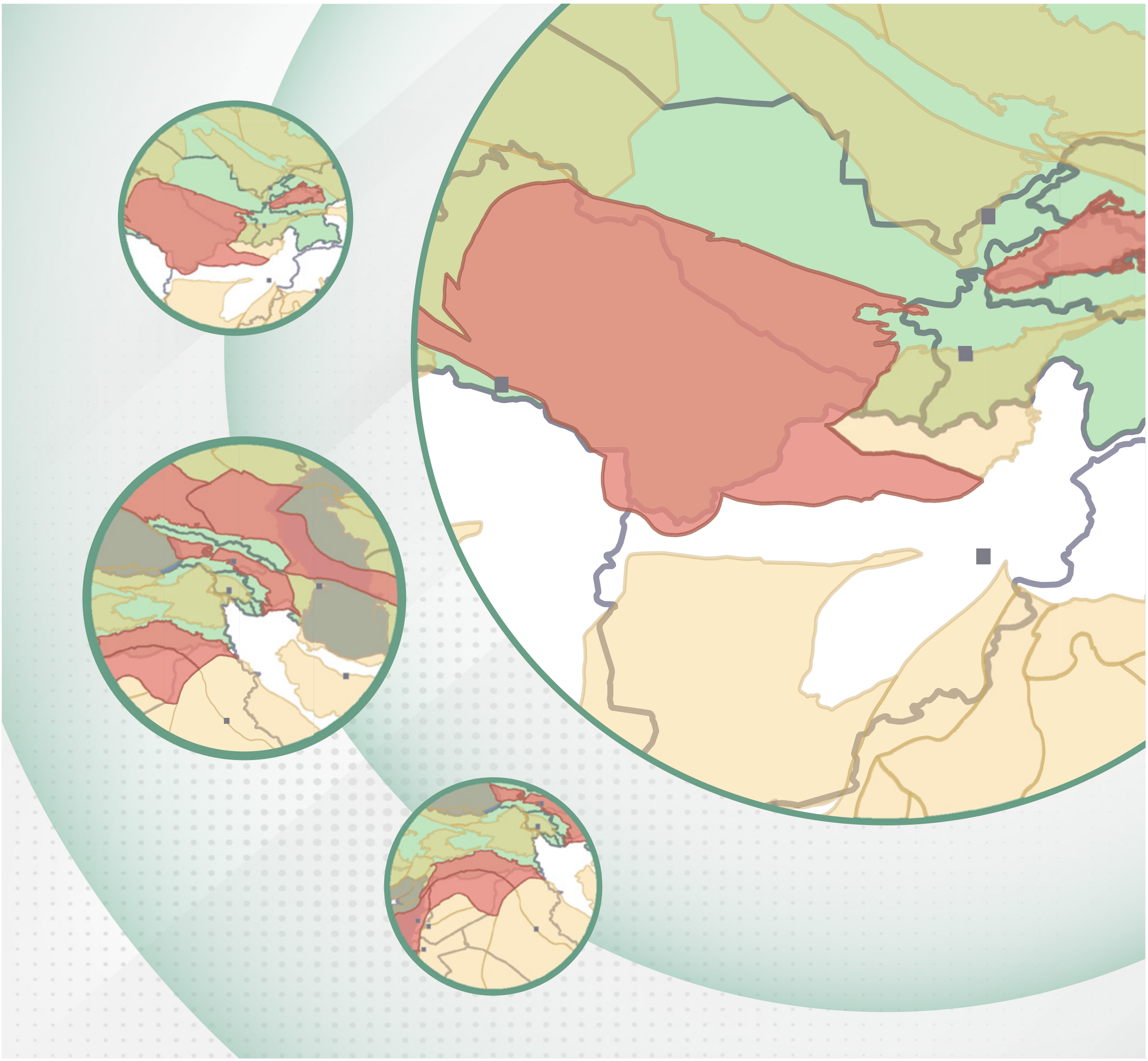
UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE

# Geologic $CO_2$ storage in Eastern Europe, Caucasus and Central Asia

## An initial analysis of potential and policy



UNECE

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# Geologic $CO_2$ storage in Eastern Europe, Caucasus and Central Asia: An initial analysis of potential and policy

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The report is dedicated to the leadership and memory of late Barry Worthington, Chair of the Group on Experts on Cleaner Electricity Systems.

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# Abbreviations and Acronyms

| | |
|---|---|
| **AMC** | advanced market commitment |
| **$CO_2$** | carbon dioxide |
| **CCUS** | carbon dioxide capture, utilization and storage (geological) |
| **CDM** | clean development mechanism |
| **CER** | certifiable emissions reduction |
| **CSU** | carbon storage unit (or sequestration) |
| **EOR** | enhanced oil recovery (using CO2) |
| **ETS** | emissions trading scheme |
| **EU** | European Union |
| **GCCUSI** | Global CCUS Institute |
| **Gt** | gigatonne |
| **IEA** | International Energy Agency |
| **IEAGHG** | International Energy Agency Greenhouse Gas R&D Programme |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **ITMO** | internationally transferable mitigation outcome |
| **LPG** | liquefied petroleum gas |
| **MRV** | measurement, reporting and verification |
| **Mt** | million tonnes |
| **NDC** | nationally determined contribution |
| **RBCF** | results-based climate finance |
| **SDM** | sustainable development mechanism (under Article 6.4 of the Paris Agreement) |
| **SRL** | storage readiness level |
| **t** | tonne |
| **TSAR** | technically available storage capacity |
| **UNFCCC** | United Nations Framework Convention on Climate Change |
| **USDOE** | United States Department of Energy |

# Executive Summary

In order to avoid the dangerous impacts of climate change, the United Nations Economic Commission for Europe (UNECE) is exploring opportunities to achieve carbon neutrality in the region that comprises the countries of South-Eastern Europe, Eastern Europe, the Caucasus, Central Asia, Russian Federation and Turkey. Getting to 'net-zero emissions' in UNECE region would require eliminating 90 gigatonnes (Gt) of $CO_2$ within the next 30 years. Carbon capture, utilization and storage (CCUS) is an essential technology in this quest.

As the name suggests, CCUS is actually a technology chain. The possibility to capture new $CO_2$ emissions at the source or extract latent ones from the air and send them into underground, for indefinite storage enables net-zero or net-negative emissions. Achieving this potential depends, first and foremost, on the availability of suitable storage sites – a geological characteristic found only in some locations. A second criteria is the ability to transport the 'supply' of captured $CO_2$ to such formations. The technical aspects of this process are at various stages of development, with transport and storage mechanisms being proven and mature, particularly in the oil and gas industry. A range of capture technologies are being developed for diverse, high-emission industries. Integration across the chain is less well-developed.

However, a multifaceted challenge hampers CCUS deployment in the region. At present, relatively little is known about the location, suitability and actual size of potential storage sites – and thus of their usefulness in relation to $CO_2$ sources. While there are clear social and environmental benefits to reducing $CO_2$ emissions, doing so carries high costs. The emerging possibility to transform depleted oil reservoirs into storage sites can, under the right conditions, deliver economic returns to oil producers. In fact, the process of using $CO_2$ to boost production (known as enhanced oil recovery or EOR) is the only well-developed 'utilization' process and could eventually decarbonize fossil fuels. To date, however, there is no business case to develop the second major storage option – saline aquifers.

These challenges bring to the fore the economic and political factors that countries and regions must consider when assessing the potential for CCUS in their climate mitigation strategies. In the region, such assessment is currently hampered by gaps in information and political commitment.

Based on the limited data and information available, this analysis finds a storage potential in oil reservoirs in the region of 62,000 million tonnes (Mt) of $CO_2$, with 56,410 $MtCO_2$ being located in Russia. The total storage capacity that is 'matched' to $CO_2$ sources is lower at 13,000 $MtCO_2$ but $CO_2$ storage capacity may increase with additional supply of $CO_2$ that needs to be stored.

Given the scale of the emissions reduction target, more work is urgently needed to understand the contributions that CCUS – along with other low-, zero-, or negative-carbon technologies – can make in the climate debate and in policy parity with other carbon-neutral electricity generation technologies (such as nuclear energy or renewable energy). The long-term aim of the project "Enhancing Understanding of the Implications and Opportunities of Moving to Carbon Neutrality in the UNECE Region across the Power and Energy-intensive Industries by 2050" is to develop a collective ability to contribute to climate change mitigation and sustainable development by transforming economies and society towards net-zero $CO_2$ emissions. Providing a clear vision of how UNECE Member States can achieve carbon neutrality and what measures they should undertake will serve as the short-term impact. The project provides the opportunity for countries to assess options to achieve set targets.

This study seeks to provide countries with tools and methodologies to carry out assessment of CCUS potential and describes policy tools that can support its development and deployment, including by stimulating private sector investment.

An important element of the policy recommendations is the proposal to shift the focus of incentive schemes from the capture stage to the storage stage by implementing a certificate scheme for CCUS that would effectively enable trade of 'units' of $CO_2$ stored. Governments could use such a mechanism to support technology development and deployment while also creating a market such that 'policy push' would eventually stimulate to 'market pull'. Conceived in line with the architecture, mechanisms and goals of the COP21 Paris Agreement, such a mechanism could also help government achieve their nationally determined contributions to climate change mitigation.

# 1. Introduction

In order to avoid the dangerous impacts of climate change, the United Nations Economic Commission for Europe (UNECE) is exploring opportunities to achieve carbon neutrality in the region that comprises the countries of South-Eastern Europe, Eastern Europe, the Caucasus, Central Asia, Russian Federation and Turkey.[1]

Getting to net-zero emissions would require eliminating 90 gigatonnes (Gt) of $CO_2$ emissions within the next 30 years. This implies pursuing two paths: i) eliminating all sources of $CO_2$ emissions, an enormously difficult and expensive goal; and ii) actively removing $CO_2$ from the atmosphere to balance out emissions that are hard to abate. Carbon capture utilization and storage (CCUS) is a technology that is essential to both paths: it reduces $CO_2$ emissions at the source or from the air and it enables net-zero or net-negative emissions.

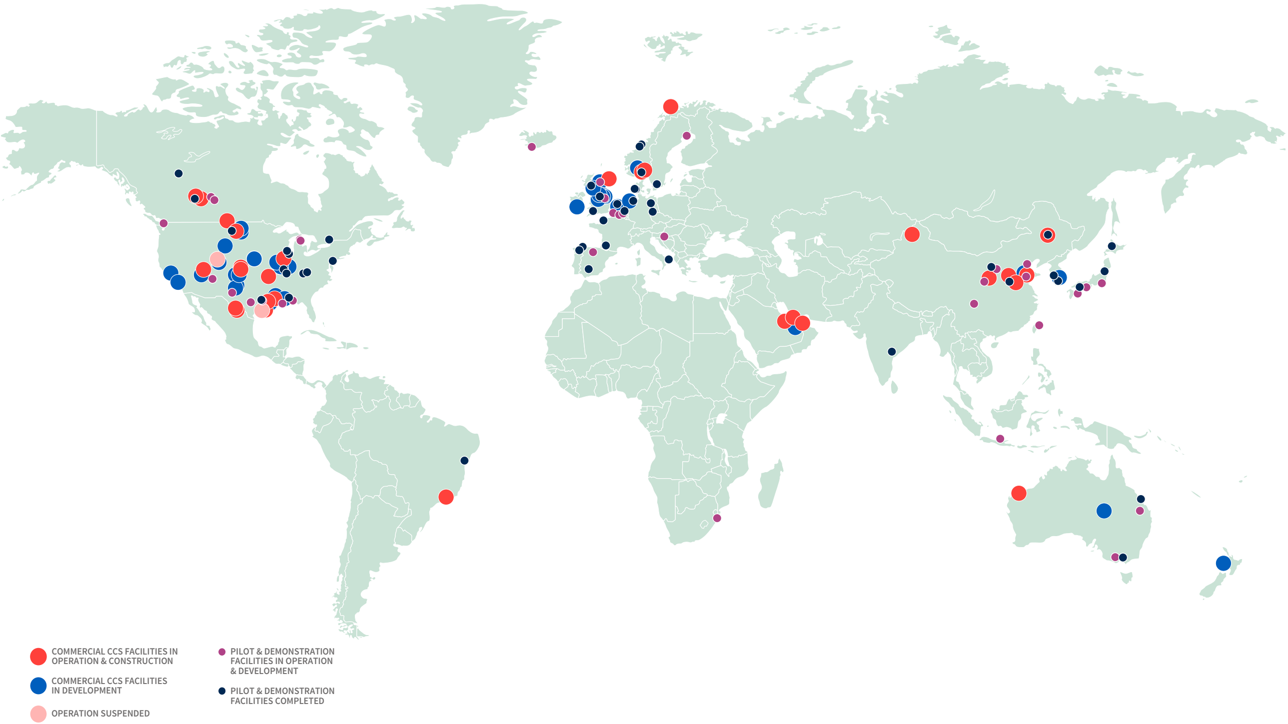
Most modelling exercises that comply with aims of the COP21 Paris Agreement emissions reduction targets show trajectories with significant gross emissions even after the point of achieving net-zero on the global scale (IPCC, 2018). This reflects the reality that fossil fuels are likely to remain an important energy vector in some industries. To constrain additional increases in mean global temperatures in the second half of this century it will be necessary to continually offset emissions from these sources through corresponding enhancements in 'carbon sinks' (G20, 2020).

Two primary options increase the volume of available carbon sinks. Reforestation or afforestation strategies focus on boosting the absorptive capacity of forests. Deployment of CCUS technologies show strong potential to rapidly remove large volumes of $CO_2$ and to keep it securely stored over long periods of time, something that is difficult to achieve with biological sinks.

At present, CCUS is not on track to fulfil its projected role in climate change mitigation. Worldwide, 19 operating CCUS facilities are injecting and permanently storing about 40 million tonnes (Mt) of $CO_2$ annually (Figure 1) (GCSSI, 2019). Massive scale up is needed to achieve the level outlined in the IEA's SDS scenario, which projects thousands of CCUS sites injecting and storing 1.5 gigatonnes (Gt) per annum.

Most of the CCUS projects operating serve a specific purpose within the oil industry: enhanced oil recovery (EOR) is a process in which $CO_2$ is injected into depleting oil

**Figure 1** **Overview of operating CCUS projects**



***Source**: Global CCS Institute, 2020*

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[1] Focus countries for this report include Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Montenegro, Northern Macedonia, the Russian Federation, Serbia, Tajikistan, Turkey, Turkmenistan, Ukraine and Uzbekistan.

reservoirs to support additional oil production by displacing in situ oil. The opportunity to recover additional oil can offset the costs associated with injecting $CO_2$. When the reservoir is depleted, virtually all of the injected $CO_2$ remains trapped (stored).

Apart from enhanced oil recovery (EOR), CCUS currently has no other purpose than that of reducing $CO_2$ emissions: in effect, the ‘utilization’ element is not yet well developed. With no business case to stimulate CCUS, virtually all other existing projects currently depend heavily on direct or indirect governmental support in the form of grants or financial support for operations, or provision of debt or equity capital.

Despite its importance for mitigating climate change, current climate policies fall short of supporting CCUS in a meaningful way. In Europe, CCUS has been included among mitigation options covered by the EU Emissions Trading Scheme (EU ETS) since 2012. Yet the scheme has failed to deliver a single CCUS project. In reality, carbon prices under the EU ETS have been well below the level needed to make the investment case for CCUS. Rather than encouraging the long-term strategic investment needed for CCUS, the EU ETS appears to have triggered investments in low-cost abatement action (Marcantonini et al. 2017, Taschini, 2020).

# 2. Considerations for Carbon Capture, Utilization and Storage (CCUS)

CCUS can serve two purposes: preventing new $CO_2$ emissions from entering the atmosphere or removing past emissions. It is important to understand CCUS is not a single technology but rather a technology chain consisting of three parts, namely:

- **Capture** refers to technologies that use a variety of chemical and physical methods to secure $CO_2$ at the point of emissions – such as fossil-fueled power plants and industrial facilities. It may also involve directly removing $CO_2$ from the air. Captured $CO_2$ can then be transported to a location where it can be used or stored for the long term.
- **Utilization** implies that $CO_2$ captured can be directed towards another end-use, an area of substantial research at present with creating new materials being one example. EOR is currently the predominant use of captured $CO_2$. Other options only store $CO_2$ temporarily or have a small potential market share of less than a few millions tonnes per year (IEA, 2019)
- **Storage** refers to mechanisms to ensure long-term containment (i.e. over thousands of years) of $CO_2$ in subsurface rock formations. This is the point at which $CO_2$ is indefinitely removed from the atmosphere.

It thus follows that deployment of CCUS depends on three elements: a supply of $CO_2$ for capture; an infrastructure system to support transport of $CO_2$; and availability of geological sites suitable for long-term storage.

As the benefits of CCUS (neglecting for the moment its utilization as part of EOR) are exclusively related to the control of $CO_2$ emissions, CCUS deployment requires a policy framework that values its climate benefits to attract investments in the technology.

## 2.1 What is geological storage of $CO_2$?

Geological storage involves injecting $CO_2$ into rock formations than can absorb and contain it for thousands of years. Rocks well suited to this are found in sedimentary basins – i.e. areas of subsidence in the Earth crust in which sediments have accumulated over geological time periods. Typically, these basins extend for thousands of kilometers. In basins, deep saline aquifers, depleted oil and gas fields, and unmineable coal seams have been found suitable for $CO_2$ storage. More recently, the possibility of storing $CO_2$ in basalt has been proposed. The first two options (aquifers and oil reservoirs) involve storing $CO_2$ in the pore space of subsurface rocks. In coal seams, the process of adsorption causes injected $CO_2$ to become firmly bound on the coal matrix. Carbon mineralization (i.e. a chemical reaction) is the storage mechanism in basalt. Because of the variability of the Earth's geology, the potential for geological storage will not be globally applicable to all countries (Cook, 2012).

Four options exist for storing $CO_2$ in geological formations: saline aquifers, oil reservoirs, coal seams and basalt formations. This report focuses on two of the four options, namely those that involve storage in subsurface pore space: saline aquifers and oil reservoirs.

## 2.2 Options for geological storage

### Deep saline aquifers

A saline aquifer is an underground structure formed of permeable rock containing salt water (brine). To be considered suitable for $CO_2$ storage, a given aquifer must meet three basic requirements:

- **Sufficient porosity, permeability and thickness.** Porosity and permeability ensure the rock will absorb the $CO_2$; significant thickness, along with lateral extension of the aquifer, is critical to containing a substantial volume. These features enable high rates of $CO_2$ injection without pressure build up.
- **Adequate depth.** Ideally, the aquifer should have a minimum depth of ~800 m. While $CO_2$ is a gas at surface, at depth it transforms into liquid-like state with high mass density, which is advantageous for storage.
- **An impermeable barrier rock (caprock or seal).** A barrier rock must overlay the aquifer to prevent vertical migration of $CO_2$, which has a buoyancy at depth, to the surface where it can escape into the air.

Worldwide, saline aquifers may provide the largest $CO_2$ storage capacity. Thibeau and Mucha (2018) provide an extensive review of national and global capacity estimates for saline aquifer storage and review current estimation methods.

To date, no economic rationale has been found to support the systematic study of the storage capacity of aquifers.

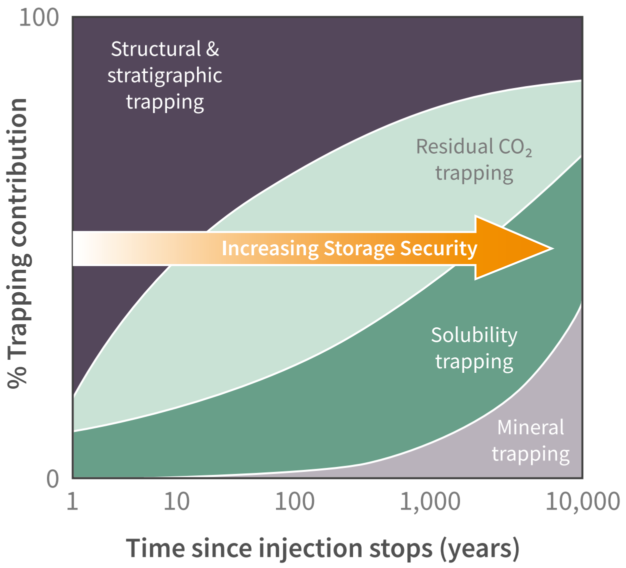
## Box 1 $CO_2$ trapping procedures in saline aquifers

Generally, four methods can be used to trap (immobilize) $CO_2$ in a rock formation and prevent leakage.

- **Stratigraphic and structural trapping** is a physical process that relies on an appropriate geological setting. The nature of rock formations and the process of injecting $CO_2$ may lead to pressure constraints that create the need for water management. Injecting $CO_2$ into the storage rock requires applying pressure in excess of the pressure of the water present in the rock. After injection, $CO_2$ rises through the storage formation until it becomes trapped by the seal. Thus, during injection, care must be taken to ensure the injection pressure does not surpass the fracture strength of the rock comprising the seal. A fractured seal carries the risk of allowing $CO_2$ to leak out to the surface, compromising the integrity of the storage.
- **Residual trapping** occurs when the pore spaces in the rock are so narrow that capillary effects can resist the buoyancy-driven upward migration of the $CO_2$.
- **Solubility trapping** occurs when $CO_2$ dissolves into water in the storage formation. The $CO_2$-rich water becomes more dense (relative to unaffected water) causing it to migrate downward to the bottom of the reservoir.
- **Mineral trapping** is triggered by a chemical reaction between minerals forming the rocks and the injected $CO_2$. For example, calcium or magnesium silicates, for example, react with $CO_2$ to form stable calcium or magnesium carbonates. These reactions occur slowly, over thousands of years.

The relative importance of these trapping mechanism is site-specific; moreover, they do not operate simultaneously but rather are sequential over long periods. Thus, physical trapping dominates during the injection phase, eventually leading to mineral trapping through chemical mechanisms. This creates a combined effect through which the various trapping mechanisms tend to increase the fraction of $CO_2$ immobilized (Figure 2).

**Figure 2** Relative contribution of trapping mechanisms



***Source***: *IPCC (2005)*

### Depleted oil and gas fields

As noted, EOR is a commonly used process by which $CO_2$ is injected into depleted oil fields as part of operations to extract oil that would be otherwise unproducible. At the end of a field's lifespan, virtually all of the $CO_2$ injected remains trapped in the reservoir.

Several factors make depleted oil and gas reservoirs good candidates for $CO_2$ storage. First, the presence of effective seals is what has allowed oil and gas to accumulate over geological time periods. Second, as the porosity and permeability of their formations have been sufficient to produce fluids, they will support $CO_2$ injection. A third point is that detailed knowledge of the geological structure and physical properties of these reservoirs is built up during exploration and production; ergo, there is less risk that injected $CO_2$ will behave in unexpected ways.

Perhaps most importantly, injection of $CO_2$ in depleted oil fields offers a commercial benefit: in fact, it is already common practice in some areas (e.g. the United States) to inject $CO_2$ for the sole to support extraction of otherwise unproducible oil – referred to as enhanced oil recovery (EOR).

However, not every oil field is amenable to EOR. Oil and reservoir properties must satisfy certain conditions ('screening criteria') to qualify.

### Storage in basalts

Having high porosity and permeability, basalt is highly reactivity with $CO_2$ such that it ultimately leads to the formation of solid carbonate minerals (calcite, dolomite, etc.). These features make basalt attractive for in situ $CO_2$ storage, which is currently in the research phase. Specifically, studies are being done to assess reactive $CO_2$ flow in basalt, how permeability can be maintained as mineralization progresses and the kinetics of mineralisation reactions (Kelemen et al. 2019). Basalt formations are found in many regions around the world and are particularly abundant in the north-west of the United States and in India. They warrant consideration as a storage option particularly in areas with no suitable sedimentary basis (Cook, 2012).

### Storage in coal

Coal deposits occur in many sedimentary basins. As a rule, coal seams are mined only to a depth of ~1,500 m. In principle, deeper lying coal seams could be suitable as underground $CO_2$ reservoirs. The storage mechanism of $CO_2$ in coal seams differs from that in aquifers or basalt formations. Once injected, adsorption causes the $CO_2$ to bond firmly to surfaces of the coal matrix.

As with EOR in oil fields, there may be an economic incentive in this case. Very often coal seams contain coal bed methane that is bound by sorption onto the coal matrix. As $CO_2$ is absorbed onto the coal matrix, the originally bound methane is desorbed and released, and can be extracted by production wells. The process is known as '$CO_2$ Enhanced Coal Bed Methane Recovery' and is used in the San Juan Basin in the United States.

A crucial criterion for the feasibility of this storage option relates to the permeability of the coal seams, which determines if the injected $CO_2$ can reach large parts of the coal matrix. Coal that is too deep to be mined is often strongly compacted and has too little permeability to support effective $CO_2$ injection. In addition, many coal seams swell when injected with $CO_2$, which significantly lowers permeability. Overall, the storage of $CO_2$ in deep, low-permeability coal seams still poses unsolved geoengineering challenges (Cook, 2012; Ranatunga, 2017).

Of the four storage options described above, this report considers only deep aquifers and oil reservoirs, reflecting their widespread distribution and significant storage potential.

## 2.3 $CO_2$ supply

The potential to store $CO_2$ depends on availability of supply – i.e. the capture and transport elements of the chain under investigation. Provided appropriate carbon capture technology is installed to produce a concentrated stream of $CO_2$ at high pressure, suitable emission sources include power generation from coal or gas as well as production of iron and steel, cement, fertilizer and ethanol, and the processing of natural gas.

## 2.4 Geographical distribution of storage and supply

An overarching challenge in CCUS is that existing sources of $CO_2$ are very often not sited in the vicinity of storage sites. To address this issue, substantial effort has gone in to mapping the geographical distributions of emission sources and storage formations.

In the European Union (EU), projects to quantitively assess regional or national $CO_2$ storage capacity have been ongoing since the early 1990s. The GeoCapacity project, funded by the European Commission, conducted a pan-European assessment that aimed to develop a European Geo-Information System (GIS) for the location of both emission sources and storage sites. Completed in 2008, it provided storage assessments for, inter alia: Albania, Bosnia-Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, North Macedonia, Poland, Romania, Slovakia and Slovenia. Including storage locations in Eastern Europe, which were new EU member states at the time, was an important aspect.

Results of the GeoCapacity projected were included in a second EU project, $CO_2$SToP. The main goal of $CO_2$SToP (completed in 2014) was to compile a European-wide dataset of geological parameters and store it in a public database, thus making it possible to estimate $CO_2$ storage capacities centrally using a common methodology.

Detailed storage atlases have been developed for other regions and countries currently hosting CCUS projects, including North America, Norway and Australia. The Norwegian North Sea Storage Atlas, developed and published by the Norwegian Petroleum Directorate, considers all relevant geological formations in the study area. It includes extensive seismic and drilling data, which could be used due to free access to the exploration and production data. The $CO_2$ Storage Atlas of the United States and Canada covers almost all of the North American continent. Due to the size of the area studied, it has been divided into seven regions. A 'carbon sequestration partnership' evaluated capacity for each region. In the US studies, a uniform assessment methodology was applied in each region.

Additional storage projects and atlases include the Queensland $CO_2$ Geological Storage Atlas, the Regional Assessment of the Potential for $CO_2$ Storage in the Indian Subcontinent, the Potential and Suitability Evaluation of $CO_2$ Geological Storage in Major Sedimentary Basins of China and the demonstration project in the Ordos basin.

It must be stressed that national storage assessments, even when they are available, may differ in their underlying assumptions and cannot be compared or aggregated to provide regional estimates of $CO_2$ storage (IEA, 2013; Kearns et al., 2016). There is a strong need for a common procedure to "allow for a transparent and robust assessment of geological $CO_2$ storage, throughout the world, across geologic settings, regardless of the amount of geological data" (IEA, 2013).

Given the distances often found between supply and storage sites, establishing an infrastructure to transport $CO_2$ is key component for successful implementation of CCUS.

## 2.5 Transport and infrastructure for CCUS

At present, steel pipelines are the most common means to transport large quantities of gas safely and cost-effectively over long distances. Pipeline transport of natural gas and oil is a mature technology used worldwide with several million pipelines operating globally. A main advantage is that pipelines allow continuous transport without needing additional intermediate storage.

Since the 1970s, starting in the United States, more than 6,000 km pipelines for $CO_2$ transport have been constructed and operated. To use pipeline capacities in a cost-effective manner, $CO_2$ is compressed into a supercritical state, giving it the density of a liquid but the viscosity of gas, which eases flow through the pipelines. Pipeline pressure is determined by hydraulics and repressurization stations may be needed to maintain the supercritical state of the $CO_2$, with obvious implications on pipeline cost (Mallon et al., 2013).

Corrosion of steel by carbonic acid is an additional design issue related to pipeline transport of $CO_2$. Captured $CO_2$ contains small percentage of water, which may react and form corrosive carbonic acid. The reaction could be controlled by drying the separated $CO_2$ to reduce the water content or by constructing pipelines using non-corrosive materials such as stainless steel. As the cost of each option varies with routing and the quantity of transported $CO_2$, the question of which is economically reasonable must be decided for each project.

A second option is to transport $CO_2$ via dedicated ships, as the properties of liquefied $CO_2$ are similar to liquified petroleum gas (LPG). Shipping of small volumes of $CO_2$ (<1,500 cubic meters) is currently practiced in the industry; the technology could be scaled up to larger carriers, making options to transport larger volumes likely in the future (Santos, 2012).

To select the appropriate means of transport and build up infrastructure, stakeholders must consider the quantities of $CO_2$ and the distances to be covered between capture and storage sites $CO_2$.

To minimize investment risk in the early stages of CCUS development, $CO_2$ transport infrastructure is likely to be developed as 'point-to-point' links between a single emission source and a particular storage site. Over time, such bilateral links could be superseded by infrastructure clusters, in which emissions from several $CO_2$ sources are combined and collectively transported by pipeline to a common storage site. Spreading the transport cost over several emitters would achieve economies of scale, thereby bringing the cost to each below what a standalone project would entail for a single source.

Given the above considerations of available storage sites, available $CO_2$ supply and the need for infrastructure and transportation to link them, planning for $CO_2$ *clusters* is an efficient and cost-efficient approach. In addition to facilitating aggregation of variable demand across diverse storage projects while also supporting stable supply, the ability to share infrastructure can reduce overall costs for all stakeholders.

# 3. Assessment of $CO_2$ Storage Potential

The starting point for determining geological storage potential in a given country is to identify the location and features of sedimentary basins. In a next step, the suitability of basins for storage should be assessed from qualitative and quantitative perspectives. The first implies investigating their 'storage prospectivity'; the second aims to estimate the volume of $CO_2$ a given formation can store.

At present, available and revelent geological information varies widely. However, for all types of storage on a global scale, incomplete knowledge and limited access to data pose challenges for robust capacity estimates. As a result, while a good understanding exists of available storage in some OECD countries with high $CO_2$ emissions (including the EU, North America and Australia), a global storage assessment is in its early phase of development.

It is important to note that storage potential – as is the case for other mineral resources – is a depletable natural resource, with its availability decreasing whenever it is used. To aid the evaluation and management of these resources the United Nations Classification for Resources provides a global framework to specify maturity and resource progression for projects. It can be adopted to categorize individual $CO_2$ injection projects according to geological knowledge, technical feasibility and economic viability (UNFC, 2019; see Appendix).

## 3.1 Qualitative assessment of storage

'How well' a given basin can store $CO_2$ is the first question to explore. Since $CO_2$ storage is dependent on the presence of sedimentary basins, carrying out a qualitative characterization of those available is a critical first step. For each basin, this includes collecting information on the size and location, the thickness and type of sediments it comprises and details of its geology. This information helps identify basins most suitable for storage. Next step involves grading basins in terms of their likely suitability for storage (Bachu, 2003). Typically done by a panel of experts, this is a qualitative exercise delivering a ranking of basins in terms of their perceived storage 'prospectivity'.

## 3.2 Quantitative assessment of storage

'How much' is the second crucial question of storage potential. Key determining factors are the volume of the storage formation and the available pore space. In addition, temperature and pressure at storage depth are estimated, as they determine the amount of $CO_2$ stored per unit volume of porous rock. At depth, low temperatures are preferred over warm as $CO_2$ can attain higher mass density, allowing for more effective utilization of the available storage space.

During the injection phase and for an extended period thereafter, physical storage mechanisms dominate the trapping of $CO_2$ – to the degree that quantitative storage assessment considers only these processes. Chemical storage mechanisms, which tend to immobilize $CO_2$ only over longer period of time, are typically disregarded in storage capacity assessments.

## 3.3 Aquifer storage capacity

Storage capacity in aquifers is assessed based on a volumetric estimate, which in one or the other form, is used internationally as

$$G=A\times h\times \varphi\times \rho\times E$$

where G denotes the technically available storage capacity (TASR), A is the areal extent of the region assessed. H denotes the gross thickness of the saline formation; $\phi$ its porosity; and $\rho$ the mass density of $CO_2$ at subsurface pressure and temperature. The symbol E denotes the efficiency of storage, defined as the share of pore volume that can be filled with $CO_2$.

The TASR comprises the pore space that can be reasonably expected to retain $CO_2$ over a long period of time without adverse environmental impact, calculated on the basis of present-day geologic and hydrologic knowledge and engineering practices. In this sense, the TASR represents an 'upper limit'. Factors that could constrain available pore space include:

- Engineering considerations related to the technologies available to access pore space
- Economics and cost
- Socio-political considerations including public acceptance and regulatory limitations

These highlight the difference between the technically available capacity in aquifers and the volume of storage that can actually be used. Taking decisions on what constraints to apply is part of any $CO_2$ storage assessment activity.

## 3.4 Oil reservoir storage capacity

In the case of oil fields, storage potential can be estimated based on available geological and petrophysical data generated and collected because of commercial interests. Here, $CO_2$ storage via EOR is determined by multiple factors acting in combination that, in turn, depend on the geology of the reservoir and, importantly, on the implementation of recovery.

Until recently, EOR was largely viewed as a technology to optimize oil production, with oil companies needing to purchase $CO_2$ for injection. Thus, EOR operators carefully calculate the utilization factor – i.e. the amount of $CO_2$ (in tonnes) used to produce an additional barrel (bbl) of oil – and have an economic interest to achieve a given oil production rate with as little $CO_2$ as possible. EOR is carried out only until the tipping point at which $CO_2$ costs exceed the revenues gained from putting extra oil on the market. Yet virtually all $CO_2$ purchased for injection to support EOR ultimately remains stored in the reservoir.

The potential to shift the practice of EOR to a mechanism than can actually reduce $CO_2$ emissions – in effect 'decarbonizing oil' – has emerged only recently. By changing how EOR projects operate, it is possible to significantly increase the volume of $CO_2$ injected so that emissions linked to the additional oil produced are partly or fully offset. With active operational reservoir and well management significantly higher $CO_2$ utilization factors are possible – and would thus support greater $CO_2$ storage. In the United States, for example, for every barrel of oil currently produced, ~0.3-0.4 tonnes of $CO_2$ ($tCO_2$) are injected and stored while combustion of oil releases 0.4 $tCO_2$ to the atmosphere (McGlade, 2019). The IEA (2015) estimates that operations aiming to co-exploit oil production and storage could see a $CO_2$ utilization of ~0.6 $tCO_2$/bbl , and refers to this EOR scenario as "Advanced EOR+" to distinguish it from "conventional" EOR. The net utilization of $CO_2$ could further increase to up to 0.9 $tCO_2$ when the focus of EOR is on storage. In this case, on a per barrel basis, more $CO_2$ is stored at production than is released upon combustion at the consumer end.

This suggests that EOR may have an important role during the initial phases of CCUS development. As the scope for implementing EOR hinges on narrow geophysical and reservoir engineering constraints, it may not present a storage opportunity in all fields. Nonetheless, as oil revenue from EOR offsets some of the cost associated with $CO_2$ storage, it can provide an economically attractive storage option.

# 4. Assessing CCUS Potential in the Focus Region

Assessing CCUS potential in South-Eastern and Eastern Europe, the Caucasus and Central Asia is particularly challenging due to a scarcity of publicly available geological data. To date, no one has undertaken reasonably detailed evaluations of $CO_2$ storage prospectivity of basins in the region or carried out comprehensive quantitative assessments of storage potential. As closing this gap is beyond the scope of this report, it aims to do two things:

- Identify basins in the region that are 'very suitable' for storage, but without the ambition to provide a full-fledged and detailed storage prospectivity map
- Identify and review existing quantitative assessments for countries for which they are available

A recent IJGGC paper featured the concept of a 'storage readiness level' (SRL) (based on the widely used concept of technology readiness levels), which will support further capacity assessments (Akhurst et al. 2021). While the early work regarding SRLs is not yet published, it should be taken into consideration in future work regarding $CO_2$ storage capacities, particularly to help catalogue the varying levels of detail captured within individual capacity assessments. This will allow for a more standardized approach to analyzing the status of storage assessments internationally.

## 4.1 Qualitative assessment

The following analysis is based on the publicly accessible Robertson Basins and Plays database (2020), which contains information on the location and extent of sedimentary basins worldwide.

Ninety-five basins are identified in the region of interest. Seventeen of these basins are categorized in the database as being well explored with discovered hydrocarbon occurrences. As characteristics of these basins are well known, they are prime targets for $CO_2$ storage. This is relevant for the location of both hydrocarbon reservoirs and aquifers, as when exploring for hydrocarbon, developers often drill 'dry wells', which may indicate the presence of aquifers suitable for storage. Basins identified are listed in Table 1 and shown geographically in Figure 3.

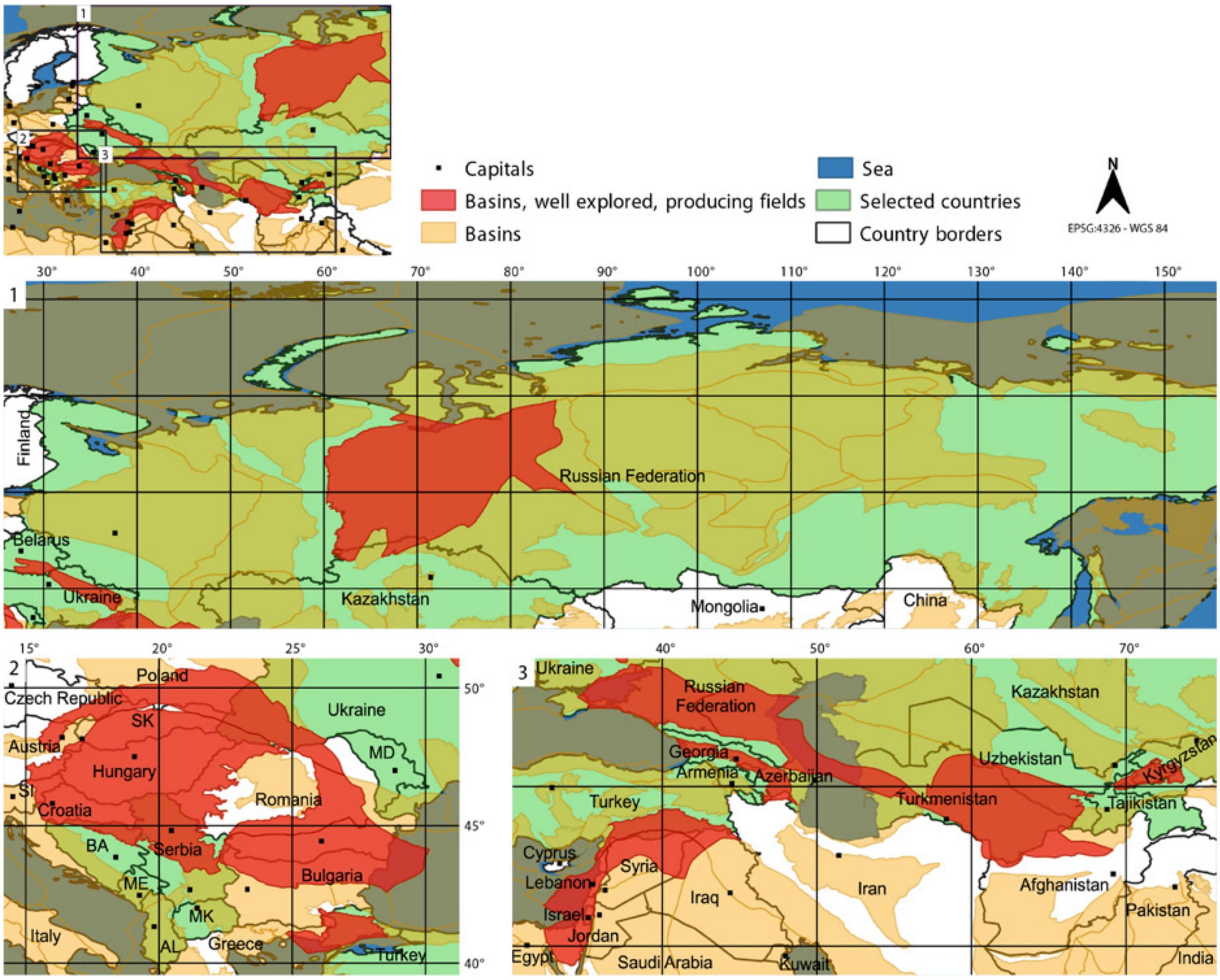
**Table 1** **Basins particularly suitable for storage, ordered according to their extent**

| Relative extent | Basin name | Basin and plays province | Max. sediment thickness (km) | Location |
|---|---|---|---|---|
| 1 | Central Sub-basin - West Siberia | West Siberia Sag | 16 | Onshore & Offshore |
| 2 | Amu-Dar'ya | Turan Platform | 15 | Onshore |
| 3 | Pannonian | Trans-Carpathian Transtensional | 7 | Onshore |
| 4 | North Caucasus | Paracaucasus Retro-arc | 14 | Onshore & Offshore |
| 5 | Indolo-Kuban | Paracaucasus Retro-arc | 11 | Onshore & Offshore |
| 6 | Sinai - Levant | Arabian Passive Margin | 11 | Onshore & Offshore |
| 7 | Moesian Platform | Para-Tournquist Platform | 12 | Onshore & Offshore |
| 8 | Euphrates - Sinjar | Arabian Foreland | 9 | Onshore |
| 9 | Northern Carpathians | Carpathian Foreland | 12 | Onshore |
| 10 | Southeast Turkey Foldbelt | Arabian Foreland | 10 | Onshore & Offshore |
| 11 | Dnieper - Donets | Ukrainian | 20 | Onshore |

|  |  |  |  |  |
|---|---|---|---|---|
| 12 | Kura - Kartli | Transcaucasus Retro-arc | 11 | Onshore |
| 13 | Southern Carpathians | Carpathian Foreland | 9 | Onshore |
| 14 | Fergana | Turan Platform | 10 | Onshore |
| 15 | Pripyat | Ukrainian | 6 | Onshore |
| 16 | Thrace | Aegean Extensional | 9 | Onshore & Offshore |
| 17 | Rioni | Transcaucasus Retro-arc | 8 | Onshore & Offshore |

***Source**: C. Weismüller and W. Heidug*

**Figure 3** Maps of basins in the region of interest; those particularly suited for $CO_2$ storage are in redtent



***Source**: C. Weismüller and W. Heidug*

Criteria used to select basins that show potential are simple but rather stringent. In particular, they imply the exclusion of storage potential in basins with limited exploration and in geological settings without hydrocarbon systems. The storage potential of Kazakhstan is a case in point: it is not recognized in this report because of exploration status of the relevant basin is insufficient (Abouv, 2020). Overall, more detailed studies are needed to provide a complete classification of basins in the countries of interest according to their storage prospectivity.

## 4.2 Quantitative assessment

Producing quantitative assessments for storage potential in the region of interest is a much more challenging task.

For the Eastern Europe, the Caucasus and Central Asia areas, the GeoCapacity project (GeoCapacity, 2009) remains the best source of the most up-to-date storage assessment data publicly available. Additionally, the IEAGHG conducted a review of $CO_2$ storage potential in basins with $CO_2$-EOR potential, which included sites in Kazakhstan, Russia and Turkmenistan (IEAGHG, 2009). A report by Kearns et al. (2017) also sought to develop a consistent database for regional geologic $CO_2$ storage capacity worldwide, which included ‘Other Eurasia’ alongside an assessment of EU countries as a whole. Some of the relevant countries have published national storage assessments, which are summarized in the following section.

## 4.3 Aquifer assessment in countries of interest

As noted in Section 2, saline aquifers may provide the largest $CO_2$ storage capacity worldwide. To date, no regional estimates of saline aquifers are available for the Eastern Europe, Caucasus and Central Asia regions. Limited public availability of quantitative data on aquifer storage potential is a particular challenge in this region. As exploration of the subsurface through seismics and drilling is costly, it is typically not undertaken without economic rationale. As a result, data for storage in saline formation is low compared to that for oil and gas fields. Some countries have carried out national assessments, the findings of which are listed below.

**Albania** reports a conservative, ‘effective $CO_2$ storage’ capacity estimate for aquifers of 20 million tonnes (Mt) (Hatziyannis, 2009). This volume is based on a salt dome in the Dumrea area (south of Elbasan) with a large diapiric body extending to a depth of 5km, with potential to store $CO_2$ in salt caverns. While a specific site has been identified and an initial assessment conducted, an initial storage concept has not yet been fully developed. (Note: A second study assessed Albania’s hydrocarbon fields.)

**Azerbaijan** is part of an extensive petroleum system in the South Caspian basin province, along with Iran and Turkmenistan, suggesting the presence of storage potential in both aquifers and oil fields. At present, no estimates for $CO_2$ storage capacity are publicly available, but SOCAR (the state-owned oil company) has expressed interest in developing CCUS in the region (Hellenic Shipping News, 2019). The USGS published information on the hydrocarbon provinces of the Caspian Sea (Smith-Rouch, 2006) but public information on geology at a basin scale seems to be limited (Alizadeh et al., 2017).

**Bosnia and Herzegovina** estimates 296 Mt of storage capacity in saline aquifers, based on assessment of the Sarajevo-Zenica basin (GeoCapacity, 2009). This should be considered a ‘first-pass’ estimate at basin scale; the geometry of the reservoir is not yet well constrained and more data acquisition is required.

**Kazakhstan** estimates 403 Gt of storage in saline aquifers (Abuov 2020), largely in the carbonate platforms in the pre-salt section of Precaspian basin and in post-salt clastic reservoirs trapped by salt-dome. Details on the assessment methodology are limited, but it appears to be a first-pass assessment.

**North Macedonia** estimates storage capacity of 390 Mt in an aquifer near the town of Kavadarci (GeoCapacity, 2009) and notes a potential maximum capacity of 1,050 Mt. The national geology mainly comprises crystalline rocks, which are not suitable for storage. The assessment is therefore based on an aquifer in Eocene sediments capped by clays, in which water has a salinity of 10,000 parts per million (ppm). Given that a site has been identified, and the structural map and wells assessed to calculate a first-pass capacity assessment, this site is at a low SRL. (Note: No hydrocarbon deposits have been identified in the country.)

**Russia** A report by Shogenova et al. (2011) included NW Russia in aquifer storage capacity estimates but ultimately concluded data were insufficient to estimate capacity for the full country. This report stated that in the European part of Russia, the Middle Cambrian sandstones of the Tiskre Formation are the most prospective aquifer, although many areas of it are too shallow. A depth of >800 m occurs only in the south-east of the Novgorod Region, within the limits of the Moscow Syneclise and at a distance of >200 km from the Eesti Power Plant.

**Serbia** has not published any quantitative capacity estimates but has identified 17 potential localities and reviewed their geology (Komatina-Petrovic, 2007). With eight potential sites identified, the Vadar zone was highlighted as having the most suitable geology for $CO_2$ storage.

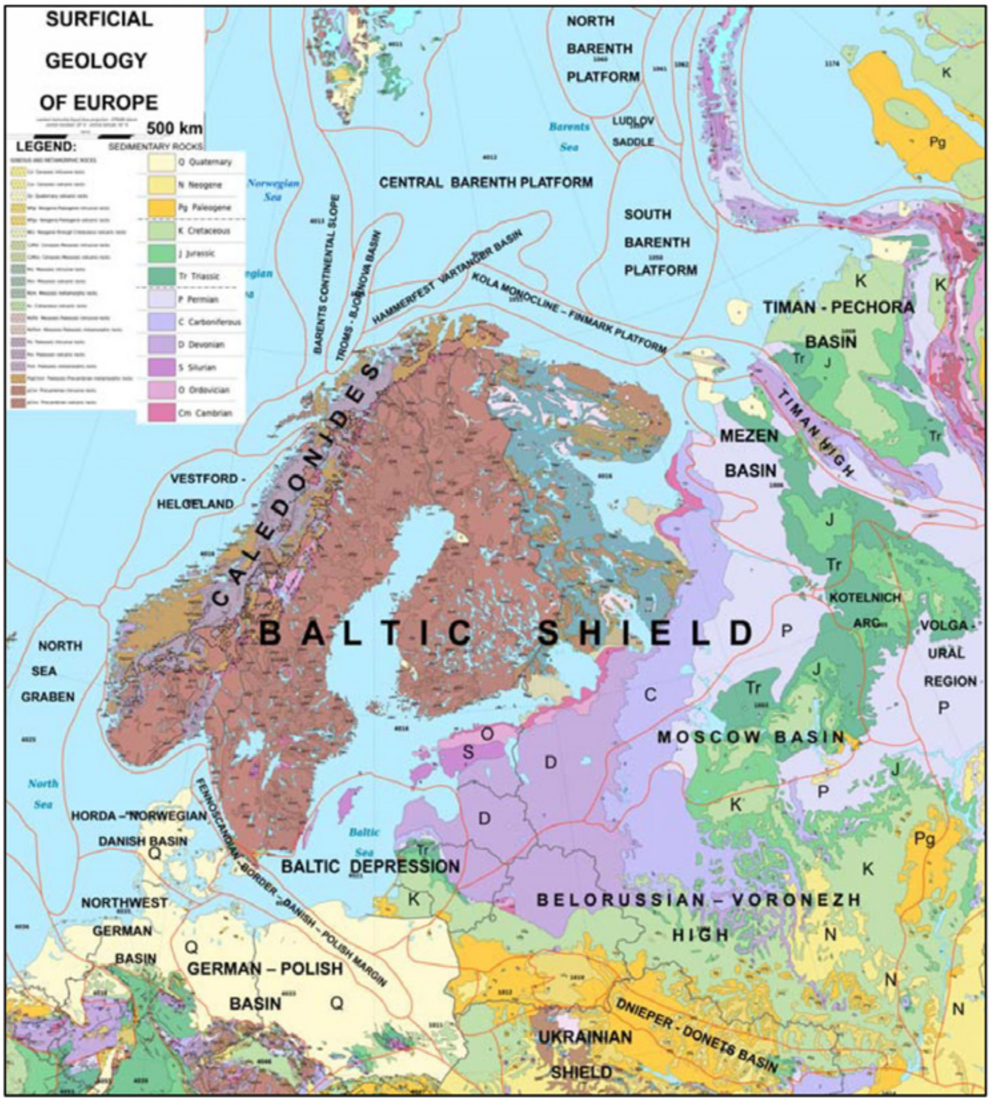
**Turkey** has conducted a few storage assessments, focusing primarily on depleting oil and gas fields. Deep saline aquifers found in Thrace region, Central Anatolia and South Eastern Turkey, as well as salt caverns of soda mines, have also been identified as potential storage options; to date, no capacity estimations have been made (Okandan et al., 2011).

(Note: The Turkish Ministry of Environment and Urbanization (2013) conducted a capacity assessment for potential $CO_2$-EOR projects and associated storage, which estimated ~108 Mt of capacity in the fields in Batman, Adıyaman and Thrace regions.)

**Ukraine**, as shown by two reports (Donetsk National University, 2013; Nedopekin et al., 2019), has storage potential in the Donbass region, located in eastern Ukraine and part of south-western Russia. The reports state total potential of 45.7 to 428 Gt. While no detailed capacity estimations were calculated, the geology in the area has been reviewed, uncovering several promising areas within Paleozoic sediments of the Donbass region, eight of which have been ranked for potential suitability (Nedopekin et al. 2019). This review implies that some elements of capacity are known based on geology, but these are not presented in the report.

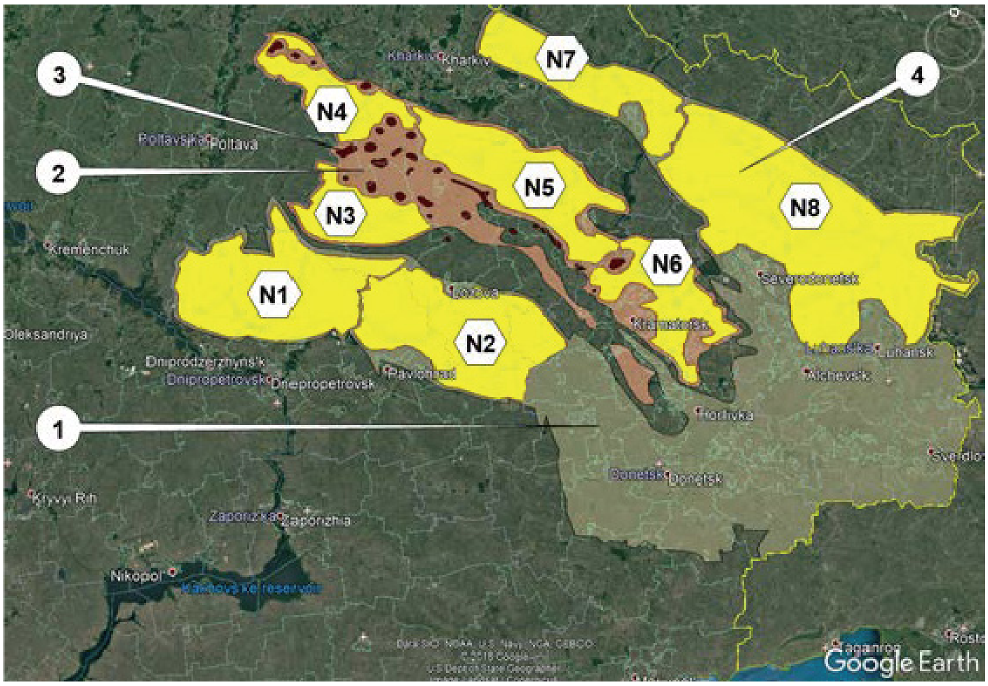
No assessments could be found regarding $CO_2$ storage in aquifers in Armenia, Azerbaijan, Belarus, Georgia, Kyrgyzstan, Moldova, Montenegro, Tajikistan, Turkmenistan, Ukraine or Uzbekistan.

**Figure 4** **Map of the region studied near Estonia, with the Moscow Basin area of Russia highlighted to show its extent**



*Source: Shogeniova et al. 2011*

**Figure 5** Map of promising areas for geological storage of $CO_2$ (N1 to N8), also showing large sources of $CO_2$ emissions (1 to 4)



**Source**: *Nedopekin et al. 2019*

## 4.4 Oil reservoir assessment in countries of interest

Analysis of opportunities for $CO_2$ storage in oil fields located in the countries of interest adopts the assumptions and methodological principles described earlier.

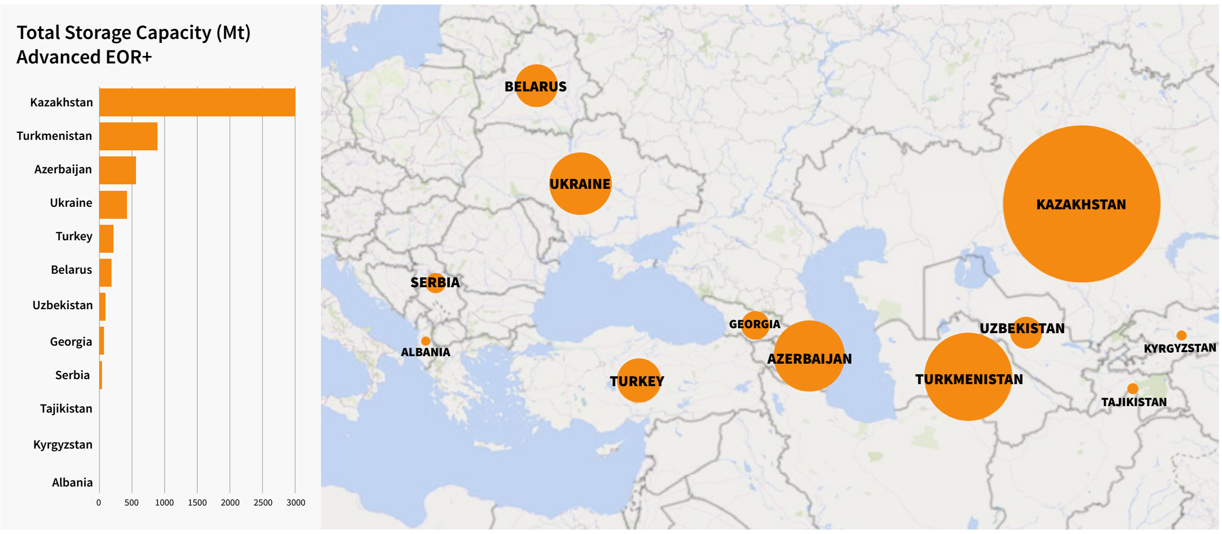
The UCube database, compiled by Rystad Energy, contains information on reservoir and production of about 35,000 oil and gas fields worldwide and was used by Ward *et al.* (2018) to estimate the global $CO_2$ storage potential in oil fields outside the United States. The present analysis follows the approach used by Ward *et al.* It imposes, in addition to the technical screening criteria that comprise reservoir engineering conditions, the following non-technical criteria to identify suitable EOR projects in the UCube dataset:

- Only fields that are abandoned, producing or under immanent development were considered. Future developments were omitted, as it is undetermined when these reservoirs would be available to function as sinks.
- Offshore fields were excluded because of their limited relevance in relation to the potential of onshore fields.
- Fields with little potential for additional production were excluded because it would be difficult to recoup the investment required. This includes reservoirs that have produced more than 80 per cent of their reserves or have less than 10 million barrels in incremental oil remaining. An exception was made for smaller fields if they could be tied into a larger field, within 20 km, that qualified as a standalone project.

For the short-listed reservoirs, the analysis also determined demand for $CO_2$ to develop each potential project, in turn allowing estimates of the total amount of $CO_2$ that could technically be stored by the project. Results are shown on a per-country basis in Figures 6 for a $CO_2$ utilisation of 0.6 $tCO_2$/bbl (“Advanced EOR+”).

Total estimated technical storage capacity in the region is about 62,000 $MtCO_2$. With potential storage capacity of 56,410 Mt $CO_2$, Russian potential is so vast as to be ‘off-scale’ and thus is not depicted on the graph. On the other end of the scale, negligible or no $CO_2$ storage potential associated with EOR was found for Armenia, Bosnia and Herzegovina, Moldova, Montenegro and Northern Macedonian.

**Figure 6** Total CO₂ storage capacity for Advanced EOR+. As Russian capacity dwarfs that of other countries it is not shown for graphical reasons



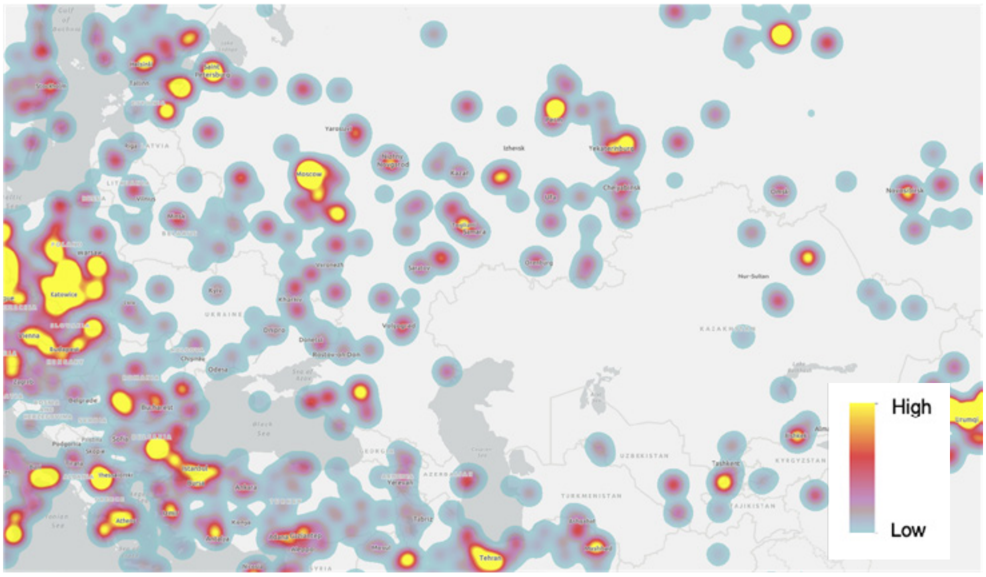
## 4.5 CO₂ supply determines how much can be practically stored

Preceding content assumes that CO₂ is readily available to be stored in locations identified. This is a courageous assumption as it suggests a collocation of CO₂ sources and sinks, which is unlikely to be met in reality. To develop a more realistic picture of the practical relevance of CO₂ storage – that is, what contribution it can make to reducing emissions – it is essential to understand the supply side of CO₂ and specifically the location of CO₂ sources.

For this, analysts can draw on data from Rystad Energy CCS database, which provides the geographic distribution of stationary CO₂ sources, tracks reported emissions and models emissions for facilities when data are not available. Emission sources include:

- Power generation from coal or gas
- Iron and steel production
- Cement production
- Gas production
- Fertilizer production
- Ethanol production

**Figure 7** Geographical distribution of stationary emission sources in 2018. Shown are regions with average annual emissions ranging from 5 million tonnes CO₂ (yellow) to 50 thousand tonnes (light blue)



*Source*: Rystad Energy CCS database

## 4.6 $CO_2$ supply and storage clusters in focus countries and region

To determine how much of $CO_2$ can be practically stored, emissions from sources would need to be matched to storage capacity of sinks. Given the uncertainty regarding location and storage potential of aquifers, current information does not allow this matching to be done for them. The situation is more encouraging for oil reservoirs. After determining potential $CO_2$ sources (from Rystad CCS database) and $CO_2$ demanded (from UCube) for candidate EOR projects, viable supply/demand pairs were identified by selecting the closest source with sufficient supply for each project. For this matching, the following conditions were imposed:

- The maximum distance for $CO_2$ transport from source to sink was arbitrarily set at 500 km.
- It was stipulated that $CO_2$ supply must be sufficient to meet peak $CO_2$ demand of the EOR project.
- Political boundaries were disregarded so that $CO_2$ is freely transported across state boundaries.

Results of this matching are shown in Figure 8 and separately for Russia in Figure 9.

**Figure 8** Storage potential and clusters Eastern Europe and Central Asia with Advanced EOR+ using $CO_2$ from currently available sources

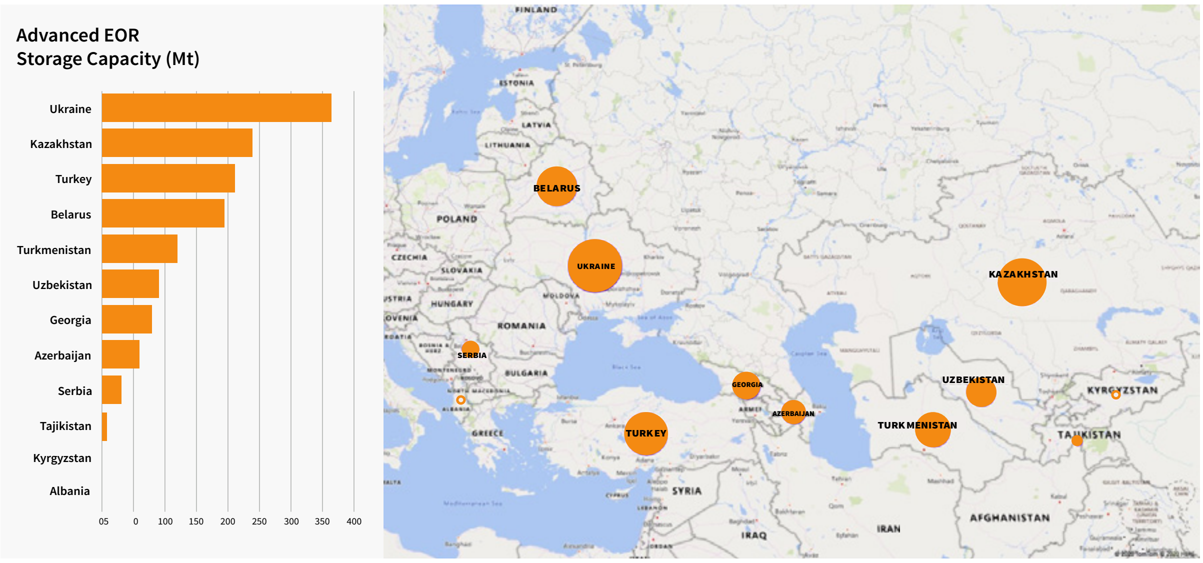


**Figure 9** Storage clusters in Russia with Advanced EOR+ using $CO_2$ from currently available sources

As can be seen, most (but not all) of the viable projects can be arranged in clusters, comprising several reservoirs in the vicinity of $CO_2$ sources. Such cluster structures have the advantage of shared transport infrastructure and a stable $CO_2$ demand resulting from the aggregation of variable demand of individual EOR projects. For Russia, four clusters were identified while all other countries in the region only have a single cluster.

Total matched storage capacity via EOR for countries is 13,327 Mt $CO_2$, as listed in Table 2. For the sake of completeness, the table also summarizes information about aquifer storage potential.

As shown, Russia and Kazakhstan in particular offer significant storage potential. Realising these opportunities implies the challenge of developing a transport infrastructure, with how it should be funded and regulated being key questions.

**Table 2** **Estimated $CO_2$ storage potential in oil fields and aquifers. Data for storage in oil fields account for constraints on $CO_2$ availability, indicating the potential that is practically available**

| Country | Practical EOR+ [Mt] | Aquifer [Mt] |
|---|---|---|
| Albania | 0 | 20 |
| Armenia | 0 | ? |
| Azerbaijan | 64 | ? |
| Belarus | 199 | ? |
| Bosnia and Herzegovina | 0 | 296 |
| Georgia | 84 | ? |
| Kazakhstan | 246 | 403 |
| Kyrgyzstan | 0 | ? |
| Moldova | 0 | ? |
| Montenegro | 0 | ? |
| North Macedonia | 0 | 390 |
| Russia - South | 472 | ? |
| Russia - Volga | 7,579 | ? |
| Russia - Western Siberia | 2,643 | ? |
| Russia - Yamal | 859 | ? |
| Russia - Other | 348 | ? |
| Serbia | 34 | ? |
| Tajikistan | 10 | ? |
| Turkey | 210 | ? |
| Turkmenistan | 122 | ? |
| Ukraine | 364 | ? |
| Uzbekistan | 94 | ? |
| **TOTAL** | **13,327** | **1,109** |

## 4.7 Economics of $CO_2$ storage in focus country oil fields

In EOR, a key financial indicator of profitability is the project's net present value (NPV), which compares – in current values – revenues and expenditure occurring over the project lifetime. Those having a positive NPV will be profitable. Calculation of the NPV also reveals the main drivers of profitability; in turn, this is relevant for designing policy to encourage $CO_2$ storage via EOR.

A key parameter for the profitability of an EOR project is the supply price of the injected $CO_2$, which could be negative or positive. In the case of current US projects, where the operator purchases $CO_2$ used for EOR, the price is negative. If, by contrast, an operator was paid for long-term storage of $CO_2$ as part of an emissions reduction scheme within climate policy, the price could be positive. In this latter case, the $CO_2$ supply price factors in the cost of $CO_2$ capture from emission sources, the cost of transport to the storage site and the $CO_2$ emission price resulting from climate change policy. For example, assuming a cost of \$50/t$CO_2$ for capture and transport, a \$10/t $CO_2$ supply price would be consistent with an emission penalty of \$60/t$CO_2$. Whether it is positive or negative, the supply price needs to be sufficiently high for the NPV at least to break-even, i.e. for NPV=0.

A detailed calculation of the NPVs for all the EOR projects in the clusters identified above is difficult and far beyond the scope of this study. It would require commercially sensitive data on cost as well as simulations of the production and storage performance of individual reservoirs, which in turn requires a rather detailed geological model of storage formation and reservoir. However, with simplifications and plausible assumptions, it is possible to generate estimates of the NPVs of potential projects to provide high-level guidance for policy making. The present analysis builds on the estimation procedure described in Ward et al. (2018).

### Box 2 Storage cost: data and considerations

$CO_2$ capture cost represents the most expensive element of the CCUS technology chain and varies with applications. The Global CCUS Institute (2017) reports the following data for first-of-kind (FOAK) and next-of-a-kind applications (NOAK):

| | **Power generation** | | | | **Industrail sources** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **\$/t$CO_2$** | **PC Supercritical** | **Oxy-comb. Supercritical** | **IGCC** | **NGCC** | **Iron and Steel** | **Cement** | **Natural Gas** | **Fertilizer** | **Biomass to Ethanol** |
| **FOAK** | 74-83 | 66-75 | 97 | 89 | 77 | 124 | 21.5 | 25.4 | 21.5 |
| **NOAK** | 55 | 52 | 46 | 43 | 65 | 103 | 20.4 | 23.8 | 20.4 |

Onshore pipeline cost exhibits modest economies of scale. Morgan and Grant (2014) report a value of \$3.10/t$CO_2$/100 mi for a capacity of 3.2 Mt$CO_2$/year decreasing to \$1.10/t$CO_2$/100 mi for a capacity of 30 Mt$CO_2$.

Aquifer storage cost is in the range of \$7.00-13.00/t$CO_2$, depending on reservoir properties (USDOE, 2014).

Storage through EOR incurs additional costs related to drilling of infill wells, $CO_2$ recycling and compression, all of which are considered in the calculation of NPVs.

**Figure 10** **Effect of $CO_2$ supply price on economic storage potential for EOR projects in clusters. Selected projects are highlighted for illustrative purposes.**

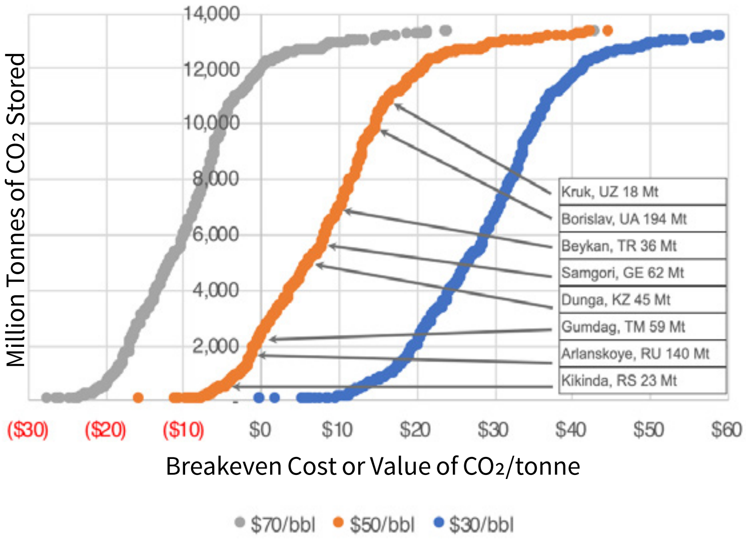


Figure 10 depicts the $CO_2$ supply prices at which NPV breaks even for all potential EOR projects in the clusters, together with the corresponding volume of $CO_2$ stored. Underlying this figure are NPV calculations, using the same set of assumptions on capital expenditures, operating cost, oil production and $CO_2$ injection profiles as in Ward et al. The discount factor is set at 10 per cent flat.

As Figure 10 illustrates, $CO_2$ breakeven prices vary among different projects. Additionally, changes in oil prices have predictable consequences. Higher oil prices correspond with lower break-even $CO_2$ prices, since producers find more value in using $CO_2$ to increase production – and will do so even if paid less for $CO_2$ storage. As shown, adoption of EOR throughout the region would require $CO_2$ supply prices in excess of $60/t$CO_2$ when oil prices are in the order of $50/bbl.

# 5. Policies for CCUS

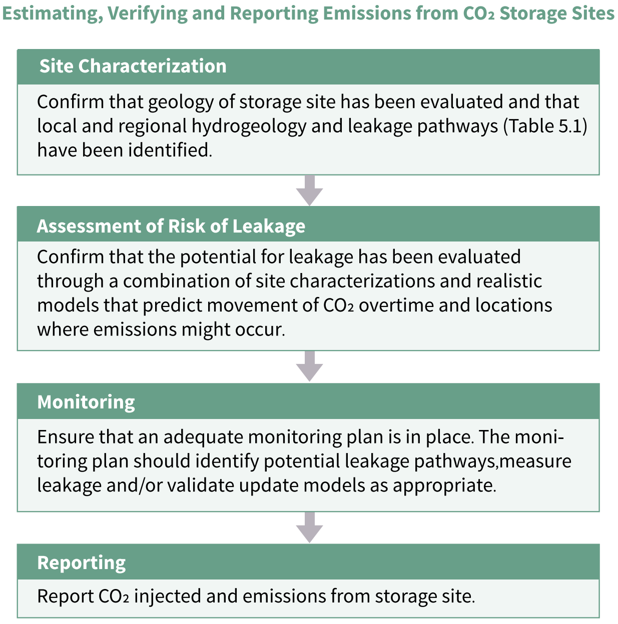
At present, development and deployment of CCUS is lagging behind the scale needed to fulfil its projected role in climate change mitigation.

Given the importance of CCUS for achieving global emissions reduction goals, a policy framework and incentives are needed to accelerate it to commercial-scale deployment. To provide credibility and legitimacy to attract international climate funding, such a scheme should be established internationally under the auspices of the UNFCCC and in line with the COP21 Paris Agreement.

Given the scale of CCUS deployment required, international and domestic actions need to be complementary, reflecting multilateral cooperation. The various mechanisms established under the UNFCCC for financing clean energies could provide the appropriate platform. Article 2 of the Kyoto Protocol, for example, explicitly mentions geological storage and encourages Parties to implement and elaborate policies on the development and increased use of carbon sequestration technologies. The IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005) provides the scientific and technical basis for further policy actions. Important milestones include:

- Agreement of the 2006 IPCC Guidelines on National Greenhouse Gas Inventories (IPCC, 2006), thereby establishing an international framework for countries to monitor and report emissions reduction from CCUS. The agreement proposes protocols for site characterization, modelling of potential leakage pathways and monitoring to ensure that injected $CO_2$ remains isolated from the atmosphere indefinitely. De facto, the Guidelines establish a high-level regulatory framework for CCUS (Figure 11).
- Agreement, in 2012, of modalities and procedures for CCUS as a clean development project activity (UNFCCC, 2011). This established guidelines and safeguards by which CCUS projects could earn certifiable emissions reduction (CER) through the Clean Development Mechanism (CDM) of the Kyoto Protocol. It thus laid the foundation for financing CCUS in developing countries. Subsequent collapse of the CER market (late 2012) caused interest in using the CDM for financing CCUS projects to wane.

**Figure 11** Procedures for estimating emissions from $CO_2$ storage sites



**Estimating, Verifying and Reporting Emissions from $CO_2$ Storage Sites**

**Site Characterization**

Confirm that geology of storage site has been evaluated and that local and regional hydrogeology and leakage pathways (Table 5.1) have been identified.

**Assessment of Risk of Leakage**

Confirm that the potential for leakage has been evaluated through a combination of site characterizations and realistic models that predict movement of $CO_2$ overtime and locations where emissions might occur.

**Monitoring**

Ensure that an adequate monitoring plan is in place. The monitoring plan should identify potential leakage pathways,measure leakage and/or validate update models as appropriate.

**Reporting**

Report $CO_2$ injected and emissions from storage site.

***Source***: *IPCC, 2006*

The COP21 Paris Agreement provides a framework for international cooperation on mitigating $CO_2$ emissions, including a blueprint for the international flows of climate finance. All signatory countries set their emissions reduction goals in the form of nationally determined contributions (NDCs). Using a range of mechanisms and options outlined in Article 6, the Agreement allows countries to embark on cooperative strategies with other countries in order to meet or exceed the level of ambition set out in their own NDCs. The Article aims to open new avenues for flexible cooperation among countries to deliver mitigation outcomes, particularly when they align around common interests.

The COP21 Paris Agreement also supports cooperation among countries in pursuit of NDCs through the formation of 'climate clubs.' This creates the possibility to establish a 'CCUS club' with the primary aim being to pool finance and technical resources to make deploying CCUS a prominent part of climate mitigation strategies, both domestically and via multilateral processes. Such a club would not necessarily need to include all countries but would need motivated members with technical interest and financial capability to deploy CCUS. Membership could increase over time, based on demonstrated benefits drawn from early experiences. Developed countries, with the greatest long-term interest in CCUS technology, may be interested in supporting CCUS projects in other countries for a number of reasons:

- Introducing CCUS to a variety of environments, including non-OECD countries, may lead to greater learning than regionally concentrated pilots and demonstrations
- CCUS development may be possible at lower cost
- Benefits of reduced climate change damage accrue globally, no matter where $CO_2$ is captured and stored
- Article 6 of the COP21 Paris Agreement provides the basis for establishing mechanisms through which co-operative action could flow

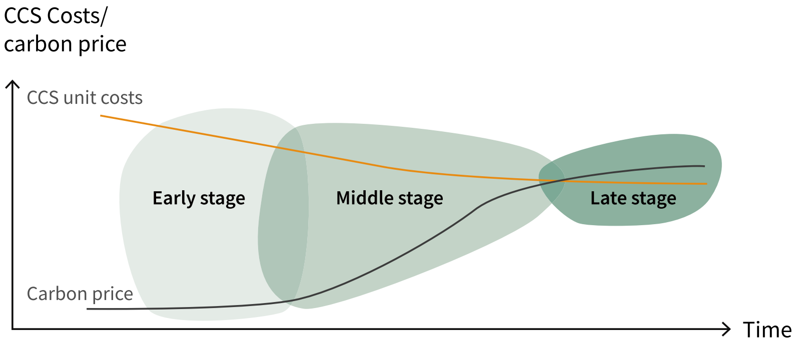
## 5.1 Policy instruments to accelerate CCUS deployment

As is the case for policy intervention in technology development and deployment, it is important to design policies that are appropriate to various stages of CCUS maturation. It is helpful to adopt the view that the path to market comprises three main stages that link and overlap (IEA, 2012; Krahé, 2013; Grubb, 2014) (Figure 12).

The first 'demonstration phase' (early) establishes the technical viability of CCUS for practical deployment (IEA 2012). In the second (middle) 'market formation' phase, the technology is exposed to limited market-based learning that, in turn, reduces risk and cost to enhance investor confidence. In the case of CCUS, this form of early market experience could come from sector-specific deployment in niche markets where CCUS could be implemented at low cost, such as EOR. Finally, 'diffusion', the third (late) stage of the deployment path, involves wide-scale deployment driven by economies of scale, infrastructure and regulatory developments that together allow CCUS to compete as a mature technology with other $CO_2$ emissions reduction options.

The nature, scale and scope of policy instruments need to be calibrated to the specific phases of CCUS development and deployment. Rather than a single instrument, CCUS requires an integrated policy framework comprising a suite of policy instruments, each designed to respond to the need of a particular technology development phase.

**Figure 12** **Distinct stages of CCUS technology development can be related to the level of CCUS unit cost and stringency of carbon policy as expressed by carbon prices**



***Source**: IEA, 2012*

### Early-stage support

Aiming primarily to incentivize research and development, support for CCUS applications in the early stages is likely to require capital grants and operating subsidies. Faced with a combination of technology risk, immature regulatory and policy frameworks, and low or absent market revenues, investors will be reluctant to commit substantial sums. Public funding via capital grants and operating subsidies could ensure that CCUS projects are demonstrated to allow for basic learning. The extent of public sector involvement is likely to vary from country to country depending on factors such as:

- Governmental ownership of the sectors involved
- Political concerns regarding pass-through of CCUS cost to customers (e.g. in the electricity sector)
- The strategic role of CCUS for building a country's technical capabilities and for its climate ambitions

Generally, this can be thought of as the 'policy push' phase of support as instruments are designed to be appropriate for pre-commercial technologies.

### Mid-stage support

At this stage, the technology is proven but significant scale-up of deployment is needed to realise cost reduction potential. As the benefits of lower cost will not be fully retained by those investing, technology-specific policies to support CCUS may be justifiable. This is broadly the stage that many more mature renewable energy technologies are successfully navigating.

Policies in this stage could consist of a quantity-support mechanism, e.g. a governmental purchasing contract or a portfolio standard with infrastructure support policy. Such a scheme might work, for instance, by governments committing to purchase a certain (and perhaps increasing) number of CCUS storage certificates each year, with these certificates obtained for every tonne of $CO_2$ securely stored.

A more innovative approach that combines market-based financing with public intervention could involve the creation of an 'advanced market commitment' (AMC). An AMC is a legally binding agreement that supports the creation of a market for CCUS by guaranteeing ex ante the purchase (at a fixed price) of a number of CCUS credits for as yet unavailable CCUS technology. AMCs gained prominence in the public health sphere in the last decades, where they are generally used to promote investments into vaccines for neglected diseases that disproportionally affect populations in the developing world. Options other than AMC to channel public funds to support CCUS in a cost-effective manner are discussed in Box 3.

However, at the domestic level, these may not be sufficient to drive CCUS deployment at the scale required. International collaboration, in conjunction with performance-oriented market-pull instruments, may be necessary to attract the required investment to accelerate deployment. These efforts could be based on a storage crediting scheme for CCUS, of the type recently proposed by Zakkour and Heidug (2019) and Zakkour et. al. (2020). A specific feature of this concept is that it invokes options for international climate financing created by the COP21 Paris Agreement (see below).

## Mature stage support

When CCUS is mature, the presumption should be that deployment will be incentivized through carbon pricing instruments alone. The justification for the use of carbon pricing (e.g. carbon taxes and cap-and-trade programs) emerges from the observation that imposing a common price on emissions reduction has the effect of equalizing marginal costs across regulated firms. This ensures reductions are achieved cost-effectively – i.e. maximum emissions reduction at minimum aggregate cost. Carbon pricing is a technology-agnostic instrument in that it ensures CCUS is deployed only when it is a cost-effective means of reducing emissions, with that cost-effectiveness improved by the earlier stages of support described above.

### Box 3 Performance-oriented instruments to create market pull

Besides AMC, other market-pull instruments have been designed to artificially create rents, thereby making investments in CCUS more attractive. Three types of instruments discussed here (Gosh et al., 2012) share the characteristic of providing ex post financial support, based on verified emissions reduction.

**Direct purchase**

Under direct purchase, participants purchase verified emissions reduction through CCUS directly from a central authority or the government. The central authority or regulator would offer to buy CCUS reductions at a pre-specified price using public funds. Determining who gets to sell the CCUS reductions and at what price are key policy design questions. Allocating funds via a reverse auction could be a cost-effective solution. The central authority would solicit bids from CCUS investors who specify the volume of $CO_2$ they are willing to supply at a given price. The central authority then chooses the bids with the lowest prices.

**Top-up instrument**

Under a top-up mechanism, the government tops up revenues from the sales of verified CCUS reductions to a pre-agreed value of CCUS reductions. More specifically, the instrument could be structured to have the central authority pay CCUS investors or CCUS reduction vendors the difference between an agreed price and the prevailing carbon price (i.e. the carbon tax rate or the market price of emission permits) when the CCUS reductions or the corresponding credits are delivered to market. If the prevailing carbon price exceeds the agreed-upon price when the CCUS investor is ready to deliver the emissions reductions – the central authority pays nothing, the CCUS investor's obligation to the buyer ends, and the credits are simply offered on the market for a higher price. As in the previous case, a reverse auction may be a cost-effective solution to deploy this instrument.

**Tradable options**

Tradable options give the option holder the right to sell verified emissions reduction at a specified price before a specified date. For various reasons, a CCUS investor may not be able to deliver promised reductions. In this case, put option contracts could provide a possible solution. Such a contract provides the CCUS investors with the right, but not the obligation, to sell to the funder a certain number of reductions at a certain agreed price by a certain time (Müller, 2008; Pizer, 2011; Grüll and Taschini, 2011). If these contracts are tradable when the current holder decides they are unlikely to use them, the possibility to sell them to other CCUS investors or CCUS reduction vendors ensures they will be used.

An important consideration across these instruments is that the first two contracts lock in the maximum potential revenues (the agreed-upon price). An option contract, by contrast, removes such obligation as the CCUS reductions vendor could simply sell emissions in the market and receive the market price. In fact, if the market price is higher than the agreed price, the CCUS reduction vendor is better off by selling into the market, and the option contract will not be exercised.

Storage-focused policy instruments of the type discussed above could also play a role in supporting the development of a $CO_2$ transport infrastructure. Given uncertainty in the future value of $CO_2$ transport capacity, investors may hesitate to invest in CCUS infrastructure, potentially resulting in under-provision of transportation services. This uncertainty is reduced through performance-based policy instruments that offer long-term contracts through which governments 'buy' a certain volume of securely stored $CO_2$ within a certain time period.

In this context, the IEA (2016) proposes the establishment of a public agency as an intermediary between emitter and storage companies. The agency would enter into long-term, 'ship-and-pay' contracts with storage service providers to develop storage sites and transportation infrastructure. This arrangement effectively removes the $CO_2$ delivery risk faced by the storage provider and could provide a bankable structure for the development of $CO_2$ infrastructure.

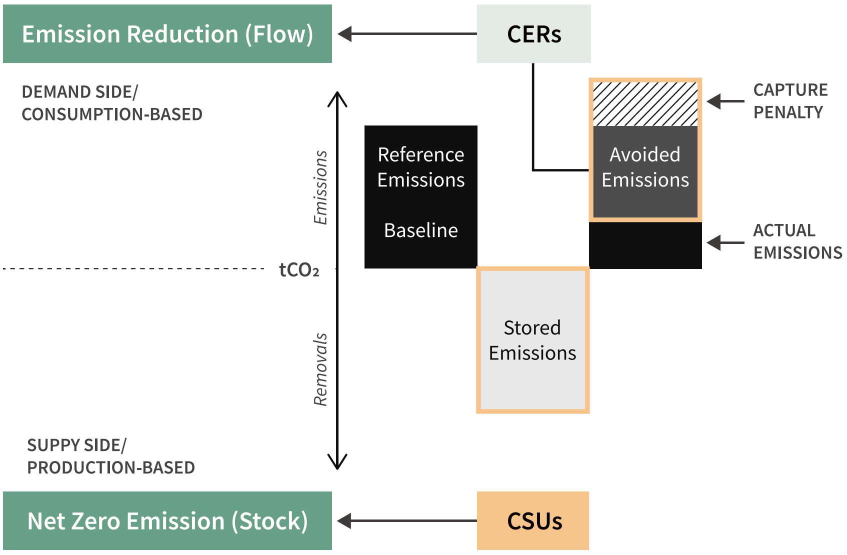
## 5.2 Certificate scheme for CCUS

Strong arguments can be made to support the view that policy should seek to incentivize the storage part – as opposed to capture part – of the CCUS technology chain. This would support the sink enhancement necessary for reaching carbon neutrality while also tying incentives to actual storage performance. As discussed above, this is a required feature of mid-stage CCUS policies. In addition, for reasons related to reducing investment risk and spelled out in IEA (2016), incentivizing storage would make it easier to finance CCUS projects.

The following section describes an international storage certificate scheme that would meet these requirements, as recently proposed by Zakkour and Heidug (Zakkour and Heidug, 2019, 2020; Zakkour et al. 2020). The core feature of this scheme would be a 'carbon storage unit' (CSU). As described above, a CCUS club could apply the provisions of the COP21 Paris Agreement to use the CSU to establish a crediting mechanism for storage (Zakkour and Heidug, 2019).

A CSU would represent a verified record of a tonne of $CO_2$ securely stored in a geological reservoir (Figure 13). The concept is similar to a renewable energy certificate (REC) (also known as a green energy certificate or a tradable renewable certificate) that offers proof of energy having been generated from renewable sources (e.g. solar or wind). When coupled with placing renewables obligations on electricity generators, an REC subsidizes renewable power in a way that complements carbon pricing. Each REC represents the environmental benefits of 1 megawatt hour (MWh) of renewable energy generation. When an entity purchases an REC, renewable energy is generated on its behalf.

**Figure 13** **A CSU is a measure of stored emissions. The difference between stored emissions and avoided emissions arises from the energy penalty of capture**



*Modified from Zakkour and Heidug, 2019*

A CSU is a non-tangible, tradable commodity that acts as proof that a tonne of $CO_2$ has been safely stored in geological formations. It would have no intrinsic emissions reduction value but would provide a verified record of geological storage.

A pledge to procure CSUs in an NDC would represent a financial and technological contribution toward CCUS deployment, with the implicit co-benefit of emissions reduction. The CSU concept has parallels with other types of 'non-GHG' targets evident in some current NDCs, such as megawatts (MW) of installed renewable energy capacity, gains in energy efficiency for certain sectors or appliances, or land area targets for afforestation. These non-GHG targets are expressed in terms other than emissions or removals, such as MWs of renewable energy deployed or square kilometers of newly forested land.

Initially, demand for CSUs would be established through a results-based climate finance (RBCF) mechanism, a method proven in other areas of climate policy. In situations where other sources of demand do not exist, RBCF involves producing flows of finance from a centralized fund to procure quantified emissions reduction or removal units. This would be the situation facing CSUs in a transitional period. In practice, CCUS club members would pledge to procure CSUs and establish a fund that, using RCBF, enters forward contracts to purchase CSUs from $CO_2$ storage operators at agreed prices, volumes and timeframes.

In addition to establishing explicit support for $CO_2$ storage, this approach aggregates and pools finance to reduce any single country's exposure to the cost of deployment. It also provides building blocks for commercial CCUS deployment in future phases.

Over time, RBCF could transition to a mechanism that creates systematic demand for CSUs. For this, club members would need to establish in their NDCs geological storage targets against which the acquisition and transfer of CSU would be counted. The coexistence of geological sequestration and emissions reduction targets would provide a double incentive to support CCUS activities, while avoiding double counting; the CSUs would not avail any explicit emissions rights to club members.

In addition, and as discussed in detail by Zakkour and Heidug (2020), the CSU concept could be used to establish pathways for decarbonizing fossil fuels. In effect, by implementing CCUS and generating CSUs through storage, oil producers could sequester $CO_2$ at rates that would allow importing countries to zero-rate end-use emissions – essentially establishing a system whereby CSUs at the production stage offset emissions from combustion of fossil fuels. Main policy drivers to stimulate this strategy would include various low-carbon fuel portfolio standards (e.g. EU Renewable Energy Directive II and low-carbon fuel standards in US states and Canadian provinces).

In summary, a storage crediting mechanism based on CSUs can address some of the issues that have hampered development and deployment of CCUS. Attractive features include:

- Applicability to a wide range of countries and circumstances. The CSU approach is a variable mechanism that can be tailored to specific national circumstances, individual projects, and the availability of other sources of finance and revenue.
- The mechanism fits well with the current state of CCUS technology development. Given that carbon pricing is unlikely to incentivize significant invest-

ment, CSUs will add an additional layer of finance to kick-start new CCUS projects. A crediting scheme involving CSU addresses the shortcomings of carbon pricing policies for CCUS and adds value to industry and consumers, while making a long-term contribution to climate change mitigation goals.

- CSUs are compatible with the COP21 Paris Agreement architecture, mechanisms and goals. A new layer of finance for CCUS can be an integral element of NDCs and internationally transferred mitigation outcomes (ITMOs). It could also dovetail with national or regional carbon pricing schemes and other incentive programs that include CCUS, allowing CSUs to drive deeper ambition than can be achieved through a common price signal for all types of $CO_2$ emissions abatement technologies alone.

# 6. Conclusion

Two significant gaps – lack of information and policy commitment – need to be closed before CCUS can support, in a meaningful way, the decarbonization strategies of the countries in South-Eastern Europe, Eastern Europe, the Caucasus and Central Asia, as well as the Russian Federation and Turkey.

Knowledge of national storage capacity and its geographical distribution is indispensable for any decarbonization strategy involving CCUS. As this analysis shows, the vast majority of these countries often have rudimentary fragmented and incomplete information, particularly regarding storage potential in aquifers. The situation is slightly better with regards to storage in oil fields but effort is needed to assure and improve the consistency and quality of available data.

Carrying out a qualitative assessment of basins suitable for $CO_2$ storage could be a first step towards closing this gap. Discussion in this report could provide the basis for a systematic approach to grading basins, using established geological criteria. Such analysis could be accomplished by a panel of experts in a short timeframe and presumably with modest budget.

Quantitative assessments of storage potential of basins identified as suitable would logically follow. To facilitate comparison of results of national assessments, an important aspect is to explicitly state assessment methodologies used. Guidance for improving the consistency of storage estimates is given in IEA (2013), which builds on expert recommendations to propose best practices. While this effort could be undertaken by national geological survey organizations, it should be coordinated internationally to ensure compatibility of assessments.

Low engagement reflects uncertainty on the part of various stakeholders and could be addressed through policy mechanisms that would provide incentives for CCUS investment, development and deployment. Policies to support CCUS have been enacted in some OECD countries, including the EU Emissions Trading Scheme and the tax credit for CCUS in section 45Q of US tax code. To date, countries outside the OECD have not established policy frameworks that could attract private investments to support CCUS deployment. Designing an appropriate policy mechanism for the regions covered in this report should be seen as an international task to foster intra-regional cooperation and demonstrate broad global commitment. For reasons given above, the mechanism should be technology-specific and aim to facilitate international deployment of CCUS.

A certification scheme for CCUS, aligned with the COP21 Paris Agreement and operated under the auspices of the UNFCCC, could provide a viable option. Establishing such a CCUS certification scheme would need the political support and buy-in of key countries with interest in CCUS, including the United States and the EU. Further work would be required to define a governance structure and establish rules and mechanisms for its operation. Rules concerning the origination of credits, including site selection and monitoring, could be based on existing UNFCCC ( IPCC, 2005) standards for CCUS. It will also be necessary to establish an accounting approach, particularly to avoid double counting of emissions reduction.

Such a CCUS mechanism would fit into the emerging international landscape of climate change policy. With countries and regions declaring ambitions to reach net-zero emissions targets in the second half of this century, there is need for policies that value and monetise sink enhancement activities as well as other types of carbon removal technology, including geological sequestration, direct air capture and forestry (G20, 2020). A CCUS certification scheme of the type discussed would facilitate using the significant storage potential available in geological carbon sinks to the extent that various studies show is needed to reach net-zero goals.

# Appendix

# Resource classification for $CO_2$ storage projects

Resource classification is a concept that has been applied in the mining as well as oil and gas industry for many decades and several acknowledged classification systems are available world-wide. The common element of the systems currently applied by industry and regulators is that they classify resources based on the technical and economical maturity of the projects designed to extract and sell these resources.

In the oil and gas industry, the **Petroleum Resource Management System**[2] , published by the Society of Petroleum Engineering and others (SPE-PRMS), is extensively used worldwide. This system is thus well known to both industry and regulators, as well as by the investor community. Resources are classified according to the level of maturity of the recovery projects, also referred to as the 'Chance of Commerciality' of each project.

The SPE-PRMS classifies oil and gas resources as:

- **Reserves** – discovered resources that can be commercially extracted.
- **Contingent resources** – discovered resources for which some level of contingency remains before they can be classified as commercial.
- **Prospective resources** - resources yet to be discovered.

Each main class is divided into sub-classes and categories, depending on the maturity of the project activities.

The **United Nations Framework Classification for Resources (UNFC)**[3] is another project-based classification system, developed by the UNECE to help define the environmental-socio-economic viability and technical feasibility of projects to develop resources. It provides a consistent framework to describe the level of confidence of the future quantities produced by each project.

Terms such as 'resources' and 'reserves' are deliberately avoided in the UNFC. It is a principles-based system in which the products of a resource project are classified – using a numerical coding system – based on three fundamental criteria: environmental-socio-economic viability (E); technical feasibility (F); and degree of confidence in the estimated quantities (G).

- **The E axis** designates the degree of favourability of environmental-socio-economic conditions in establishing the viability of the project, including consideration of market prices and relevant legal, regulatory, social, environmental and contractual conditions.
- **The F axis** designates the maturity of technology, studies and commitments necessary to implement the project. These projects range from early conceptual studies through to a fully developed project that is producing.
- **The G axis** designates the degree of confidence in the estimate of the quantities of products from the project.
- The categories and sub-categories are the building blocks of the system and are combined in the form of 'Classes'.

The UNFC is aligned with some other classification systems via so called Bridging Documents, including the SPE-PRMS.

## UNFC as applied to injection projects for the purpose of geological storage

In recent years, the UNECE Expert Group on Resource Managements (EGRM) has also developed specifications for how to apply the UNFC to other energy-related commodities, including several renewable energy resources and injection projects for the purpose of geological storage, such as $CO_2$ storage. Recovery projects are replaced with injection projects, with associated quantities reflecting what can be stored in the recipient reservoirs of the different injection projects, given the defined project activities and costs. These quantities can then be classified based on the same E, F and G categories. The injection projects specifications were first published in 2016[4] .

The injection projects specifications include definitions and supporting explanations for each category and sub-category. For the E and F categories, the numbers represent a defined level of development. The G categories represent a low, best and high quantity estimate or, in other words, the uncertainty in the estimated stored quantities. The E, F and G categories and sub-categories can be combined to create classes that define the level of maturity of the injection project. Table A.1 shows what is expected to be the most commonly used combinations, but other combinations may be equally valid depending on the specifics of the evaluated projects.

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[2] The latest update from 2018 can be downloaded from www.spe.org

[3] The 2019 edition and specifications for its application are available at the UNECE web site: www.unece.org

[4] They can be found on the UNECE web site under Areas of Work along with other commodity-specific specifications.

**Table A.1** UNFC classes defined by categories and sub-categories as applied to injection projects

| UNFC Classes Defined by Categories and Sub-Categories as Applied to Injection Projects for the Purpose of Geological Storage | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Total Geological Storage | Lost Quantities | | | | | | | | |
| | Injected and Stored Quantities | | | | | | | | |
| | | v | Categories | | | Sub-class | Categories and Sub-categories | | |
| | | | E | F | G | | E | F | G |
| | Future storage by commercial injection projects | Commercial Injection Projects | 1 | 1 | 1,2,3 | Active Injection | 1 | 1.1 | 1,2,3 |
| | | | | | | Approved for Development | 1 | 1.2 | 1,2,3 |
| | | | | | | Justified for Development | 1 | 1.3 | 1,2,3 |
| | Future storage in known reservoirs by commercial injection projects | Potentially Commercial Injection Projects | 2 | 2 | 1,2,3 | Development Pending | 2 | 2.1 | 1,2,3 |
| | | | | | | Development on Hold | 2 | 2.2 | 1,2,3 |
| | | Non-Commercial Injection Projects | 3 | 2 | 1,2,3 | Development Unclarified | 3.2 | 2.2 | 1,2,3 |
| | | | | | | Development not Viable | 3.3 | 2.3 | 1,2,3 |
| | Storage Not Feasible | | 3 | 4 | 1,2,3 | Storage Not Feasible | 3.3 | 4 | 1,2,3 |
| | Potential future storage in undiscovered reservoirs by injection projects | Screening Projects | 3 | 3 | 4 | Geological Storage Identified | 3.2 | 3.1 | 4 |
| | | | | | | Geological Storage Indicated | 3.2 | 3.2 | 4 |
| | | | | | | Geological Storage Inferred | 3.2 | 3.3 | 4 |
| | Storage Not Feasible | | 3 | 4 | 4 | Storage Not Feasible | 3.3 | 4 | 4 |

**Total geological storage** in an evaluated area or portfolio of projects is the sum of all quantities that have been and will be stored by current and/or planned projects and quantities that may be stored by future, not yet defined injection projects (screening projects). It may also include quantities reflecting areas or reservoirs where storage for some reason is not feasible. This last category is comparable to unrecoverable volumes in place in oil and gas projects.

**Commercial injection projects** are those confirmed to be commercially viable. They may or may not be commercial in the traditional sense; as long as the project's environmental-socio-economic viability and technical feasibility can be confirmed, the project can be classified as commercial[5]. It can also be sub-classified as economic to develop on its own (E1.1) or as a project made viable through government subsidies and/or other considerations (E1.2). (Not shown in Table A.1).

The F3 sub-categories have been developed specifically for application to injection projects to facilitate differentiation of screening projects at different stages of evaluation before a defined injection project has been identified.

## The SPE-SRMS – Storage Resource Management System

In 2017, the SPE also published a version of its resource management system adapted for $CO_2$ storage, the Storage Resource Management System (SPE-SRMS).[6] This is based on the SPE-PRMS, again following the same principles of project-based classification of storage resources. The storage resources are classified as:

- Storage capacity – quantities anticipated to be commercially accessible in the characterized geologic formation through application of development projects.
- Contingent storage resources – potentially accessible quantities in known geologic formations, but where the applied project(s) are not yet considered mature enough for commercial development.
- Undiscovered storage resources – where the suitability for storage has not been ascertained within the target geologic formation.

Project maturity sub-classes are also identified in line with the SPE-PRMS (Table A.2).

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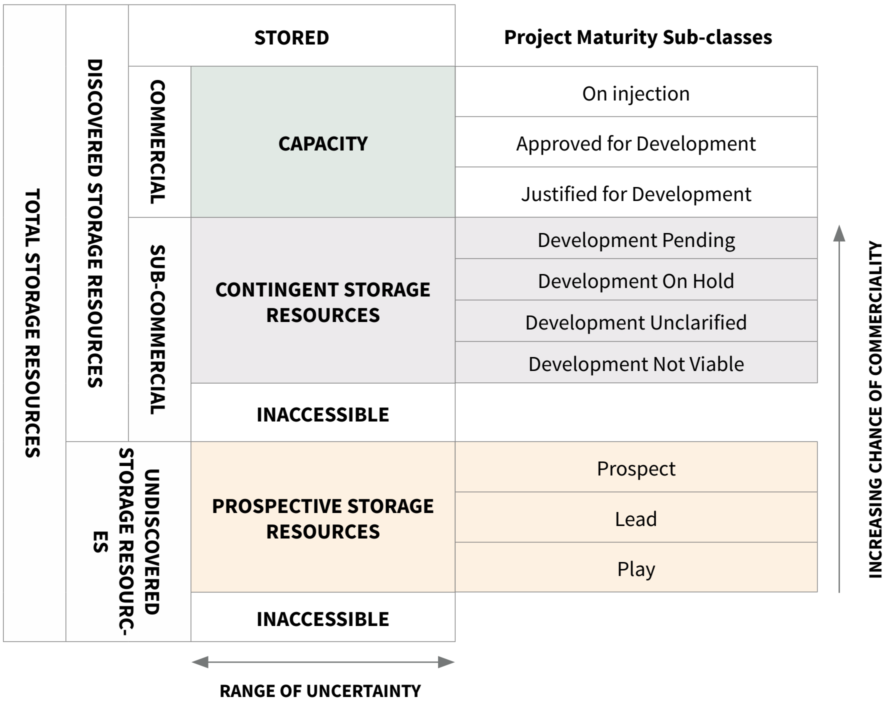
[5] In the UNFC injection projects specifications, the term 'commercial projects' is still used. The 2019 update replaces this with 'viable projects', defined as projects for which the environmental-socio-economic viability and technical feasibility have been confirmed.

[6] The complete SPE-SRMS document is available at www.spe.org

**Table A.2** **SPE-SRMS Classes and Sub-classes based on project maturity**



| | | | STORED | Project Maturity Sub-classes |
|---|---|---|---|---|
| TOTAL STORAGE RESOURCES | DISCOVERED STORAGE RESOURCES | COMMERCIAL | CAPACITY | On injection |
| | | | | Approved for Development |
| | | | | Justified for Development |
| | | SUB-COMMERCIAL | CONTINGENT STORAGE RESOURCES | Development Pending |
| | | | | Development On Hold |
| | | | | Development Unclarified |
| | | | | Development Not Viable |
| | | | INACCESSIBLE | |
| | UNDISCOVERED STORAGE RESOURCES | | PROSPECTIVE STORAGE RESOURCES | Prospect |
| | | | | Lead |
| | | | | Play |
| | | | INACCESSIBLE | |

The storable quantities are also categorised based on uncertainty. For storage capacity, quantity estimates are categorised as proved, probable and possible capacity, identical to categorisation of reserves under the PRMS. Storage capacity can also be sub-divided into developed capacity, where injection and storage is taking place and undeveloped capacity when injection has not yet started.

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# Geological $CO_2$ storage in Eastern Europe, Caucasus and Central Asia

## An initial analysis of potential and policy

This report has explored potential for $CO_2$ storage in Eastern Europe, the Caucasus, and Central Asia, which can support achieving Sustainable Development Goals and attaining carbon neutrality targets.

The study highlights tools and methodologies that countries can use to assess potential and develop policies in support of carbon capture, utilization and storage (CCUS), which can make CCUS technologies a reality sooner.

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