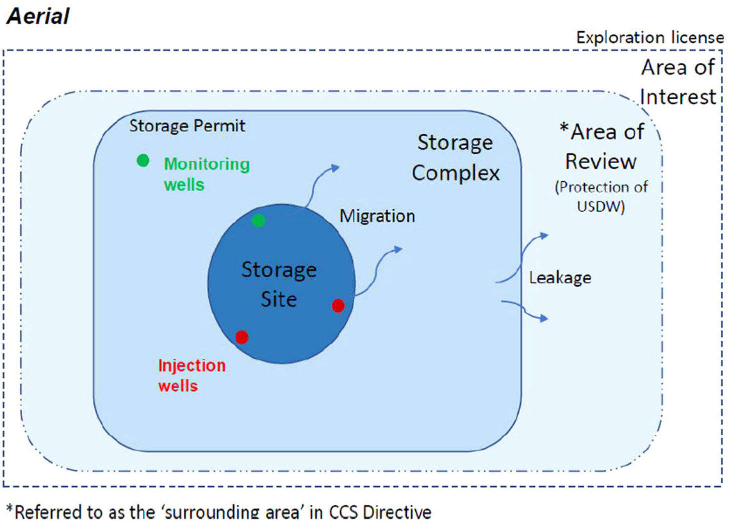

Fig. 14. – Conceptual map view of the CO_2 storage site/complex definitions.

7˙1. *The "storage site" and "storage complex" concepts.* – International laws that rule CCS projects attach major importance to permanent CO_2 storage in the subsurface. In particular, the CCS European directive stresses the importance of analysing larger areas than the doublet reservoir-caprock (fig. 14), and introduce the following definitions:

- *storage site*: the defined volume within a geological formation used for the geological storage of CO_2 and associate surface and injection facilities;
- *storage complex*: the storage site and surrounding geological domain which can influence overall storage integrity and security, that is, secondary containment formations.

Therefore, a more comprehensive approach to subsurface characterization must be applied compared to the reservoir-oriented analysis that are usually carried out in oil & gas exploration/exploitation (fig. 15).

7˙2. *Leakage prevention.* – In real storage systems many possible leakage pathways may jeopardize a CCS project (fig. 16). Leakage may occur due to the inefficiency of the geological containment (*i.e.*, top-, fault-seal failure) or it could be related to existing infrastructure, mainly legacy wells.

A risk analysis should be performed, in order to set up a risk register with all possible sources of leakage. Dedicated studies must be performed to find the best actions to mitigate the identified risks. In depleted reservoirs, the presence of many wells without CO_2-proof cement poses considerable risks during the project execution: a closed system is required in order to proceed with CO_2 injection. In deep aquifers, most leakage risks are associated with geologic uncertainties because of inadequate documentation, in contrast

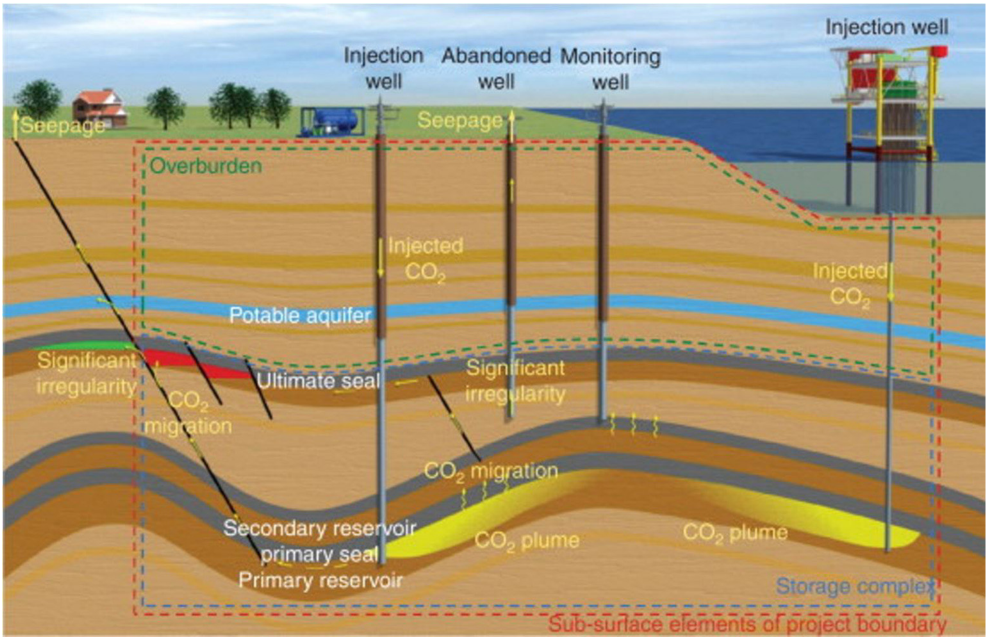

Fig. 15. – Conceptual cross-section of the CO_2 storage site/complex definitions. Highlighted in green, the outline of the "overburden" is also shown [7].

to oil wells. The geometry of the reservoir, its internal permeability distribution and the effectiveness of the seal are the major risks.

7˙3. *Comparison between saline aquifers and depleted reservoirs.* – Saline aquifers have the largest capacity compared to the other reservoir types because they are available worldwide. Nevertheless, estimates of their CO_2 capacity are subject to a high degree of uncertainty, mainly because the knowledge of saline formations is quite limited.

Depleted reservoirs are well-known, structural trapping is proven (although related to different fluids) and volumetrics can be accurately computed with more confidence. In addition, depleted reservoirs are located in areas where existing infrastructure could be repurposed for CO_2 injection rather than hydrocarbon production. The pore pressure regime of the reservoir plays a crucial role for the injection strategy into depleted reservoirs or aquifers. When a rock reaches the fracture pressure, cracks are generated and permeability is enhanced, allowing the fluids to escape. The fracture pressure represents the highest limit that can be reached in injection operations. In depleted reservoirs, hydrocarbon production is likely to reduce the virgin reservoir pressure, allowing a larger "safe window" for injection operations compared to aquifers, that did not experience previous depletion. On the other hand, an excessive pressure reduction could move the CO_2 PVT([4]) conditions to the hydrate phase, which is not compatible with fluid injection.

([4]) PVT = Pressure, Volume, Temperature.

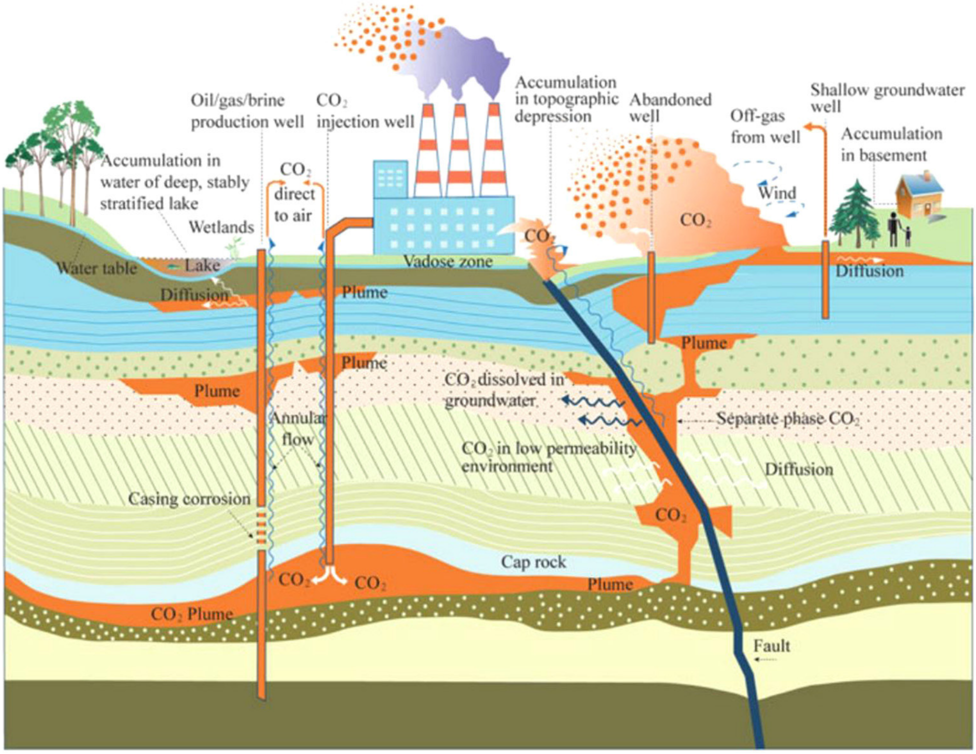

Fig. 16. – Possible leakage pathways of sequestered CO_2 [8].

8. – Monitoring

Each CCS project must have a dedicated MMV (Measurement Monitoring and Verification) program, which consists of a set of direct and indirect (mainly geophysical) measures to ensure conformance and containment [9]:

- *Containment*: the current security of CO_2 storage by verifying geological containment, well integrity, and the absence of any environmental effects outside the storage complex. Also, by detection of early warning signs of any unexpected loss of containment trigger, if necessary, additional safeguards to prevent or remediate any significant environmental impacts.
- *Conformance*: pressure and CO_2 accumulation inside the storage site are consistent with model-based forecasts and, if necessary, calibrate and update these models. Evaluate and, if necessary, adapt injection and monitoring to optimize storage performance. Provide the monitoring data necessary to support CO_2 inventory reporting.

Monitoring can be broadly divided in:

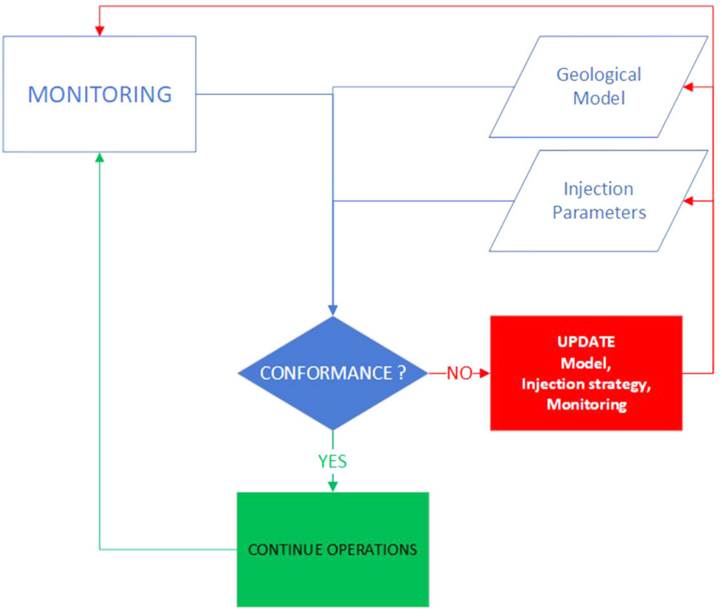

Fig. 17. – Block diagram of the MMV workflow. The geological model and the selected injection parameters are compared to the monitoring data. If there is conformance, operations can continue as planned. If not, an update of the geological model, injection strategy and monitoring should be implemented.

- Site storage monitoring—related to the injection management.
- Environmental monitoring—related to data acquisition for leakage detection.

Storage monitoring is aimed at the detection of the evolution of the CO_2 plume inside and, possibly, *outside* the reservoir. This is usually done by repeating geophysical surveys, such as 4D seismic, which records changes in seismic response due to the CO_2 that is replacing brine or hydrocarbons in the reservoir. Environmental monitoring is aimed at ensuring the environmental sustainability of the operations. It includes leakage detection, micro seismic monitoring and ground deformation monitoring.

The MMV workflow (fig. 17) should have strong feedback on the geological model and the injection strategy. The verification of the conformance between the expected system response and the actual data acquired during monitoring should guide the continuous update of the model, during and after operations.

8˙1. *Geophysical 4D monitoring*. – Repeating the geophysical measurements over the years allows monitoring the evolution of the CO_2 plume. The periodicity of the data collection depends on the threshold of detectability of the changes in the properties, of course, on the costs.

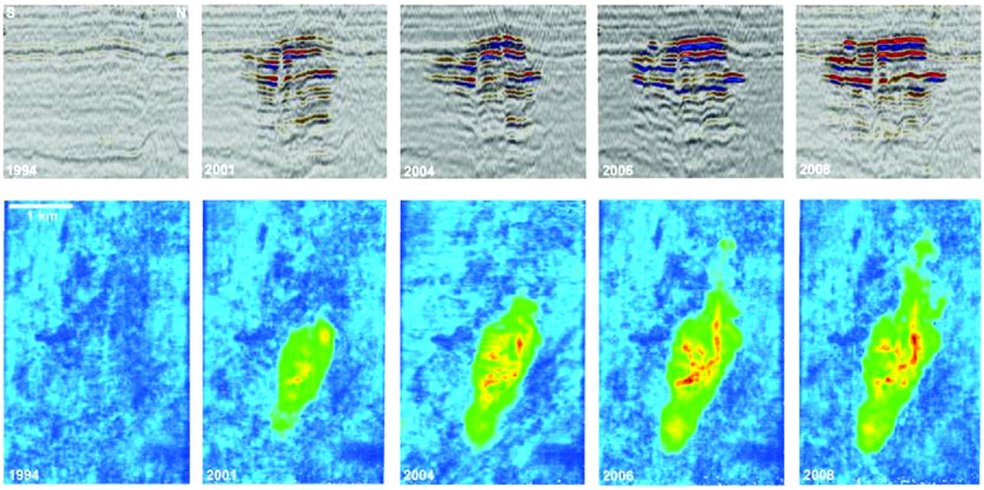

Fig. 18. – A spectacular example of 4D seismic from the Sleipner CO_2 storage field (Norway). From left to right the baseline survey and periodic monitoring survey are shown, documenting the evolution of the CO_2 plume over the years in cross-section (top) and plane view (bottom) [10].

8˙1.1. 4D seismic. The reflection seismic method is recognized as the most effective monitoring technology because it can recognize subtle variations in CO_2 saturation with a 3D coverage. The physical principle of reflection seismics is that any acoustic impedance changes in the subsurface can produce a reflected sound wave when struck by an artificially generated seismic pulse. Acoustic impedance is related to the density and the velocity of the rocks according to the following simple formula:

$$I = \rho V_p,$$

where ρ is density and V_p acoustic velocity. The injection of CO_2 displaces the fluids in the pore spaces changing both velocity and density of the rock. Such changes can be detected by carefully analysing the seismic data acquired at different times. A baseline survey is required just before injection begins, and if the subsurface has a good 4D response, time-lapse seismic can easily be used to track the evolution of the CO_2 plume over the years, including potential leakage paths (fig. 18).

8˙1.2. 4D gravity/electromagnetic/borehole seismic. Since CO_2 is lighter than brine (and heavier than natural gas), density variations can be detected by repeated gravimetric measurements. The (small) difference in CO_2 density compared to water can be used to track the plume during injection through 4D gravimetric surveys. The feasibility of such monitoring depends on the depth of the reservoir, the saturation and the amount of CO_2 injected, so it is not always applicable. In particular, the spatial resolution of the method is not comparable with 4D seismic.

Another non-seismic method that can be used for monitoring is electromagnetics (EM). When CO_2 replaces some of the saline pore fluid in an aquifer, the bulk electrical resistivity increases significantly, and this change can be monitored with electromagnetic measurements in the wells and at the surface. EM methods are very effective when surface and borehole data are combined, but they require a high density of boreholes with short distances between them. The same is true for borehole seismic techniques, which can provide very high-resolution 4D images but are geometrically limited due to the distribution and number of boreholes.

8˙2. *Well monitoring.* – Geophysical monitoring is "indirect", since CO_2 saturation is derived from proxy measurements (*i.e.*, density, velocity, resistivity). Wells, instead, allow direct CO_2 measurements by sampling the formation fluid. They represent an important factor of any MMV program, especially in depleted reservoirs. One or more dedicated measuring holes are used for monitoring: they provide information about the CO_2 plume with unparalleled resolution.

Fluid sampling is not the only information that can be provided by newly drilled or repurposed wells: petrophysical parameters, caprock mechanical properties, cores, cement status are examples of data that can be collected in wells.

8˙3. *Microseismic monitoring.* – The injection of CO_2 increases reservoir pore pressure, and thus it changes the stress distribution within the reservoir. Such changes may generate unwanted fractures in the weakest parts of the reservoir that should be detected and analysed to avoid induced seismicity. A microseismic network is a group of seismic sensors that are evenly spaced around the storage site, aimed at detecting any micro-earthquake that could be related to injection operations. Moreover, in seismic active areas, it can be used to identify naturally occurring earthquakes with better accuracy.

Building a microseismic network (fig. 19) is easier for onshore reservoirs, while offshore stations are costly and difficult to manage (fig. 20). If the storage project makes use of depleted fields, the existing platforms can be used to deploy microseismic stations. The platform provides power and communication facilities, while the sensors are placed on the sea bottom.

8˙4. *Ground deformation monitoring.* – The pressure increase due to CO_2 injection into a reservoir usually has only insignificant effects on the surface. However, especially for shallow reservoirs, a measurable bulge right above the storage site can occur. In order to detect possible ground deformations, a monitoring strategy must be implemented. Many technologies are available for such monitoring:

– High precision leveling

– Settlement gauge/piezometer

– LiDAR/Photogrammetry

– InSAR

– Hi-res bathymetry

– Continuous-GPS.

Fig. 19. – Example of a hybrid (onshore/offshore) microseismic network. Stars indicate the locations of seismic stations. Their number, azimuthal distribution and characteristics must comply with local guidelines, and are the result of a dedicated feasibility study. The green contour indicates the area of the depleted field, while the red and blue contours are at a distance of 5 and 10 km from the field.

Each of them has its own accuracy and applicability, so they are usually applied in combination. The site location (onshore or offshore) plays a fundamental role: leveling, piezometers and InSAR cannot be used in offshore environments. In addition, measurements should be combined according to the characteristics of each technology. For example, GPS is extremely precise, but provides only point measurements (fig. 21), while InSAR is less accurate, but can cover a large area.

8·5. *Surface leakage monitoring.* – Measuring CO_2 leakage is very difficult because of the high natural CO_2 "noise" in the biosphere. A baseline survey aimed at detecting annual, seasonal and daily variations of CO_2 natural emissions must be included in the monitoring plan. CO_2 can be detected using pH measurements, variations of CO_2 *vs.* O_2 concentrations, vegetation changes, tracers and direct CO_2 detectors.

8·6. *Geophysical and geological studies for CCS projects.* – Despite some differences, the regulatory framework for CCS is quite homogeneous regarding containment. The importance of preventing any leakage at the surface and ensuring permanent containment of CO_2 in the reservoir is recognized worldwide.

Fluid-dynamic, geomechanical and geochemical (G&G) modeling are indispensable to assess the containment of a reservoir for CO_2 storage. However, prior to modeling,

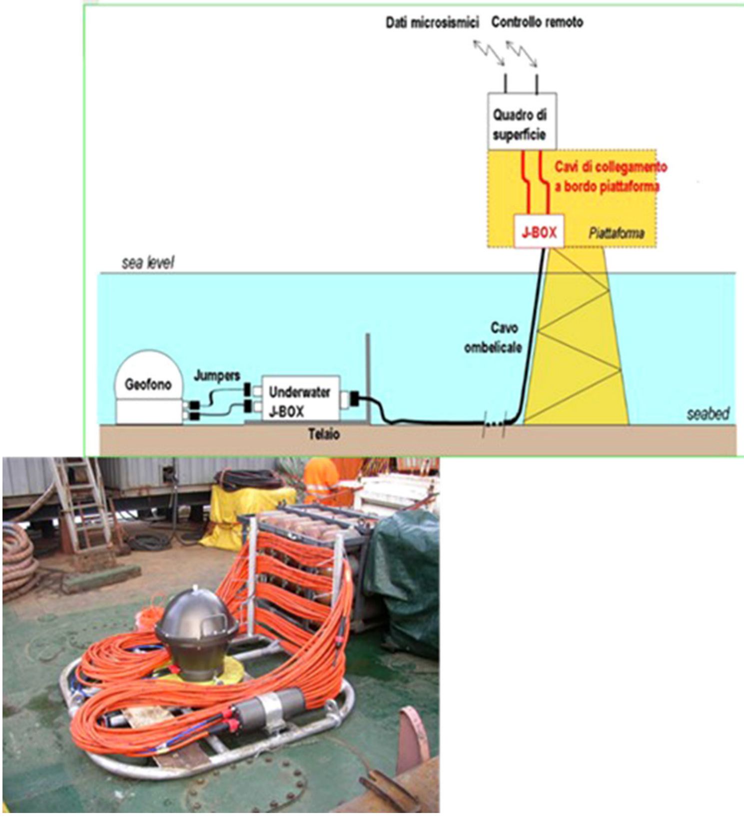

Fig. 20. – Schematic view of an offshore micro seismic station (top) and photograph of the underwater sensor (bottom).

a comprehensive characterization of the subsurface should be carried out. Integrated G&G studies provide geological/geophysical analysis of both the storage complex and overburden successions, in order to better assess their properties at various scales, and mitigate problems associated with injection and storage. Such studies can be summarized as follows:

– *Geophysical characterization*
  - seismic inversion (acoustic, elastic, Extended Elastic Impedance)
  - rock physics modeling
  - calibration to rock properties
  - classification/segmentation
– *Structural characterization*
  - structural interpretation

Fig. 21. – Continuous GPS onshore station.

- structural modelling
- fracture studies for caprock and reservoir
- fault seal analysis

– *Stratigraphic/sedimentological characterization*

- biostratigraphic analyses on core/cuttings (with different tools based on lithology)
- stratigraphic definition/revision of well-tops
- well top homogenization on neighbouring fields
- Paleoenvironmental reconstructions
- characterization of the depositional model
- seismo-stratigraphic/sedimentological analysis (on both seismic and attributes)
- integration with petrographic/mineralogical data
- analysis of the carbonate pore network

– *Basin-scale fluid migration analysis*

- qualitative analysis for monitoring purposes

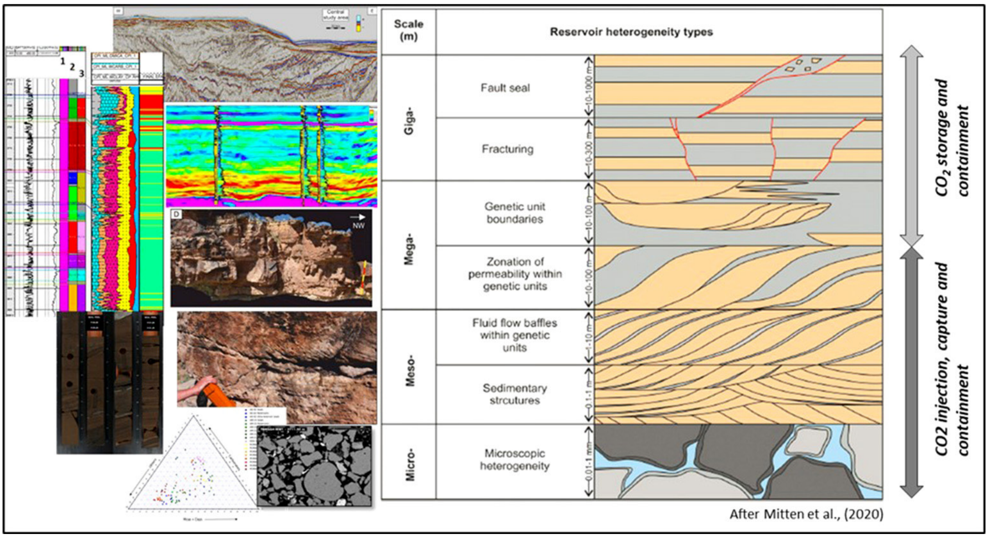

Fig. 22. – "Scale factor" in subsurface characterization. Different data are used at different scales.

The study area must be larger than the extent of the sites used for injection purposes to allow an adequate geologic evaluation. The geological characteristics of the basin should drive the selection of the area to be investigated for both the storage complex and the overburden, and a comprehensive G&G dataset is required (fig. 22).

The result of the integrated studies is the correct definition of the storage complex and the overburden, in terms of geometries and petrophysical parameters within a 3D "geological shared model" (fig. 23). This model is the basis for any subsequent dynamic modelling. Depleted reservoirs are less prone to geological uncertainties than saline aquifers, but the fact that the reservoir is "known" should not preclude the importance of reviewing data and updating models, within and outside the reservoir.

8˙7. *Modelling.* – Similar to oil & gas exploitation, fluid-dynamics modelling is the reference study for the evolution of the CO_2 plume. Efficiently and accurately solving the equations governing fluid flow in subsurface reservoirs is very challenging because of the complex geological environment and the properties of fluids (especially CO_2) at high pressure. Complex multiphase and multicomponent systems should be modelled to describe miscible gas injection processes during CO_2 sequestration.

With respect to confinement, geomechanical modelling is of paramount importance. It determines if and how the pressure changes in the reservoir during injection may affect the integrity of the caprock or ground level movements (*i.e.* subsidence, swelling). The results of fluid-dynamic modeling in terms of pressure variations are the inputs for the geomechanical modelling, although sometimes a coupled approach is used to understand the changes in effective stress dynamics with the decrease in reservoir pressure due to

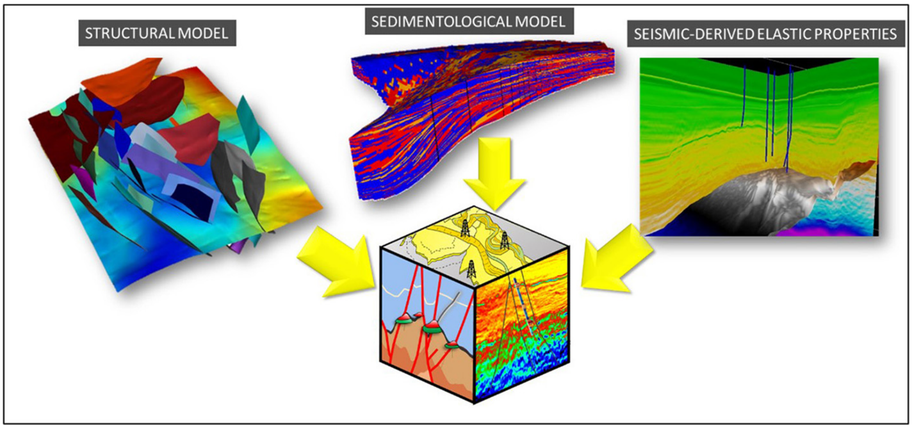

Fig. 23. – A "shared model" approach to integrated G&G studies. All results from each discipline are combined into a single 3D geological model, that can be used as input for all further modelling.

injection. Geomechanical modelling also provides an indication about the stability of faults around the reservoir, which is an important information when to evaluate induced seismicity.

As CO_2 is not inert at reservoir pressure and reacts with brines and rocks, reactive transport modelling (RTM) is very important in CCS projects. RTM in porous media refers to the creation of models that link chemical reactions with transport of fluids in the reservoir. Such models predict the of the spatial and temporal distribution of chemical reactions that occur along a flow path.

9. – CCUS in Eni

Eni is committed to the implementation of CCUS because:

- It is a mature and scalable technology that is considered the only viable option for energy-intensive industries.
- When combined with other measures, CCUS is a cost-effective way to rapidly reduce greenhouse gas emissions.
- It is an enabling technology for the future elimination of carbon dioxide.
- It promotes the development of a blue economy and, through utilization, a circular economy of CO_2.
- It enables synergies with existing facilities with minimal footprint, boosting local economies, employment levels and creating long-term value.

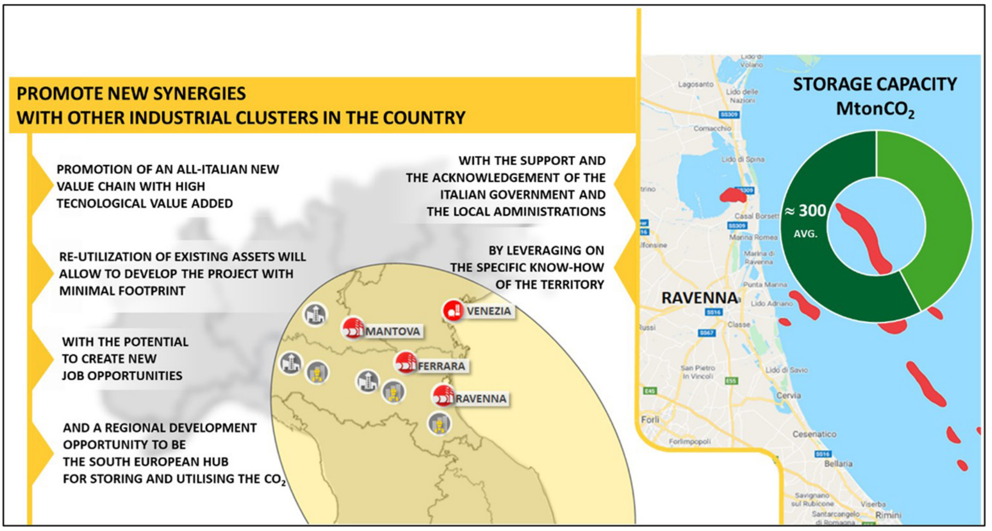

Fig. 24. – Adriatic Blue CCS project. The aim is to de-carbonize Italian industrial districts by means of CO_2 injection in offshore depleted gas reservoirs. Existing facilities (pipelines, platforms) will be re-purposed.

"Without CCUS as part of the solution, reaching our climate goals is practically impossible. We simply cannot afford another decade of muted progress". IEA, Fatih Birol - November 2018.

Eni has several ongoing projects in the world of CCS (Carbon Capture and Storage) and CCU (Carbon Capture and Utilisation) technology.

Eni is optimizing every stage of the process, from transport to fluid-rock interaction and field monitoring systems, to make the technology more efficient and facilitate its large-scale application. On the operational side, Eni plans to build one of the world's largest CO_2 storage hubs —the first in the Mediterranean— off the coast of Ravenna. The conversion of depleted gas fields in the Adriatic Sea into exclusive permanent CO_2 storage sites and the reuse of a small part of the existing infrastructure will provide a quick and concrete solution for reducing emissions in the Italian industrial sector at very competitive prices. CCS is in particular the only readily available option for so-called hard-to-abate sectors such as cement, steel, chemical plants, etc., where a significant share of carbon dioxide emissions is linked to the industrial process and therefore cannot be avoided by *e.g.*, electrification or renewables. Internationally, Eni is also a partner in HyNet North West in the United Kingdom, in the Liverpool Bay area on the north-west coast of the country. Outside Europe, we are also assessing the feasibility of a CO_2 capture project in the United Arab Emirates at Ghasha and investigating a CCS application in Libya, for the Bahr Essalam project. in addition, Eni is exploring opportunities to develop CCS projects in Australia and East Timor.

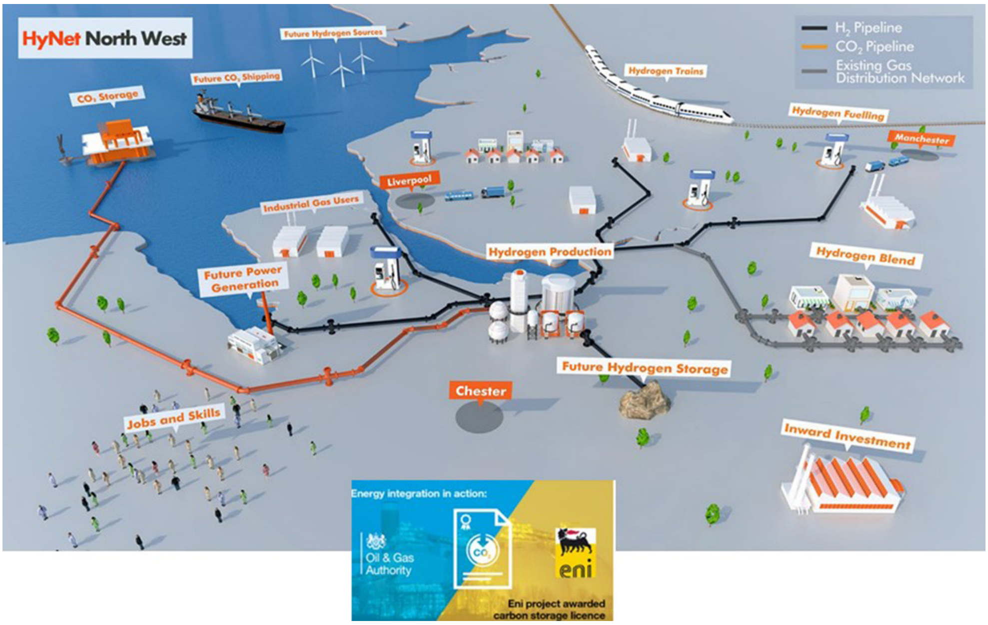

Fig. 25. – Overview of the HyNet project (Eni operator): decarbonisation of refineries, fertiliser and cement plants, H_2 production with Autothermal Reforming (ATR) in Northern Wales. Storage licence awarded in October 2020. Planned start-up: 2025.

The presence of depleted gas fields and decommissioned plants at the Ravenna offshore site provides Eni with a unique opportunity to create a large hub for the storage of CO_2 generated by onshore production (fig. 24). The Ravenna project is not only aimed at reducing Eni's emissions. By combining our extensive knowledge of reservoir dynamics with new technologies, we aim to create the leading centre for carbon dioxide capture and storage for Italy and the Mediterranean in the Middle Adriatic. Above all, we aim to provide a concrete solution for all of Italy's strategic industrial sectors, such as cement, steel, paper and chemicals, which account for about 20% of Italy's emissions and for which there are currently no viable technological alternatives that could be rapidly implemented. Part of the expected initial 4 Mtpa of the project will be reserved for these industrial sectors, which, may then be rapidly increased, to over 10 Mtpa of CO_2 in the following years, thanks to the availability of large storage capacities (500 Mt).

Regarding activities in the UK, in October 2020 Eni received a licence from the UK Oil and Gas Authority for the HyNet North West project, which aims to build a storage hub in Liverpool Bay. This project also involves the reuse of Eni's depleted offshore fields, with Eni taking operational responsibility for CO_2 storage and transport activities, to reduce emissions generated by the region's major industrial centre, where a large 4 Mtpa hydrogen production plant will also be built. The project is scheduled to start in 2025, with the possibility of expanding the capture capacity to

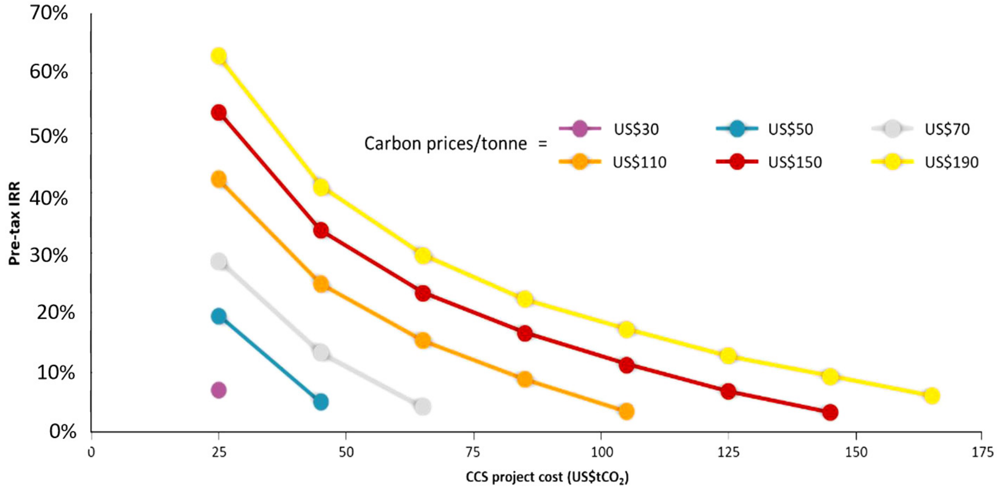

Fig. 26. – CCS project costs *vs.* pre-tax-Internal Rate of Return. The current carbon price ($<$ 30 \$/ton) hinders the economic viability of any CCS project [1].

10 Mtpa by 2030. The business plan was submitted to the UK authorities on July 9, 2021 and, in October 2021 Eni UK, on behalf of the HyNet Consortium Cluster, was able to announce that its application to the Cluster Sequencing process had been accepted as a Track 1 project. This will enable Eni UK and its supporting Hynet companies to become one of the first UK industry clusters to apply carbon capture and storage (CCS), to significantly reduce carbon emissions in the UK. Meanwhile, several Memoranda of Understanding have already been signed with companies interested in capturing, transporting and storing their emissions in Eni UK's depleted fields. The agreements signed so far cover the hard-to-abate sectors and will play a critical role in decarbonising the industrial area in Northwest England and North Wales (fig. 25).

10. – Remarks on the economic viability of CCS

No CO_2 storage project is currently economically viable. Governmental incentives are essential to drive existing and planned CCS project. The CO_2 price is far below the break-even point, regardless of the project type or the amount of CO_2 injected. The carbon price needs to be at least \$ 50/ton for most stand-alone CCS projects to be economically feasible. The average global carbon price is currently around 23 \$/ton. At a carbon price of \$ 190/ton, even a CCS project costing \$ 150/ton can generate a 10% return on investment (fig. 26).

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