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## Enabling onshore CO<sub>2</sub> storage in Europe: fostering international cooperation around pilot and test sites

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### Abstract

To meet the ambitious EC target of an 80% reduction in greenhouse gas emissions by 2050, CO<sub>2</sub> Capture and Storage (CCS) needs to move rapidly towards full scale implementation with geological storage solutions both on and offshore. Onshore storage offers increased flexibility and reduced infrastructure and monitoring costs. Enabling onshore storage will support management of decarbonisation strategies at territory level while enhancing security of energy supply and local economic activities, and securing jobs across Europe. However, successful onshore storage also requires overcoming some unique technical and societal challenges. ENOS will provide crucial advances to help foster onshore CO<sub>2</sub> storage across Europe through:

1. Developing, testing and demonstrating in the field, under “real-life conditions”, key technologies specifically adapted to onshore storage.
2. Contributing to the creation of a favourable environment for onshore storage across Europe.

The ENOS site portfolio will provide a great opportunity for demonstration of technologies for safe and environmentally sound storage at relevant scale. Best practices will be developed using experience gained from the field experiments with the participation of local stakeholders and the lay public. This will produce improved integrated research outcomes and increase stakeholder understanding and confidence in CO<sub>2</sub> storage. In this improved framework, ENOS will catalyse new onshore pilot and demonstration projects in new locations and geological settings across Europe, taking into account the site-specific and local socio-economic context. By developing technologies from TRL4/5 to TRL6 across the storage lifecycle, feeding the resultant knowledge and experience into training and education and cooperating at the pan-European and global level, ENOS will have a decisive impact on innovation and build the confidence needed for enabling onshore CO<sub>2</sub> storage in Europe.

ENOS is initiating strong international collaboration between European researchers and their counterparts from the USA, Canada, South Korea, Australia and South Africa for sharing experience worldwide based on real-life onshore pilots and field experiments. Fostering experience-sharing and research alignment between existing sites is key to maximise the investment made at individual sites and to support the efficient large scale deployment of CCS. ENOS is striving to promote collaboration between sites in the world through a programme of site twinning, focus groups centered around operative issues and the creation of a leakage simulation alliance.

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## 1. The ENOS project

### 1.1. Context

Currently, only a few large-scale CO<sub>2</sub> Capture and Storage (CCS) demonstration projects exist in Europe, either in operation or preparation, and they are all offshore storing CO<sub>2</sub> in deep geological formations (e.g. Sleipner and Snøhvit - NO, ROAD - NL, Peterhead and White Rose - UK). The onshore large-scale integrated CCS demonstration projects that were in preparation under the EEP and NER300 schemes have largely been either cancelled or suspended (e.g. Janschwalde - DE, Belchatow - PL, Florange - FR, Getica - RO, Compostilla-Duero - ES). Although there are general financial and economic constraints involved in getting large-scale integrated projects off the ground, the challenges are much greater when the storage site is onshore, mainly due to safety and environmental concerns

However, in order for the EU to reach its commitment of an overall reduction of greenhouse gas emissions of at least 80% by 2050, CCS needs to be deployed widely and applied to power plants and key industries by then. This means storing 3 to 13 billion tonnes of CO<sub>2</sub> across Europe by 2050. In light of these figures, Europe cannot rely solely on the North Sea, despite its great and readily available storage potential; CO<sub>2</sub> geological storage also needs to be deployed onshore. Developing onshore storage, relatively near the emission points, will contribute to reducing the costs of CCS, enable territories to manage their CO<sub>2</sub> emissions locally, and build lasting public confidence in CCS as a mitigation option that can also contribute to local economic development. Therefore to reach the EU's ambitious goal of greenhouse gas emission reduction, while ensuring the security, flexibility and competitiveness of energy supply, deployment of onshore CO<sub>2</sub> storage will be crucial.

The ENOS project is an initiative of CO<sub>2</sub>GeoNet, the European Network of Excellence on the geological storage of CO<sub>2</sub> [1,2,3], and a result of its recognition of the need to support onshore storage as a priority in today's context. CO<sub>2</sub>GeoNet is committed to facing the technical and societal challenges for CCS through coordinated research and the global dissemination of scientific knowledge on CO<sub>2</sub> storage.

### 1.2. Objectives of the project

ENOS will focus on onshore storage, with the demonstration of best practices through pilot-scale projects and field laboratories, integration of CO<sub>2</sub> storage in local economic activities and creating a favourable environment for CCS onshore through public engagement, knowledge sharing and training.

The objective of the project is to enable the development of CO<sub>2</sub> storage onshore in Europe by:

1. Developing, testing and demonstrating in the field, under “real-life conditions”, key technologies specifically adapted to onshore contexts. Research and Development (R&D) at pilot sites and experiments under real-life conditions will allow demonstration of technologies for safe and environmentally sound storage in relevant environments. The portfolio of field sites in ENOS will also provide great opportunities for on-site training and dialogue with local authorities and civil society.
2. Contributing to the creation of a favourable environment for onshore storage across Europe, by i) supporting knowledge sharing to maximise the benefits of demonstration from each site, ii) integrating

research results and setting out best practices on key topics based on the findings from real-life experiments, iii) supporting the preparation of new pilot projects and upscaling from pilot to demonstration, iv) bringing innovation to society through dialogue and communication and v) promoting CCS through training and education.

Involvement of a range of stakeholders and the general public in the development of best practices will enable the project partners to discuss, test and include wider requirements for CO<sub>2</sub> storage implementation. This will produce well integrated research outcomes and, at the same time, increase understanding by stakeholders, including the public, of the necessity for wide implementation of CO<sub>2</sub> storage. In this framework of improved understanding, the project will support the preparation of new onshore pilots and demonstration projects in various countries and geological settings in Europe, also taking into account the specific socio-economic context of the territories concerned and local benefits such as job creation or preservation.

Although the project is designed to address concerns specific to onshore storage, a number of outcomes from onshore pilots and field experiments will be also useful for offshore storage development. In particular, it is easier and cheaper to test certain storage technologies onshore rather than offshore. This will be highlighted in the best practices that will be produced by ENOS.

### 1.3. Work Programme

The main objective of ENOS is to help to remove the immediate hurdles to onshore CCS deployment by further developing key technologies and preparing a favourable (societal, regulatory and technological) environment. The main challenge facing onshore CCS is to gain the confidence of the public, but also of operators, emitters, investors, policy-makers, and regulators. This incorporates:

- a. Demonstrating through practical experience that injection operations can be run safely and efficiently onshore, which is key for optimising operations and to enable a positive regulatory environment;
- b. Ensuring that estimated matched storage capacities are sufficiently reliable and also affordable to verify, which is needed to enable investment in projects and therefore the deployment of CCS;
- c. Demonstrating our capacity to understand, detect and manage potential leakage risks, which is key for regulatory issues and to demonstrate storage is environmentally sound and safe for human health;
- d. Integrating CO<sub>2</sub> storage into the local economic activities so that the benefits are also reflected at the local scale, which is vital to enable the deployment of CCS;
- e. Engaging the local population in the storage projects, without which project development is impossible.

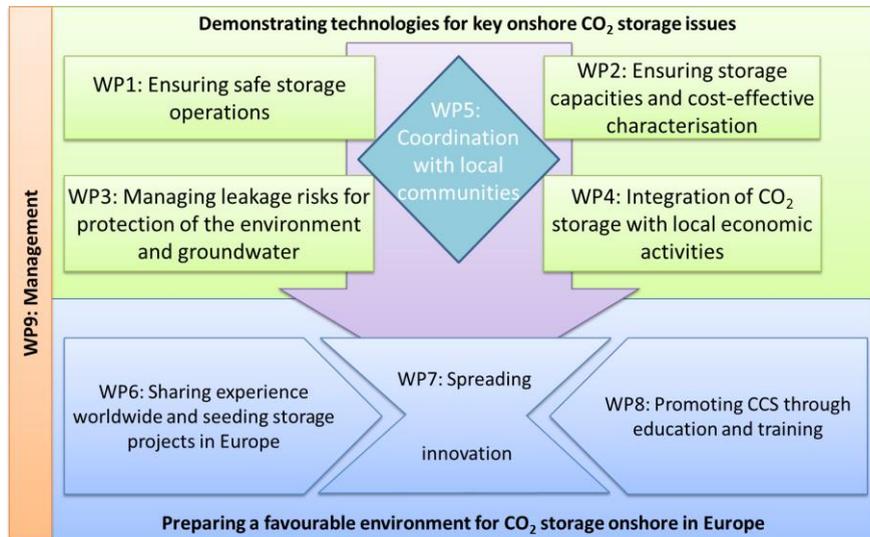
The experience acquired on these issues at the various sites will be compared with other experiences worldwide, and then integrated into protocols, proposed standards and best practices. This knowledge will be made available to operators, regulators and scientists through the ENOS innovation management strategy and education and training. Involvement of industrial partners and input from external stakeholders will ensure that the deliverables are fit for purpose.

The ENOS work programme will be organised into 9 work packages (WP) as follows. A first group of WPs (1 to 4) will focus on demonstrating technologies able to tackle key issues for onshore CO<sub>2</sub> storage in close connection with the local communities (WP5). The 4 key issues identified are: ensuring safe storage operations (WP1), ensuring robust storage capacities and cost-effective characterisation (WP2), managing leakage risks for protection of the environment and groundwater (WP3) and integrating CO<sub>2</sub> storage with local economic activities (WP4). WP5 will aim to establish a collaborative relationship between research teams and the local communities, focusing around new/future pilot sites. It will bring research outcomes and their impacts on society to the population and bring concerns and societal challenges to the researchers.

The second group of WPs (6 to 8) will prepare a favourable environment for CCS onshore in Europe. Relying on the results from WP1-5, they will maximise the impact and innovation potential of ENOS. WP6 aims to share experience with other onshore projects in the world, and drawing on all past experiences, to support the preparation of new pilot and demonstration projects in Europe. By integrating research outcomes and bringing them to stakeholders and the market, WP7 will allow the spreading of innovation achieved in ENOS, mainly through best

practices and identification and protection of project intellectual property. WP8 will address training and capacity building needs for a new generation of scientists. Lastly, WP9 will be dedicated to project management. Figure 1 illustrates the ENOS project structure.

Figure 1: ENOS Work Package (WP) structure



ENOS has been endorsed by the CCS Joint Programme of the European Energy Research Alliance (EERA) of the SET-Plan, thanks to the proposed work programme that addresses the alliance research priorities

#### 1.4. Progressing technologies from TRL 4-5 to TRL 6

ENOS will focus on progressing technologies that have already reached Technology Readiness Level (TRL) 4 (validated in laboratory) or TRL5 (validated in relevant environment, i.e. in the field, occasionally/with small equipment) with the aim of bringing them to TRL6 (demonstrated in relevant environment, i.e. in the field, over long periods with adapted equipment) by the end of the project. The technologies considered will be those most needed to enable onshore CO<sub>2</sub> storage, advancing site characterisation operation, risk assessment, monitoring and management of leakage risks. These are necessary to answer specific onshore storage concerns, such as:

- a. Increased data availability for improved site characterisation, through low cost and smart drilling adapted to onshore context;
- b. Improved site characterisation enabling a better assessment of storage capacity and performance, particularly for onshore deep saline aquifers;
- c. Adapted and specific monitoring technologies and strategies for onshore settings;
- d. Preservation of groundwater used for human consumption;
- e. Preservation of onshore terrestrial and aquatic ecosystems, to protect the environment and human health;
- f. Detection and quantification of any CO<sub>2</sub> leakage (emissions) at ground surface;
- g. Increased understanding and prevention of induced seismicity, crucial to onshore context;
- h. Management of multiple uses of the subsurface;
- i. Integration of onshore CO<sub>2</sub> storage with local economic activities.

### 1.5. Real-life conditions

Real-life conditions are critical to the objectives of the Work Programme. ENOS has therefore built a comprehensive portfolio of sites, representing a variety of geological and socio-economic contexts and different stages of the storage lifecycle. This set of sites, with a good range of onshore contexts in various Member States, will allow technologies already at levels TRL4-5 to be tested and increased to TRL6, while favouring CO<sub>2</sub> storage development across Europe. All the proposed sites have either already benefited or shall benefit from funding outside the present call (industrial, national, European or own funding) and their operational plans extend beyond the scope of the ENOS project. The activities proposed in ENOS are complementary to those already funded and will enable additional research on these sites, liaising with other sites and comparison of results and experience, therefore maximising knowledge sharing in Europe and smart alignment of financial resources from various European stakeholders. The sites can be divided into three categories: operational storage pilot, field laboratories for leakage simulation and storage sites in the planning and characterisation phase. Table 1.1 summarises the sites operated by ENOS partners and the issues related to onshore storage that they will be used to address.

#### **Operational storage pilot site:**

*Hontomin – Spain:* The Spanish CO<sub>2</sub> storage technology development site, where injection at 1 500 m depth in a fractured carbonate reservoir in an anticlinal dome structure began in 2014. The site has been developed and equipped through the EEP scheme and national funding and has been recognised by the European Parliament as a key test facility for onshore CO<sub>2</sub> storage. The site will allow acquisition of experience in a complex setting on issues that a future CO<sub>2</sub> storage operator might face, e.g. pressure management, low matrix permeability, impact of fractures or control of induced seismicity. A significant budget (2M€) from ENOS will be dedicated to buying and injecting 10ktonnes of additional CO<sub>2</sub> in order to work in real-life conditions. At Hontomin ENOS will:

- a. test safe injection and innovative monitoring tools,
- b. develop a protocol for safe management of the site including induced seismicity control
- c. underpin the importance of local community engagement during the operational phase.



Figure 2: The Hontomin Pilot site: injection infrastructure and CO<sub>2</sub> tanks

**Field laboratories for leakage simulation:**

CO<sub>2</sub> will be injected at two sites in order to simulate unwanted migration and leakage of CO<sub>2</sub>, and advance our ability to detect and quantify CO<sub>2</sub> leakage onshore. The experiments will enable a better understanding of the processes involved in CO<sub>2</sub> migration within overburden, provide critical field data on CO<sub>2</sub> migration in a faulted context and reactivity in an aquifer and offer the opportunity to test cutting-edge monitoring technologies.

*Sulcis Fault Lab* - Italy: As part of the 10 year Italian R&D program for CCS demonstration in Sardinia, an experimental open research platform is being created to study CO<sub>2</sub> flow along faults. CO<sub>2</sub> will be injected near a fault at 200-300 m depth from 2017 onwards. Wells will enable monitoring of the CO<sub>2</sub> behaviour underground.

*GeoEnergy TestBed (GTB)* – United Kingdom GeoEnergy Research Centre, GERC (a UNOTT and BGS joint venture) owns and funds a site that will enable fully-monitored injection and migration of CO<sub>2</sub> into the Sherwood Sandstone (an important UK resource for CO<sub>2</sub> storage, oil & gas extraction, and a major onshore aquifer) at depths of up to 250 m. It will enable the study of a heterogeneous mudstone caprock, injection into a shallow near-surface control aquifer (~ 25 m depth), and research into leakage migration along localised natural faults. Site characterisation is underway, with the first borehole planned for summer 2015, and CO<sub>2</sub> injection will start end 2016.

**Storage sites in the planning and characterisation phase:**

*LBr-1* - Czech Republic: LBr-1 is a depleted oil field in the Czech Republic where a small-scale storage pilot is in preparation through the REPP-CO<sub>2</sub> project (see page 7). The reservoir, Miocene sandstones at ~1100 m depth hydraulically connected to an aquifer, is a typical example of a hydrocarbon-bearing structure in the Vienna Basin, one of the oldest hydrocarbon provinces in Europe. The site will be used to i) assess the potential for unwanted migration and/or leakage through abandoned boreholes and faults and ii) investigate reservoir behaviour in the presence of CO<sub>2</sub> and hydrocarbons, including possible mobilisation of hydrocarbons and use of CO<sub>2</sub> for Enhanced Oil Recovery (EOR).

*Q16-Maas site* – The Netherlands: The Dutch gas field Q16 Maas with onshore surface installations is currently under consideration, as part of a Dutch programme (see page 6) for the development of a CO<sub>2</sub> buffer prior to utilisation. The 2 800 m deep Triassic sandstones of the gas reservoir have an estimated storage capacity of about 1.8 Mt CO<sub>2</sub>. This large buffer will offer storage for industrially produced CO<sub>2</sub> in the wintertime and back production in summertime for greenhouse horticulture companies and thus guarantee the security of supply with increasing demand for CO<sub>2</sub>, which is commonly used in greenhouses to enhance plant growth. Underground buffering is the only solution considering the scale of the buffer capacity needed. Such buffer storage could also be necessary for other uses of CO<sub>2</sub> and for collecting emissions before sending them to larger storage sites, including offshore. Site specific data will be used to study the conditions of back production of CO<sub>2</sub> (for use or transfer) and to assess the economic viability of implementing such facilities.

*Sulcis pilot* - Italy: As part of the 10 year Italian R&D programme for CCS demonstration in Sardinia, a full chain pilot project is under preparation. The target reservoir is a limestone aquifer at a depth of about 1 300 m [3]. The initial 3 year programme (2014-2017) is funding activities ranging from site characterisation to test injection, in addition to the fault test infrastructure mentioned above. It includes i) geological and geochemical studies; ii) seismic survey, geological and geophysical modeling and exploration; iii) experimental injection of CO<sub>2</sub>. In ENOS, this site will allow analysis on applicability of low cost drilling technology and possibly implementation of smart characterisation tools.

Country	Site	Type of storage	Depth	Reservoir	Phase	Issues related to onshore storage addressed
Spain	Hontomin	Deep saline aquifer	1500 m	carbonate	injection	b. Site characterisation techniques enabling a better assessment of storage capacity and performance c. Onshore adapted and specific monitoring technologies and strategies d. Preservation of groundwater used for human consumption e. Preservation of onshore ecosystems, to protect the environment and human health f. Localisation and quantification of any CO <sub>2</sub> leakage at ground surface g. Increased understanding and prevention of induced seismicity
UK	GeoEnergy Test bed (GTB)	Injection site into shallow aquifer with caprock	250 m	sandstone	characterisation and injection	c. Onshore adapted and specific monitoring technologies and strategies d. Preservation of groundwater used for human consumption e. Preservation of onshore ecosystems, to protect the environment and human health f. Localisation and quantification of any CO <sub>2</sub> leakage at ground surface
Italy	Sulcis Fault Lab	Injection tests through faults	250 m	fault through volcanic rock, clays, limestones	characterisation and injection	c. Onshore adapted and specific monitoring technologies and strategies d. Preservation of groundwater used for human consumption e. Preservation of onshore ecosystems, to protect the environment and human health f. Localisation and quantification of any CO <sub>2</sub> leakage at ground surface
Czech Rep.	LBr-1	Depleted oil field	1100 m	sandstone	characterisation	d. Preservation of groundwater used for human consumption i. Integration of onshore CO <sub>2</sub> storage with local economic activities f. Localisation and quantification of any CO <sub>2</sub> leakage at ground surface h. Management of the multiple uses of the subsurface
Netherlands	Q16Maas	Buffer storage in depleted O&G fields	2800 m	sandstone	characterisation	i. Integration of onshore CO <sub>2</sub> storage with local economic activities h. Management of the multiple uses of the subsurface
Italy	Sulcis pilot	Deep saline aquifer	1500 m	limestone	characterisation	a. Low cost and smart drilling to increase data availability for improved site characterisation b. Site characterisation techniques enabling a better assessment of storage capacity and performance

Table 1.1: Site portfolio for ENOS and issues these sites will help to address

### 1.6. Local community engagement

Onshore CO<sub>2</sub> geological storage is highly reliant on the confidence the local authorities and population will place in the technologies and the storage projects. ENOS will undertake innovative work to involve the local population with the research teams and create a space for dialogue to encourage a favourable environment where storage can be implemented. This work will be undertaken at sites in the planning and injection stages.

### 1.7. Knowledge sharing in Europe and globally

Building on experience and initiatives of CO<sub>2</sub>GeoNet, an ambitious programme of knowledge sharing and dissemination will be undertaken in order to maximise the impact of ENOS and other CCS projects. The aim is to pass on the experience gained from onshore experimental sites within the ENOS portfolio and worldwide to projects under creation in Europe and thus improve their chances of coming to fruition. The resulting knowledge will also be passed on to the next generation of scientists, through dedicated training sessions, and integration of specific modules into academic curricula.

## 2. Fostering international cooperation around pilot and test sites

To accelerate the deployment of safe, large-scale and commercially viable CCS projects, it is essential that the community of leading pilot and industrial-scale, projects shares knowledge and experiences. The number of sites actually injecting CO<sub>2</sub> in the underground is still too limited and fostering experience sharing and research alignment between existing sites is key to maximise the investment made at individual sites.

Learning from the successful operation of these projects is seen as crucial for enabling the widespread commercial application of near zero emission power plants or industrial installations to allow Europe to reach its environmental objectives, stimulate job creation, and generate a sustainable economic and industrial base.

ENOS will build up on the previous experience from CO<sub>2</sub>GeoNet and from the Demo Network with the GCCSI. Enhancing experience sharing amongst pilot sites and field experiments worldwide and providing opportunities for research alignment will leverage research investments made at each of the different sites as well as in previous and current research projects.

ENOS will develop three initiatives to promote knowledge sharing:

1. Site twinning between similar pilot sites:
2. Leakage simulation network:
3. Experience sharing Focus Groups:

### *2.1. Storage Site twinning programme*

A twinning programme, aimed at creating a durable close working relationship between onshore site owners, is being set up. It consists of mutual visits, regular exchanges of information and data, discussions on real-life issues encountered by the twinned sites operations and where possible identification of collaborative actions to address those issues through research alignment and cooperation. The twinning partnerships that are being initiated are i) Sulcis, – Janggi (Korea) – South Africa Pilot CO<sub>2</sub> Storage Project; ii) Hontomin – Batelle site in Michigan Basin (USA) – Otway (Australia) and iii) LBr1 – Kansas Wellington Field.

### *2.2. Leakage simulation alliance*

Worldwide there are several sites planning to study CO<sub>2</sub> leakage in different environments and conditions through real-life field injection experiments. The alliance will foster cooperation and allow comparison and generalisation of results. The sites proposed for the alliance are the GeoEnergy Test Bed (UK) and the Sulcis fault (Italy) sites from ENOS, as well as the Carbon Management Canada (CMC), South Korean K-COSEM and South African Bongwana Fault (natural analogue) site. If possible other sites will be added during the course of the project.

Activities will consist of site visits, workshops, data exchange and joint reports/publications. It is proposed that one workshop will be held in Canada in conjunction with the annual CMC workshop to allow attendance at both events and a visit to the CMC Field Research Station.

Visits will explore the possibility of collaborative working across the sites through separate funding mechanisms. This sub-task will build on an existing project funded by the UK CCS Research Centre project involving visits by BGS and UNOTT to forge collaborative links between the GeoEnergy Test Bed and the sites in South Korea, South Africa and Canada.

### *2.3. Experience sharing Focus groups*

ENOS will create several experience sharing groups, which will each target a specific issue that is relevant to all sites. The work will rely on each participant's own research activities with the aim of sharing experience (both successes and failures), exchanging datasets where relevant, and identifying the necessary developments of technologies and methodologies. In contrast to the activities of the twinning program, the focus groups will be open to many sites and research teams and focused on a single issue. European sites will be invited to join.

Anticipated topics for the focus groups are: site characterisation, CO<sub>2</sub> injection management, site monitoring strategy or relation with the local population. The final decision on the topics will be taken in the coming month in agreement with the site owners interested to participate in the groups. The participant of the groups will meet regularly (physically or through webinars) to share their experiences, the issues they face and the potential solutions to overcome them.

## 2.4. International Partners

The partners that will participate in the collaboration programme are:

- Batelle in the USA, running an EOR-storage large-scale test in the oil-bearing carbonate reefs of the Michigan Basin,
- CO2CRC running the Otway site in Australia
- Kansas Geological Survey, preparing to inject CO<sub>2</sub> at a pilot scale in Wellington Field in Sumner County, in the USA.
- KIGAM in South Korea running an onshore pilot Janggi
- K-COSEM Leakage simulation site, Environmental Impact Test (EIT) facility at Eumseong, South Korea
- SACCCS in South Africa, currently preparing a pilot as part of the South African CCS road Map
- CMC in Canada setting up a leakage simulation site, where CO<sub>2</sub> will be released at 300-500m depth

Additional site owners interested to share their experience will be welcome to join the initiative.

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