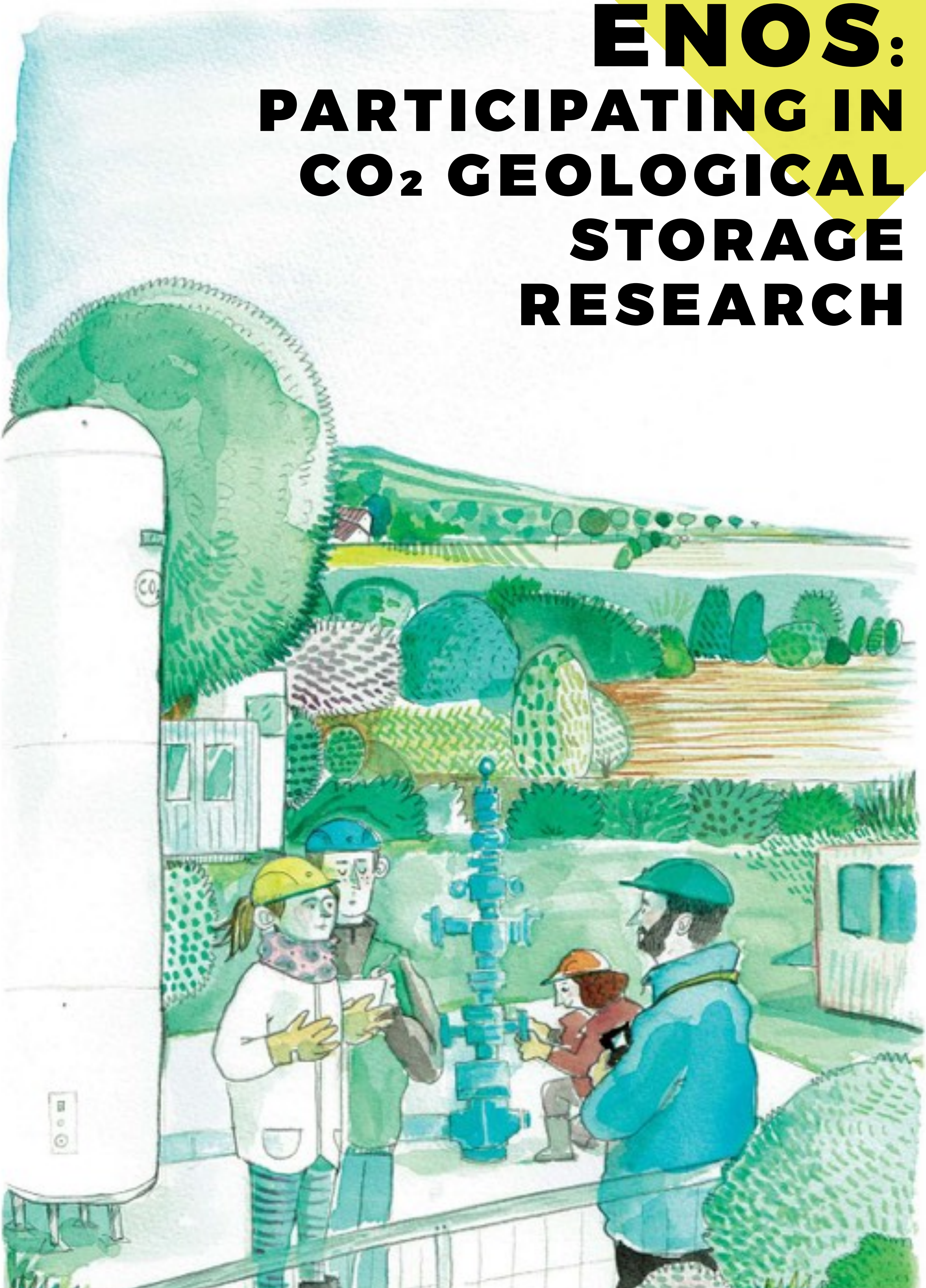
ENOS: PARTICIPATING IN CO_2 GEOLOGICAL STORAGE RESEARCH



CO_2 STORAGE EXPERIMENTAL SITE
SAPIENZA UNIVERSITY OF ROME – CERI –

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

ENOS

PUTTING ENOS RESEARCH INTO CONTEXT

THE ENOS "VISION" FOR ONSHORE CO_2 STORAGE IN EUROPE: STRENGTHENING THE SCIENCE FOR A TECHNOLOGY THAT IS SAFE, ECONOMIC, AND SUPPORTED BY THE LOCAL COMMUNITIES

CREATING A SPACE WITH LOCAL COMMUNITIES TO REFLECT TOGETHER ON ENOS RESEARCH

THE ENOS PROJECT AND THE SCIENTIFIC COMMUNITY WORKING ON CO_2 STORAGE

TESTING THE STORAGE TECHNOLOGY IN REAL LIFE CONDITIONS

HOSTING A STORAGE SITE

THE ROLE OF CCS FOR LOCAL DEVELOPMENT

CO_2 STORAGE IN THE TERRITORIAL AND TECHNOLOGICAL CONTEXT

WHAT DO YOU THINK? PROS AND CONS OF CCS

CO_2 STORAGE ISSUES ADDRESSED IN ENOS

BETTER STRATEGIES FOR MONITORING CO_2 BEHAVIOUR: PROTECTING THE ENVIRONMENT AND GROUNDWATER

ENOS AND THE DEVELOPMENT OF SAFE STORAGE SITES

REDUCING RISKS TO AN ACCEPTABLE LEVEL

ENOS WILL CONTRIBUTE TO REDUCING CO_2 STORAGE COSTS

ENOS WILL EXPLORE HOW CO_2 STORAGE CAN BRING ECONOMIC BENEFIT IN ADDITION TO REDUCING CO_2 EMISSIONS

ENOS WILL IMPROVE THE CONCEPT AND PRACTICE OF CO_2 STORAGE MONITORING

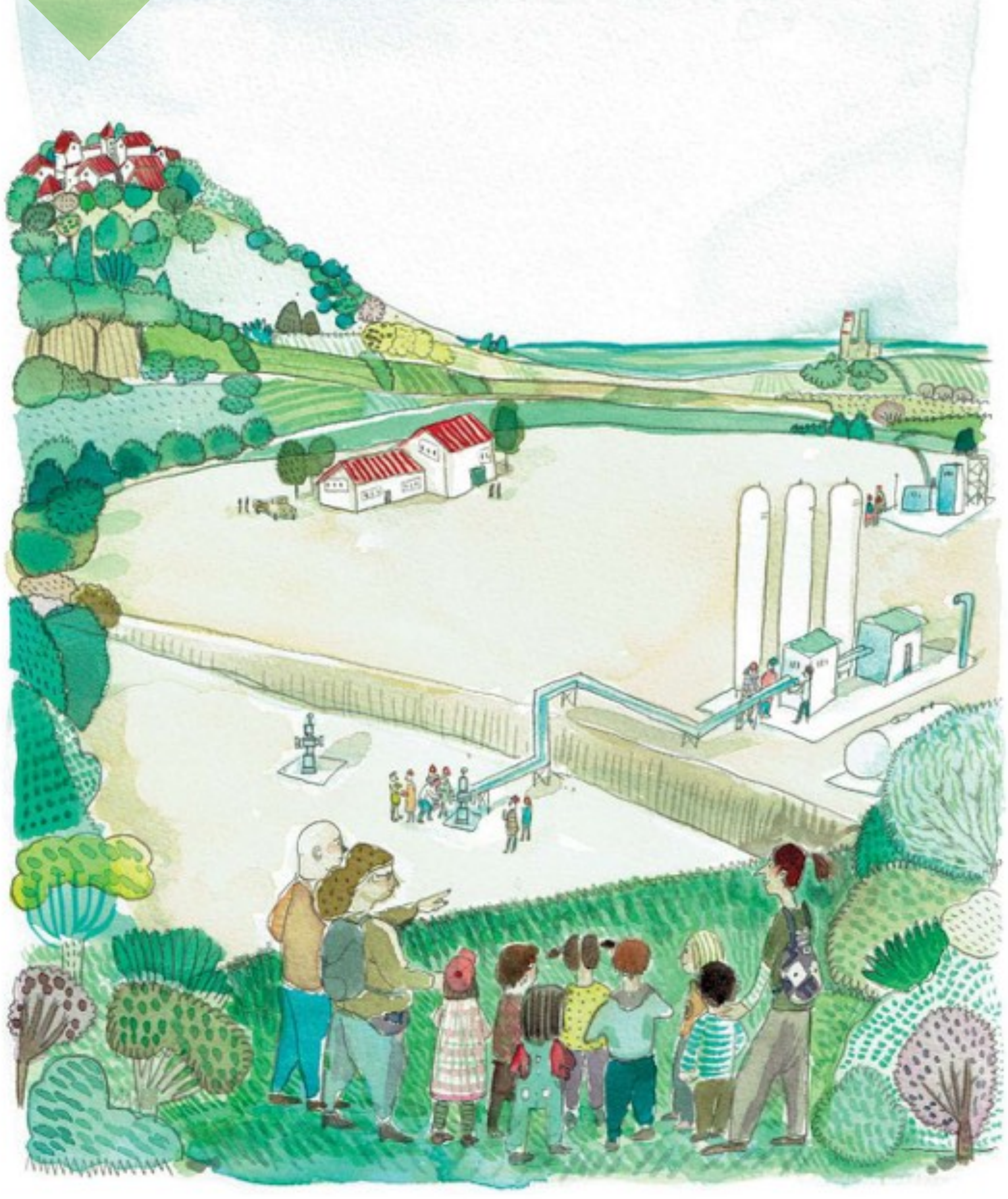
HELPING PEOPLE TO BE INFORMED AND TO FOLLOW THE DEVELOPMENT OF A STORAGE PILOT

MANAGING THE COMPLEXITY OF STORAGE THROUGH MODELLING

FOSTERING INTERNATIONAL COLLABORATION

INCREASING THE PREPARATION OF RESEARCHERS AND PROFESSIONALS IN THE FIELD OF CO_2 GEOLOGICAL STORAGE

THE ENOS "VISION" FOR ONSHORE CO_2 STORAGE IN EUROPE



CO_2 STORAGE PILOT SITE
SAPIENZA UNIVERSITY OF ROME – CERI –

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

THE ENOS "VISION" FOR ONSHORE CO_2 STORAGE IN EUROPE: STRENGTHENING THE SCIENCE FOR A TECHNOLOGY THAT IS SAFE, ECONOMIC, AND SUPPORTED BY LOCAL COMMUNITIES

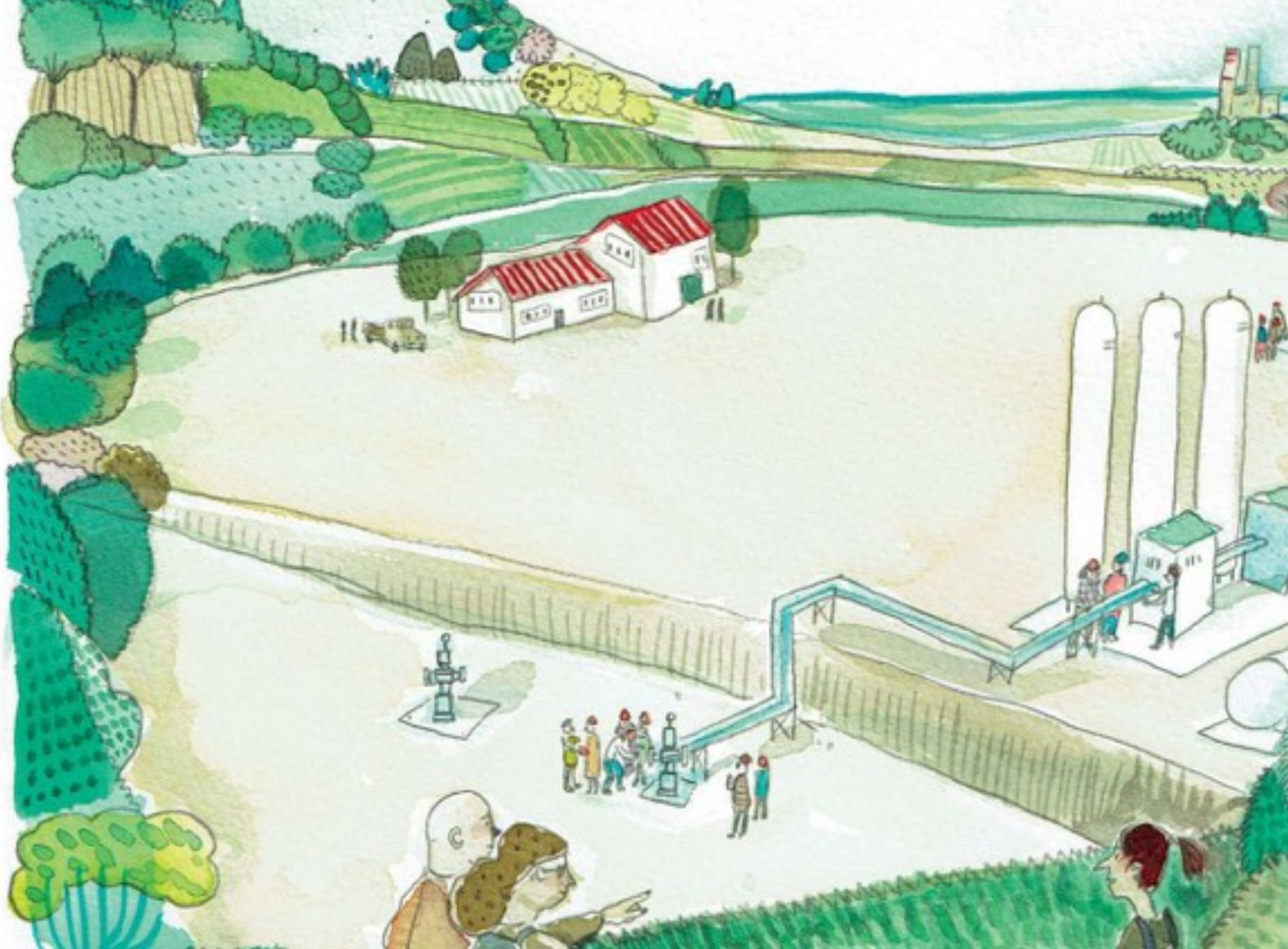
Carbon dioxide Capture and Storage (CCS) could play a key role to meet the ambitious target set by the European Union of an 80% reduction below 1990 level of greenhouse gas emissions by 2050. For this to happen, the technology needs to move rapidly towards full-scale implementation, with geological storage solutions based both onshore, underground on the mainland, and offshore, under the seabed.

In particular, onshore storage offers increased flexibility and reduced infrastructure and monitoring costs. Enabling onshore storage can support strategies to reduce CO_2 emissions at the territory level, enhancing the security of energy supply and local economic activities, and securing jobs across Europe.

ENOS ADDRESSES THE NEED TO REFINE THE TECHNOLOGY FOR ONSHORE APPLICATION

and to identify best practices that can make onshore CO_2 storage successful both at the technical and social level. The research in ENOS aims to enable CO_2 storage sites that are increasingly safe, economic and synergic with other commercial activities. ENOS will develop, test and demonstrate key technologies and methods in the field, under "real-life conditions". Best practices will be identified using experience gained from the field experiments, with the participation of local stakeholders and the public.

ENOS is a European research project working for the development of a technology that respects scientific requirements, is implemented by specifically trained professionals, is understandable by all, and carried out in collaboration with local communities.



REFLECTING TOGETHER ON ENOS RESEARCH

GROUP DIALOGUE
SAPIENZA UNIVERSITY OF ROME – CERI – CC BY NC ND

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

CREATING A SPACE WITH LOCAL COMMUNITIES TO REFLECT TOGETHER ON ENOS RESEARCH

Coordination of the research development with local communities is one of the key features of the ENOS project. This is an innovative concept and is meant to support the management of highly complex technological innovation. When technicians develop industrial scale technologies, without involving social stakeholders, a gap is often created between how a technology is seen by professionals and by the public. This can lead to technologies that are not fully satisfactory from a social point of view. Creating opportunities for civil society to provide input directly, during the research process, can help researchers to better address public wishes and concerns.

Whereas collaborative science and society research processes are not new in other sectors, this approach is just starting for CCS. In addition, these studies usually involve technical stakeholders or civil society organisations, rather than the local population who live near existing or potential storage sites, despite the fact that these are the stakeholders most affected by technical choices made by scientists and operators.

ENOS will therefore prioritise local residents, who will be involved in the production of best practices for the development of storage sites. Researchers and citizens will be able to explore together the different aspects of the technology and of its implementation, going deep into the issues that the project is addressing, looking together for the best solutions and practices for the development of CO_2 storage sites.

THE WORK WILL BE CONDUCTED WITH THE LOCAL COMMUNITIES IN FOUR COUNTRIES:

in Italy, in the Sulcis area, where studies for geological characterisation have been on-going for some years, to build up knowledge for a prospective pilot site; in Spain, where an advanced pilot site is operating at Hontomin; in The Netherlands, where no specific project is planned, but interesting benefits could come from associating CO_2 storage with CO_2 use; and in the United Kingdom, at the GeoEnergy Test Bed (GTB) experimental site, Sutton Bonington.

THE SCIENTIFIC COMMUNITY WORKING ON CO_2 STORAGE

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

THE ENOS PROJECT AND THE SCIENTIFIC COMMUNITY WORKING ON CO_2 STORAGE

The ENOS project is a recent addition to a larger effort that CO_2GeoNet, the European Network of Excellence on the Geological Storage of CO_2, has been conducting over the last 13 years. The scientific community represented in the network has a long standing commitment for research on CO_2 storage, to strengthen the scientific basis of this technology. CO_2GeoNet was first formed in 2004 under the Sixth European Framework Programme for Research and Technological Development, to support the collaboration of the various research groups working throughout Europe on this topic. The European Commission (EC) considered it important to unite efforts, given the great potential of Carbon dioxide Capture and Storage to significantly reduce CO_2 emissions from sectors that make intensive use of fossil fuels, like power generation and heavy industry. In 2009, after the end of the EC funding, CO_2GeoNet became a non-profit scientific association under French law, continuing its commitment to coordinate, produce and disseminate CO_2 storage research. With time the community has grown more and more. It now includes 26 research organisations from 19 countries and it has established links with many other research institutions and networks around the world. Recently CO_2GeoNet has identified research into onshore storage as a priority in today's context, together with the need for an integrated approach which comprehends scientific, technical, social, economic, regulatory, educational, and communication issues. This has led to the ENOS project, which aims to fill the gaps that still exist, for defining the best practices for onshore storage in Europe.

ENOS WILL BRING TOGETHER THE CONTRIBUTION OF MANY DISCIPLINES, AS WELL AS THE INPUT OF CIVIL SOCIETY,

including citizens and a variety of potential end-users. Building on the experience of CO_2GeoNet, ENOS will thus further refine the technology and its safety, look for possible synergies of CO_2 storage with other economic activities, understand how to coordinate its development with local communities and pave the way for new pilot projects, contributing to training and communication, and collaborating with other international research centres.

TESTING THE STORAGE TECHNOLOGY IN REAL LIFE CONDITIONS

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

ENOS

TESTING THE STORAGE TECHNOLOGY IN REAL LIFE CONDITIONS

Technology Readiness Levels (TRLs) are standards that define the level of development reached by a given technology, until that technology is ready for application. The levels are labelled from 1 to 9, from the initial idea, through laboratory tests and field verification, up to a fully operational product. ENOS will take some technologies that have already been demonstrated in the laboratories and test them in the field.

In this way, it is possible to understand their functioning under conditions that are similar to those of future applications at commercial storage sites.

The technologies considered are those most needed to enable onshore CO_2 storage, advancing site characterisation operation, risk assessment, monitoring and management of leakage risk.

At the Hontomin pilot site, in Spain, tools will be validated for a wide range of technologies and methodologies related to injection operations and associated monitoring. At the GeoEnergy Test Bed in the UK and the Sulcis Fault Lab in Italy, suitable tools will be developed to monitor potable water reservoirs, the protection of which is the first priority during all the storage operations, improving their sensitivity and finding solutions to lower the cost of their long-term deployment.

BY INCREASING THE LEVEL OF READINESS OF THE TECHNOLOGY ENOS WILL HELP ACCELERATE ITS AVAILABILITY TO COMMERCIAL OPERATORS,

which is a fundamental step to enable more precise evaluations of the financial investments required for the implementation of a storage site.

Testing of the technologies will be accomplished by cooperating at the Pan-European and global level, exchanging experiences with researchers working at other sites worldwide. The resultant knowledge will be introduced in training and education through Master's degree courses, online learning activities, and summer schools.

HOSTING A STORAGE SITE

CO_2 INJECTION EXPERIMENT OVERVIEW
SAPIENZA UNIVERSITY OF ROME – CERI – CC BY NC ND

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

HOSTING A STORAGE SITE

In the future, if CCS is going to be widely adopted, more communities could be asked to host a CO_2 storage site. What would this entail? In ENOS we would like to help answer this question, both providing information on the practical aspects that involve the population and collecting ideas and experiences from the local communities that are hosting the research sites.

There are different kinds of sites for studying or for implementing CO_2 storage. We can distinguish:

Experimental site: a field laboratory where specific technologies are developed or tested. The objective is not to store CO_2, but rather to conduct experiments on specific topics, using small quantities of CO_2, to improve the monitoring of sites, to test new tools and reduce their cost, to collect data for computer modelling, and various other goals.

Pilot site: it has the purpose of testing the technology and the storage concept as a whole, the complete process. Therefore, it implements on a small scale the same operations that would be put in place by a demonstration or real storage project. Quantities of CO_2 injected are very limited, but in this case the objective is to check how a small storage reservoir in a real world setting works, test injection tools and strategies, test monitoring strategies, and all the other aspects that would have to be considered for a storage site.

Demonstration site: the technology is tested on a large scale to show that it is ready to become commercial. The objective is not so much to show that it works – which in principle has already been proven at pilot sites – but rather to optimise all the processes, which are affected by scale, and cut down costs. It can develop into a full storage site.

Industrial storage site: fully developed site where the storage of CO_2 will be undertaken, for climate reasons to reduce CO_2 emissions, or done in conjunction with other economic purposes, like enhanced oil recovery or other CO_2 uses.

Both experimental and pilot sites are essential for the good development of the technology. Testing a technology requires practical experiments. This helps to find critical points and to solve them. Small scale installations are also key to identify and address remaining challenges, to refine and bring the technology nearer and nearer to high efficiency operations, with the least possible impact and cost.

Pilot and demonstration sites enhance confidence in the ability of underground rocks to safely store CO_2, and local demonstration of CCS technology will encourage further project development. So far, onshore storage has been tested and demonstrated at only a few pilot sites in Europe (i.e. Ketzin - Germany, Lacq-Rousse - France, and recently Hontomín - Spain). Pilots help research to move forward and are complementary to demonstration and industrial deployment. They are a powerful tool to enlarge and strengthen some geo-technological sectors, which will be necessary for future deployment of CCS, such as reservoir engineering, drilling, geophysical exploration, sedimentary geology, geoscientific laboratories or geological consulting. This is particularly needed in countries with scarce hydrocarbon resources, where these sectors may not be as advanced. Pilots will also provide data for other technologies, such as geothermal energy, enhanced oil recovery (EOR), etc.

Understanding what aspects are relevant to local communities in the process of storage site selection, development and operation is still limited. Communities and sites present a very high degree of variability, and combining geological, engineering and social requirements is an important part of the preparation phase for a storage site. This requires a site-specific process. Therefore we need to understand and build more experience on how such an individualised process can develop.

ENOS IS GOING TO INTERACT WITH LOCAL RESIDENTS AND STAKEHOLDERS IN FOUR DIFFERENT CONTEXTS: TWO EXPERIMENTAL SITES, ONE IN ITALY AND ONE IN THE UK;

one pilot site in Spain and a highly industrialised area in the Netherlands, where storage could find interesting application associated to CO_2 use. ENOS will also work in the Czech Republic to understand the possible development of a depleted oil and gas reservoir into a pilot storage site. By hosting an experimental or pilot site in their territory, communities can give valuable contributions to scientific and technological innovation and they also get back a greater knowledge of the local geological resources, which they can use for their benefit.

ROLE OF CCS FOR LOCAL DEVELOPMENT

MAKING DECISIONS TOGETHER
SAPIENZA UNIVERSITY OF ROME – CERI – CC BY NC ND

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020
RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

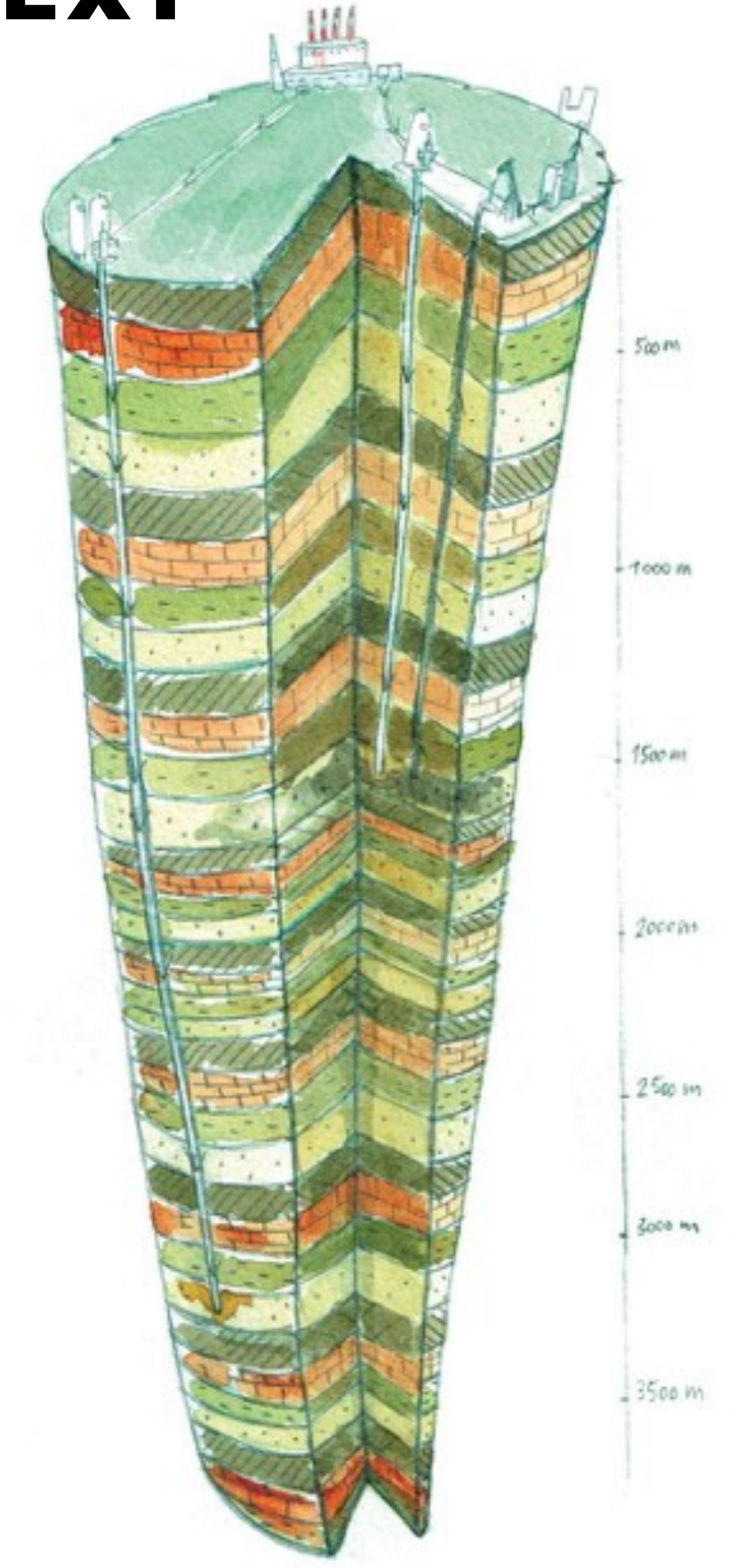
THE ROLE OF CCS FOR LOCAL DEVELOPMENT

CCS can produce a substantial reduction of CO_2 emissions, thus contributing to mitigating climate change on a global scale. However, the benefits it could bring to local development will be critical for the communities that will decide whether to host a storage site. Up to now, local benefits of CCS implementation have been little investigated, as research was centred on the technology itself. In addition, many studies have been directed to offshore storage, as Europe has a large potential for it in the North Sea. However, if storage is to be deployed on a large scale, it will also be necessary to conduct onshore storage, which is also cheaper and easier to monitor. Therefore, understanding all aspects of implementing the technology onshore, including benefits for the local communities, is as important as ever. From the point of view of the local communities, it is essential to know that emissions are not reduced at their expense or in ways that could be detrimental for them.

ENOS WILL ADVANCE OUR KNOWLEDGE OF HOW THE IMPLEMENTATION OF CCS AND CO_2 STORAGE IN PARTICULAR CAN IMPROVE THE LOCAL SITUATION

with regard to the environment, for reducing pollution, favouring employment and economic activities in general. Researchers in conjunction with local stakeholders and residents will try to understand better how the presence of a storage site could, in certain cases, become a benefit for the territory, leading, for instance, to increased technological or commercial development in the area. The possible implementation of CCS will be considered taking into account the specific socio-economic context of the territories concerned.

CO_2 STORAGE IN THE TERRITORIAL AND TECHNOLOGICAL CONTEXT



CO_2 STORAGE AND CO_2-EOR
SAPIENZA UNIVERSITY OF ROME - CERI -

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

CO_2 STORAGE IN THE TERRITORIAL AND TECHNOLOGICAL CONTEXT

When we imagine the implementation of CO_2 storage, we should not see it in isolation. To get a fuller understanding of CO_2 storage in a territorial context, it will be important to consider it in relation to other technologies or industrial operations which take place, either at surface or underground.

The full chain of carbon dioxide capture and storage (CCS) is formed by several elements and the distances between them are key. Storage cannot be separated from the capture of CO_2, where it is emitted, and from transport of the CO_2 to the storage site. Therefore, the location of a storage site, which is first of all determined by the geological characteristics of the area, is also related to the position of large CO_2 emitters. Connecting CO_2 emission points from the power and industry sectors, with the places where the CO_2 can be stored requires the coordination of numerous industries that intensively emit CO_2, and the design of an overall system to reduce their CO_2 emissions. Large emitters without the possibility of storing in their neighbourhood can additionally require the use of technologies for long distance transport, via pipeline or ship. In some cases, transboundary agreements, to store the CO_2 produced in one country in the reservoir that is available in a neighbouring country, may be necessary.

CCS also relates in a variety of ways to oil and gas fields and operations. Natural gas that is extracted can be very rich in CO_2. In such a case, to be able to sell the methane, the oil and gas company will need to separate it from the CO_2. With CO_2 storage it is possible to reinject the CO_2 into the underground, avoiding its release into the atmosphere. Another situation, where we see the association of CO_2 storage with oil and gas operations, is when the injection of CO_2 takes place together with the extraction of oil or gas, which is called "enhanced oil recovery (EOR)". This is a technology that can be used when an oil and gas reservoir is almost depleted, to facilitate the extraction of the remaining hydrocarbons. Finally, CO_2 storage could be complementary to extraction technologies, if used for restoring pressure in gas fields that are undergoing exploitation or are already depleted, in order to avoid subsidence.

Through connections with other technologies, CO_2 storage can help us to achieve "negative" emissions, and also better exploit the energy that is produced by renewables. For example when we grow biomass, it absorbs CO_2 from the air by photosynthesis, acting as a natural CO_2 capture mechanism. If we then burn the biomass for producing energy, and we capture and store the CO_2 released during the combustion, we not only avoid CO_2 emissions, but also subtract CO_2 from the atmosphere.

REGARDING RENEWABLES, CO_2 STORAGE COULD SUPPORT A FULLER USE OF THE ENERGY PRODUCED.

Since we cannot "regulate" the sun and the wind, there are moments when renewable power plants produce more energy than we need. This energy could be used for making synthetic hydrocarbons with CO_2. CO_2 storage and CO_2 use could thus develop jointly, exploiting the energy peaks from renewables to provide energy during periods of low production. There are also other uses of CO_2 that could be associated with storage and which imply complex technological and industrial associations. These include the use of the CO_2 in the agricultural industry, for instance in greenhouses, to increase growth rates.

Finally, an important and delicate issue is the relationship of storage and storage operations with other uses of the subsurface and related technologies. More and more, the underground is the object of a variety of operations, as a source of resources (like hydrocarbons or minerals, geothermal energy), for temporarily storing resources (like natural gas), or as a place for disposing wastes (garbage, industrial fluids, radioactive waste). When considering the potential areas for storage and subsequently managing them, these other forms of use of the subsurface will have to be taken into account, to analyse possible interactions and to avoid interference or conflict of interests between technologies. Since any use of the subsurface has the potential to have an impact, this issue must be addressed and minimised. When many of these uses of the subsurface occur in the same area, it will be critical that such work be coordinated and integrated, to ensure safe and efficient use of local resources.

WHAT DO YOU THINK? PROS AND CONS OF CCS

CONCEPT CO_2 STORAGE

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

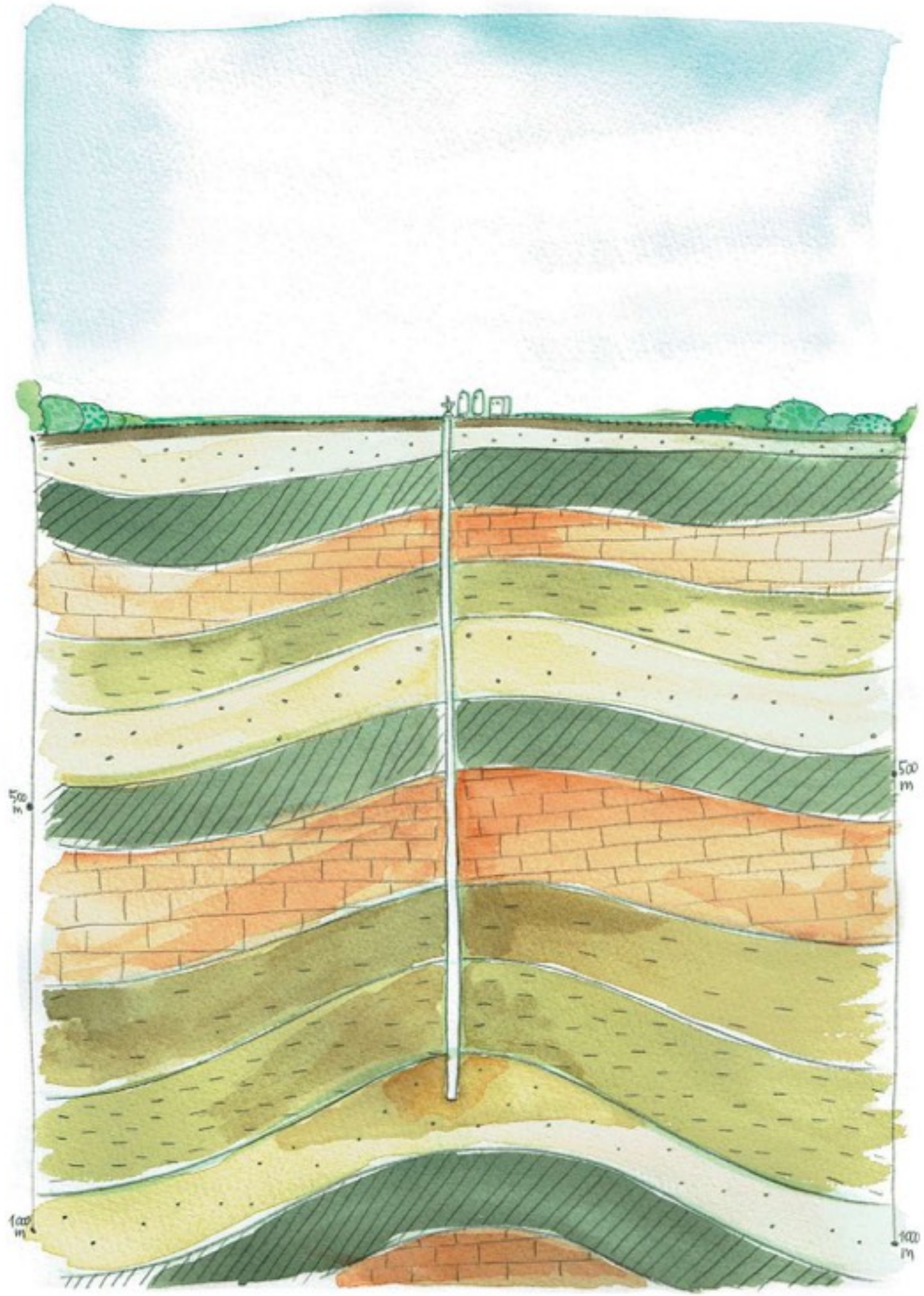
WHAT DO YOU THINK? PROS AND CONS OF CCS

CCS is a technology that allows for the storage of CO_2 in a safe way and for the long term. It is based on a strong scientific background and a large knowledge base, inherited from the oil and gas sector. Of course, like all technologies that can improve our quality of life, CCS can have downsides that should be recognized and, as much as possible, solved. In addition, the decision to implement it must take into account all the other technological options for reducing CO_2 emissions, to identify what are the best choices at a given point in time and in a given context. A correct evaluation of the technology and its possible role will thus rely on a balanced consideration of the advantages and disadvantages related to its implementation. Although making this analysis is not the objective of ENOS, it may be useful, for those who are not familiar with CCS, to summarise the public discussion of the technology's pros and cons. This is a complex issue and we realise that it will not be possible to give an exhaustive, complete, or totally impartial presentation. Within the limits of our researchers' perspective, we will only attempt to briefly illustrate what appear to be the most important highlights or topics regarding CO_2 storage. We will try as much as possible to give useful elements for discussion, "food for thought" so that even people who have never heard about CCS before can start to consider it. We hope that this can be a basis for exchange, during the ENOS activities, on all those aspects that are important for everyone: researchers, local residents, policy makers, environmental activists, industrial operators or other stakeholders. Of course for us, as researchers in the field of CCS, it will be particularly interesting to hear the point of view of non-professionals on CO_2 storage, such as members of the public and other social stakeholders, who will participate in the ENOS activities.

Returning carbon to the underground

Each day we consume considerable amounts of fossil fuels around the world. In many cases the massive burning of fossil fuels takes place at large power generating or industrial plants. If we take a moment to look at the substance that is being burned, we realise that the carbon, of which fossil fuels are made, is the same carbon that, once released to the atmosphere, forms the problematic CO_2 that is contributing to warming our climate. CO_2 geological storage has the significant advantage of allowing us to put this same carbon back underground, from where we extracted it. This can be a "bridging solution" which gives us the time needed for the transition to other low carbon technologies. Some people criticize this concept because they think we should, instead, stop extracting and burning fossil fuels altogether. In this way we would not need to store the CO_2 in the underground. This kind of reflection gives rise to many questions, on whether we can afford to stop using fossil fuels in the short term, how this could be done, how long it might take, where it could be started, and so on. In the meanwhile, fossil fuels continue to be used and account for about 80% of energy production globally. Until this situation changes, can we afford to keep burning oil and gas without storing CO_2 underground?

GROUP DIALOGUE
SAPIENZA UNIVERSITY OF ROME – CERI – CC BY NC ND



CO_2 STORAGE
SAPIENZA UNIVERSITY OF ROME – CERI – CC BY NC ND

The geological concept: is CO_2 storage safe?

Many of the discussions around CCS, and storage in particular, revolve around the issue of safety, especially as information on this topic is scarcely disseminated. The concept of CO_2 geological storage was born from the observation of CO_2 and methane gas reservoirs that are present in nature, where the gas has been trapped in the deep subsurface for thousands or millions of years. Research has thus demonstrated the long term technical feasibility and safety of CO_2 storage. Today, from the point of view of professionals who work on CCS, the technology does not present any serious risk. However, it can be difficult for many people to imagine how a gas can remain trapped in the underground. Gas naturally flows upwards and the safety of CO_2 storage sites is thus often questioned. Will the CO_2 remain in the reservoir or will it escape one way or another? What risk could this pose for human health? Some people also observe that a natural geological trap, like oil and gas reservoirs which have not been drilled, is different from underground fields where there are wells that could act as pathways for gas leakage. Research that has addressed these concerns shows that these conditions represent limited risks that can be managed. More generally, when a site is properly chosen, the geological structures act as barriers, which make the possible escape of CO_2 from the reservoir a very low probability. Another aspect of strong interest, with regard to safety, relates to induced seismicity. People often ask: "Can we exclude the possibility that CO_2 storage might cause earthquakes?" During the injection phase small seismic activity cannot be excluded. When we extract fluids from the underground (water, oil or gas) or we inject them, underground rocks and fluids tend towards a new equilibrium and resultant small movements can lead to the release of energy. This is what researchers term "micro-seismicity", small earthquakes that are not perceived by humans and normally are only detectable using monitoring instruments. During the process of selection of a storage site, predictive modelling and other techniques are used to ensure that any ground movement that may be caused by storage operations will not constitute a risk. Similar to what happens for water extraction at very high flow rates and for oil and gas operations, safety will be ensured by proper management and operation of the storage site.

Lessening or increasing pollution through CCS?

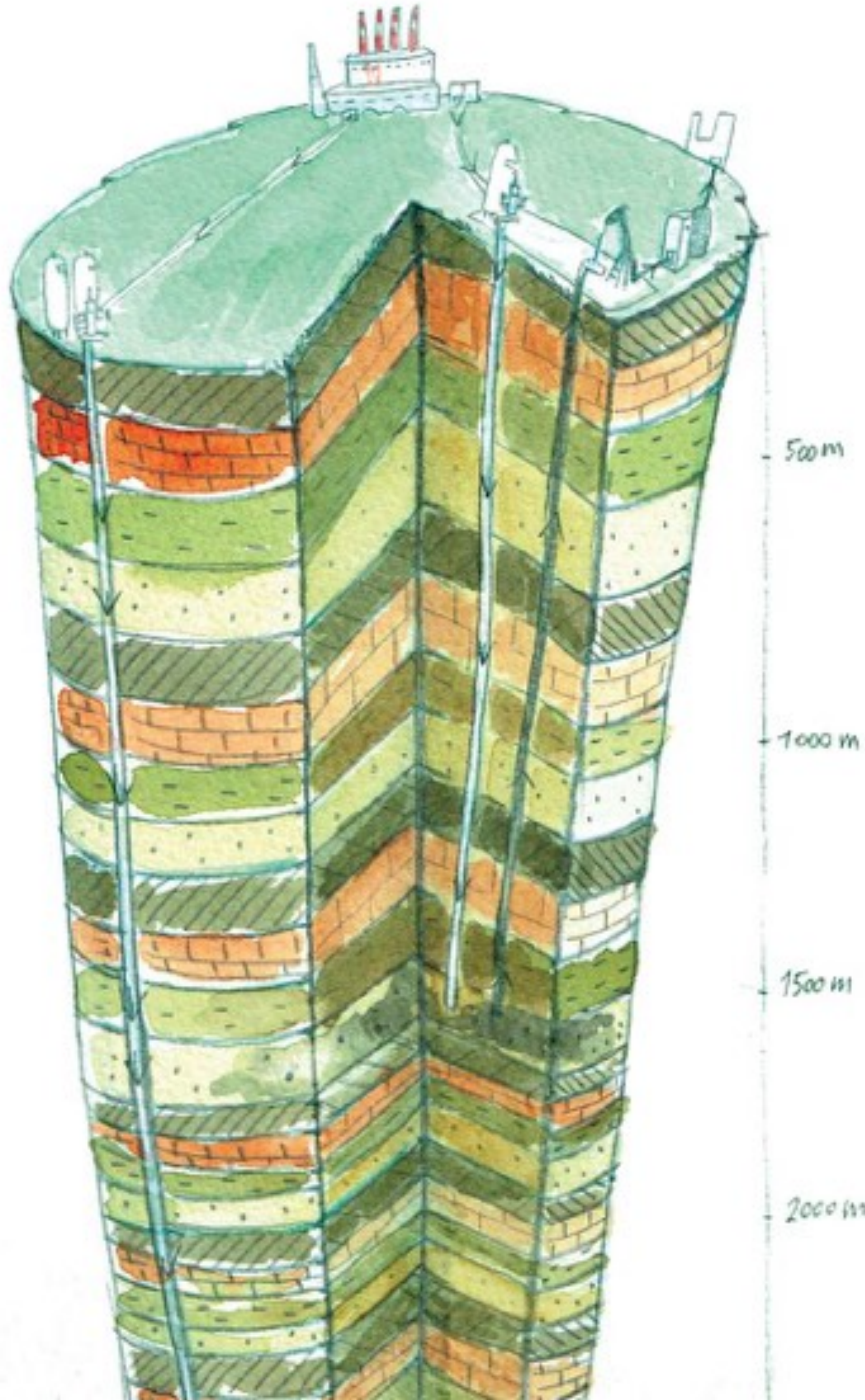
CCS can bring additional environmental side benefits. The sophisticated process for capturing and storing CO_2 can also reduce other pollutants, such as sulphur compounds or particulates. If we consider that CCS would require a complete upgrade of many power plants around the world that presently are very heavy polluters, the role of CCS for environmental protection could be much greater than just reducing CO_2. That said, the pollution related to the implementation of CCS needs to be taken into account, with the building of large-scale infrastructure and the risk of continuing to use fossil fuels beyond the period of time that is strictly necessary to switch to other forms of energy production. A specific aspect that needs consideration here is the so-called "energy penalty": the capture of CO_2 at large power and industrial plants requires a significant energy input (with the exception of some industrial processes which directly facilitate CO_2 separation and capture). The additional energy requirement implies a higher quantity of fuel must be burned, to produce the same amount of energy. This is a major downside of the technology, although it must be considered that the optimisation of the technology could considerably reduce the energy required for CCS.

Can CCS be implemented in Europe?

Being able to manage the complete carbon cycle, protecting the environment, ensuring a reliable energy supply and opening the way to new and more sustainable forms of energy production are key goals of European energy policy. Understanding if and how CCS can play a role is as urgent as ever. Europe in the past was at the forefront of CCS development. Norwegian researchers in the 1980's started to think about the possibility of putting the carbon, released through the combustion of fossil fuels, back underground. In 1996 this idea became a reality at Sleipner, in the North Sea, with the injection into a deep saline aquifer of CO_2 separated from the natural gas that was being extracted. After this promising start, pushed by a timely carbon tax, the pathway of CCS has been uneven. Plans at the European level for the demonstration of the technology have stalled. Some of the forerunner countries, like The Netherlands, Denmark or Germany, have encountered significant difficulties related to public opinion or opposition at the local community level. While funding issues together with the lack of public support have delayed the development of the technology, the use of fossil fuels has continued to produce emissions just as before. Additionally, considering CO_2 in a future perspective, not only as a greenhouse gas but also as a potential commodity (for instance associated with renewables to produce synthetic hydrocarbons), it may be even more important for Europe to advance research and demonstration of CCS.

Implementation readiness

A number of issues must be considered to address the point of CCS readiness for implementation, such as the status of the technology, the existence of (or plans for) the necessary infrastructures, the costs, and governing national and European regulations. In terms of technology, it can be stated with confidence that the knowledge and material exists right now, as CCS (or CO_2-EOR) is already taking place at numerous sites throughout the world. Infrastructure, on the other hand, is at a much earlier stage. For example, pipeline networks that would transport the CO_2 from where it is produced to its final destination, are not yet in place in Europe and would have to be built. This also raises the point of costs, as, for example, construction of such infrastructure would be expensive. The capture of CO_2 is also, at present, very expensive, however investment in research and general support of deployment of the technology have great potential to reduce these costs, as has occurred for energy production via both solar and wind. For these latter two, governments established a long-term vision, regulations, and subsidies that created a favourable economic environment. Similarly, stable and predictable regulations for CCS would permit companies and local governments to have a long-range vision for the implementation of CCS, thus favouring investments in the technology which could make it less expensive.



CO_2 storage can allow for large scale CO_2 emissions' reduction

CCS can manage large amounts of CO_2 produced at industrial sources like power plants, cement factories, steel plants or oil refineries, and be combined with many other energy supply solutions like biomass or geothermal energy production. It can provide a much-needed answer for responsible fossil fuel use, and can be a major source of job creation. For example, the deployment of CCS could catalyse new jobs in the provision of services, the manufacture of components, and the construction of CCS plants. Several economic models have estimated the economic impacts of climate change, concluding that the benefits of strong and prompt action far outweigh the projected economic costs of inaction. CCS could be an important part of this effort.

Can CCS be implemented in Europe?

A common discussion about CCS regards its cost. It requires the building of very large infrastructures for capturing and transporting the CO_2 and consistent investments to identify good sites for storage. Due to the very low price of CO_2, at least at present, spending for CCS is not economical. On the other hand, supporters of CCS note that investing in CCS today can save us from much higher costs in the future, which would be triggered by climate change. When compared to other low carbon technologies, CCS can even be a cheaper solution for reducing CO_2 emissions, one which, however, requires large upfront investments. Who should pay for these investments? If it should be industry, then the cost might affect the whole economic system, impacting on profit and employment. What is commonly suggested is that public funds should be used now, to support the full development of the technology, bringing it to a cost level which facilitates its integration in the industrial system.

CCS and the use of local energy sources

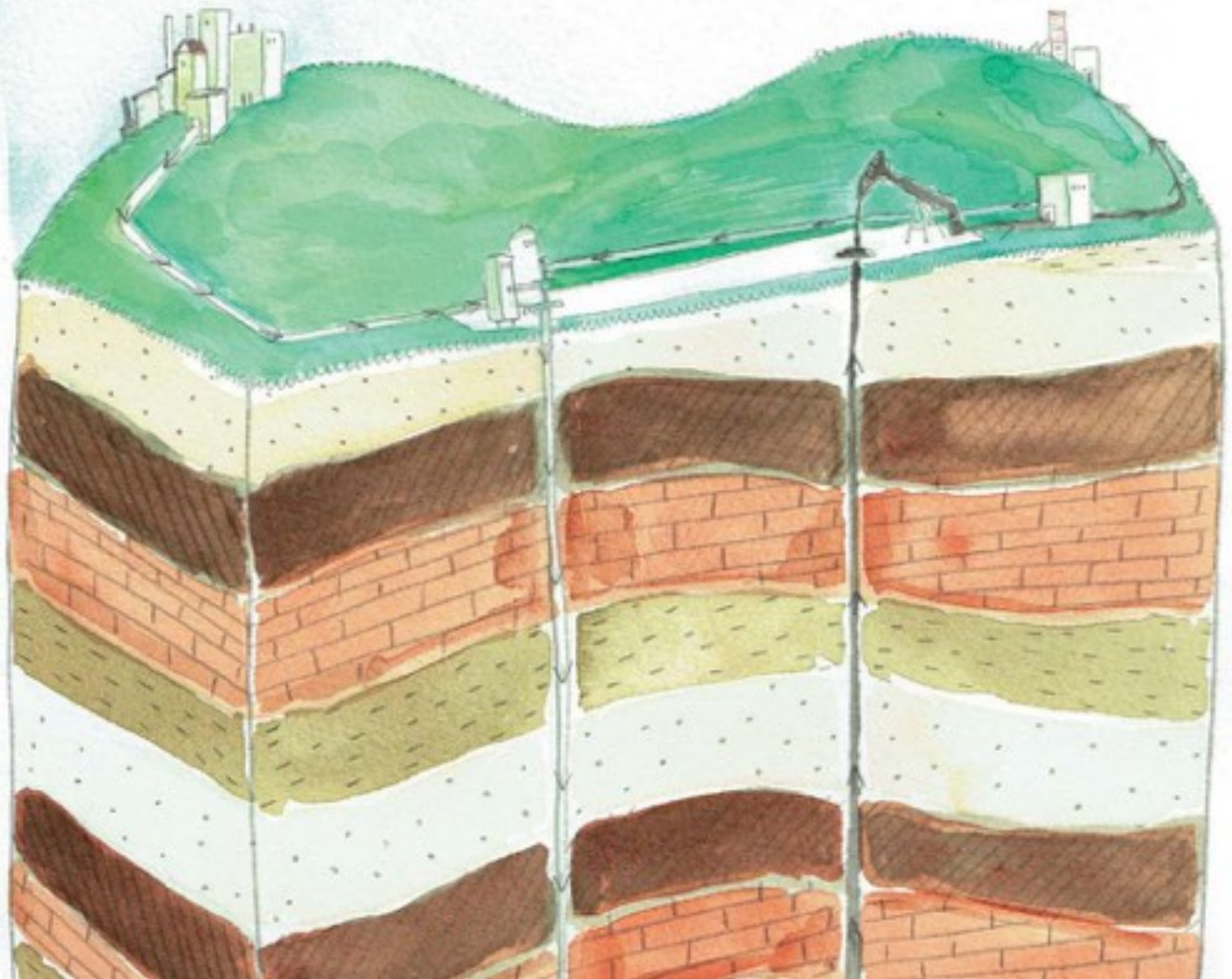
A major problem for all countries is finding resources to produce energy, one of the main commodities that allows us to live comfortably. Making use of resources that are locally available is therefore the first option that is considered, even if local energy sources may not be ideal in terms of the environment and climate. In this context, the use of fossil fuels which are still very abundant in many places of the world, appears to some countries as the only way to produce sufficient energy to allow for development at an affordable cost. CCS, together with other technologies that limit the impacts of coal and natural gas use, could make them more sustainable. This would, over the long term, reduce the overall costs that would have been associated with a "business as usual" approach (such as the health costs of pollution).

CCS can reduce emissions from energy intensive industry

When discussing CCS applied to coal or gas power plants, a common objection is that we should not aim to make fossil fuel use more sustainable, but rather stop it altogether, as soon as possible, by using alternative forms of energy production, like renewables or nuclear, which do not carry the problem of CO_2 emissions. This kind of alternative does not yet exist for some energy intensive industries, such as steel or cement factories, chemical or paper production. These industries account for a considerable proportion of CO_2 emissions, due both to the use of fossil fuels and to CO_2 emissions related to the industrial processes themselves. CCS can play an important role to prevent these industries from releasing large amounts of CO_2 into the atmosphere.

Different perspectives on CCS: advantages and disadvantages

Arguments regarding benefits and downsides of CCS often coincide, as the same characteristics of the technology can be seen as advantageous or disadvantageous depending on the different perspectives. For instance, CCS can help abate CO_2 emissions of coal power plants. This is seen positively by those who think that we will not be able to do without coal for many years, or that in some countries of the world development cannot happen without coal. It is instead seen negatively by those who think that coal use should be given up as soon as possible, because of its environmental impact. Similarly, those who oppose the use of fossil fuels fear that CCS could extend and increase their consumption, while others think that as long as fossil fuels are used, all the possible ways to reduce their emissions should also be used, making their consumption more "responsible". Another focus is on large scale industrial activities, which at present could not take place without fossil fuels, because of the intensive energy supply they require. CCS could make them more sustainable, and less likely to migrate to other countries to escape the carbon issue. But this is seen negatively by those who think that we should move towards a different economic model, in which large scale industrial activities are reduced. It is clear that the real characteristics of the technology play a very limited role in these discussions, which relate to much wider technological challenges. However, improvements of the CCS technology, and reduction of its implementation costs, could probably make it easier to find the best way forward.



WHAT DO YOU THINK?
PROS AND CONS OF CCS

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020
RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

MONITORING TO PROTECT THE ENVIRONMENT AND GROUNDWATER

GEOCHEMICAL MONITORING
SAPIENZA UNIVERSITY OF ROME – CERI – CC BY NC ND

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

BETTER STRATEGIES FOR MONITORING CO_2 BEHAVIOUR: PROTECTING THE ENVIRONMENT AND GROUNDWATER

Reducing CO_2 emissions is the principal goal of Carbon Dioxide (CO_2) Capture and Storage (CCS). By locking the CO_2 underground, it is returned to where it was originally, because most man-made CO_2 originates from the burning of fossil fuels, like coal, oil and natural gas, which were extracted from sub-surface rocks. The injection of man-made CO_2 into the deep underground avoids the release into the atmosphere of this greenhouse gas, which can negatively influence the climate. Concern has been expressed, however, regarding the potential for the accidental leakage of some of this CO_2, and what impact it may have on the local environment and groundwater. The ENOS project will study what may cause the gas to migrate towards the surface, testing the sensitivity and effectiveness of tools designed to monitor for potential leakage and groundwater quality. This work will be conducted at two different sites, where we will inject small amounts of CO_2 at different depths. Additionally, we will conduct experiments at sites where natural, geologically produced CO_2 is leaking to the surface, in laboratories, and using existing data from other locations.

ISSUES ADDRESSED IN **ENOS**

Fresh groundwater. CO_2 in itself does not affect the drinkability of water: many people drink sparkling water. However, many studies have been done to check the possible effects of CO_2 on the minerals that are in contact with the water. These studies have shown that, when CO_2 is in contact with groundwater, it usually remains within drinking standards. In ENOS we will expand on these existing results by studying a variety of rock types under different conditions, to see if some sites may be more vulnerable than others. This will be done by analysing the groundwater chemistry before, during, and after we inject CO_2 at our two experimental sites. We will use these results, together with information about the composition of the local rock, to model the chemical changes and to determine what features are the most appropriate to be monitored at each site. In addition, we will install sensors in water wells at the injection sites, to conduct the first field tests of new groundwater monitoring tools, designed to give early warning of any leakage, so that any impacts can be minimized.

Leakage detection. We will test numerous innovative monitoring tools that can quickly locate a leak on the surface. If CO_2 were to leak from the reservoir and migrate towards the surface, it could have a limited impact on vegetation over a small area. It could pose a health risk only if it accumulates at high enough concentrations in enclosed spaces (like gullies). In ENOS we will use both the CO_2 injection sites and the natural leakage sites to fill gaps in our knowledge regarding the potential style of leakage, which influences the impact the gas may have. For example, diffuse leakage will cover a larger area, but have a smaller impact than focused leakage. Detailed sampling will map leakage distribution, and the identification of different isotopes, as variants of a specific chemical element, will be used to distinguish low level leakage from natural biological background values. This will also include: sensors in the soil that will continuously monitor CO_2 concentrations at multiple points and transmit this data in real time to a central laboratory; a robot that measures CO_2 at the ground surface and maps its distribution; sensors mounted on a remote controlled drone, which can rapidly fly over an area to look for leaks.

Wells. The ENOS project will use existing data from a number of abandoned wells in the Czech Republic and Romania to conduct innovative dynamic computer modelling of leakage scenarios. When a deep well that was drilled to recover oil or natural gas or to inject CO_2 comes to the end of its life, it is closed with cement plugs to prevent it from becoming a direct link between a storage reservoir and the surface. Although modern cements, steel alloys and techniques are quite effective at isolating these wells, older abandoned wells may be less well sealed. While such wells may leak, it is still not completely clear how the leakage may develop over time and space. The aim of this work will be to quantify the potential leakage through abandoned wells, using computer models, in order to reduce the possible risks presented by boreholes during the operational life of a CO_2 storage site.

Faults. The ENOS project will study the possible flow of CO_2 along faults. To date, only limited research has been undertaken on faults, because of their complexity and the difficulty of studying them at depth. The ENOS project addresses this knowledge gap by conducting extensive research on this topic, such as pressure modelling at the Italian and Czech Republic sites, and flow measurements at locations where natural CO_2 is leaking along faults towards the surface. In addition, a CO_2 injection experiment will be conducted to image the CO_2 migration pathway, using geophysical tools, to understand the mechanisms that control CO_2 flow.

ENOS AND THE DEVELOPMENT OF SAFE STORAGE SITES

THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020
RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

ENOS

ENOS AND THE DEVELOPMENT OF SAFE STORAGE SITES

Large volumes of carbon dioxide (CO_2) have been injected deep underground for nearly 50 years, as a way to extract more oil from hydrocarbon reservoirs. The first site developed specifically for the storage of manmade CO_2 became operational in 1996, within the Norwegian "Sleipner" project in the North Sea, injecting up to 1 million tonnes per year of CO_2, separated from extracted natural gas. Other subsequent CO_2 storage sites include In Salah in Algeria, Snøhvit in the Barents Sea off Norway, Quest and Aquistore in Canada and Decatur in Illinois, USA. This extensive experience has shown that the technology exists to conduct CO_2 injection and that it can be done safely. Knowledge and technologies can always be improved, however, and the ENOS project will focus much of its research effort on improving storage site safety during all phases of site development and operation. Much of this work will be conducted at small- to medium-scale pilot injection experiments, thus permitting testing under real-world conditions.

ISSUES ADDRESSED IN **ENOS**

Improved storage site selection. The choice of a storage site location is the single most important decision to ensure the safety of the site, since it is the geological structure itself which has to work as a good and long-lasting trap for the CO_2. Therefore, it is important to make accurate estimates of the total amount of CO_2 that can be injected, while at the same time ensuring reservoir integrity. ENOS will use computer models, with input data from real sites, to improve CO_2 storage capacity estimation methods. New tools will also be developed and tested to facilitate site characterization, including statistical software that will optimize data gathering and interpretation in real time, as well as low-cost drilling methods.

Understanding interaction between CO_2 and the reservoir rock. Injected CO_2 reacts with its reservoir rock, causing some minerals to dissolve and others to form. This may influence injection capacity, CO_2 movement, and the chemistry of the reservoir water. ENOS will perform experiments on rock samples from the pilot injection sites and perform computer modelling to determine the most important chemical reactions, and how they may influence water properties and rock porosity and permeability.

Monitoring. ENOS will examine a number of innovative monitoring techniques, testing different systems together, under harsh and challenging real-life conditions, to determine their effectiveness. This will include monitoring of the storage reservoir itself as well as the shallow or surface environment.

Efficient storage operations. The ENOS project will conduct experiments at the Hontomin injection pilot site in Spain, and run computer simulations to test different injection strategies, to maximise both safety and the amount of CO_2 stored. These experiments will include continuous and discontinuous injection approaches, as well co-injection of CO_2 and brine, focussing on how to manage operation parameters (temperature, pressure and flow rates) to ensure storage integrity.

Understanding induced seismicity issues. Induced seismicity is ground motion caused by human activities. Concern has been raised that the injection of CO_2 at high pressures may cause weak seismic activity, as can also be caused by other human activities (for example, hydrocarbon production and geothermal activities). ENOS will conduct site fault analysis at the Hontomin pilot site, monitor natural seismicity, and perform computer modelling to optimise the reliability of monitoring techniques and to develop protocols to minimise induced seismicity.

Developing an early warning "traffic light" style system to facilitate decision making. For quick intervention in case of leakage, monitoring data need to be collected and understood in real time. ENOS will develop algorithm methods to optimise data collection and will use Key Performance Indicators (KPIs) based on data from the Hontomin site, to develop an early-warning "traffic light system". This is an integrated computer program that automatically analyses the data collected through monitoring and warns you, in real time, if there is something wrong, so that corrective measures can be taken.

Making results applicable for other reservoirs. The ENOS project will compare its injection test sites with active similar sites located in the USA, Korea, Australia, and South Africa as well as other pilot sites in Germany, France, Israel, Norway and Iceland. Site operators will discuss real-life issues encountered at the different sites and exchange data and knowledge to accelerate development. Although no two injection sites are exactly the same, lessons learned at one location can often be applied at sites that are similar. This allows for knowledge, techniques, and technologies related to safety to be spread more rapidly and more cost effectively.

Distinguishing natural from injected CO_2. A certain amount of CO_2 produced by biological organisms is always present in the soil and in the atmosphere. Therefore, for site safety monitoring, it is crucial to be able to distinguish natural biological CO_2 from injected CO_2 that may leak from the reservoir. ENOS will test cutting edge methods at experimental and natural CO_2 leaking sites to determine the origin of low levels of CO_2 in the soil.

Involving the local communities in storage site development. ENOS will work together with small groups of local residents and other stakeholders living near the research sites to understand what is regarded as most important for safety, from the point of view of the local communities. The outcomes of this work will be integrated in the best practice manual produced at the end of the project.

ENOS AND THE DEVELOPMENT OF SAFE STORAGE SITES

GEOPHYSICAL AND AIRBORNE MONITORING
SAPIENZA UNIVERSITY OF ROME – CERI – CC BY NC ND

THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020
RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

REDUCING RISKS TO AN ACCEPTABLE LEVEL

CO_2 INJECTION EXPERIMENT
SAPIENZA UNIVERSITY OF ROME - CERI - CC BY NC ND

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020
RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

REDUCING RISKS TO AN ACCEPTABLE LEVEL

All human activities have some form of risk, which needs to be kept within acceptable levels, relative to the expected gain. Carbon dioxide Capture and Storage (CCS), like all industrial activities, will also have risks, and these will have to be weighed against the benefit of slowing the effects (and risks) of man-made climate change. A lot of work has already been done to minimise the risks of CCS, which under the best technologies are now considered to be negligible. The ENOS project will further advance work in this area to improve tools and protocols for risk management.

ISSUES ADDRESSED IN **ENOS**

Induced seismicity. Human activities that change the balance of pressures and stress fields in the underground can generate small movement along faults. This movement, referred to as induced seismicity, produces waves that can be measured at the surface by monitoring tools. Recently, concern has increased regarding induced seismicity that may be caused by subsurface fluid injection and extraction (such as conventional and shale gas production, gas storage, waste water injection, geothermal activities, and CO_2 storage). Once the natural seismicity of the area has been ascertained, it is important to determine whether induced seismicity can, under certain circumstances, be strong enough to pose a risk. ENOS will work on the development of a 'traffic light' system for early warning, which aims to give site operators the tools to detect induced seismicity, determine its cause and location, and recommend changes to the injection strategy to reduce that risk, all in (near) real-time. The majority of research on induced seismicity will be conducted at the Hontomin injection site, where a network of sensors is monitoring the area. The reliability of this network will be tested and then improved. Data from the network will be studied, to help separate natural events from those which may be linked to the injection of CO_2.

Possible impacts on groundwater. Reserves of fresh groundwater occur in aquifers close to the surface, whereas CO_2 storage is performed much deeper underground (below 800m). However, unexpected leakage from a storage reservoir into an aquifer could cause chemical reactions and/or changes to the composition of groundwater. Most research to date has indicated that any such impact would be spatially small, and that natural processes would maintain water quality within legal drinking water limits. Nonetheless, more work would be helpful to increase our understanding of the possible reactions of different rock types, in different geological settings. Within ENOS we will address this issue primarily by monitoring groundwater quality before, during, and after CO_2 injection at our experimental and pilot test sites. Results from rock and water analyses will be interpreted using computer models that will help determine the long-term effects. New continuous monitoring tools, which will give early warning of possible leakage, will be developed and tested.

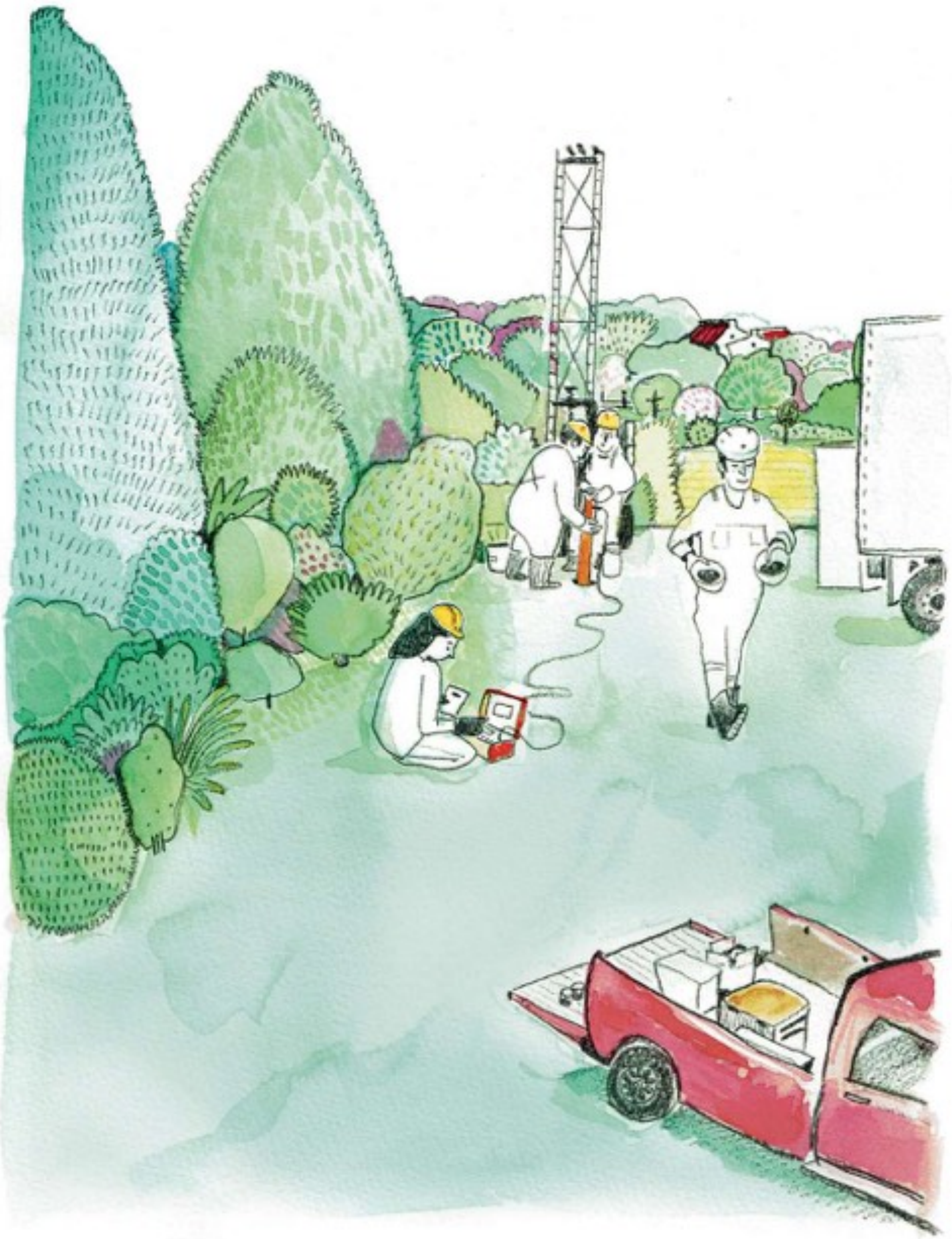
Possible leakage pathways through faults and abandoned wells. ENOS will study both faults and wells, to determine their capability to act as a barrier or a conduit to CO_2 movement. As CO_2 tends to move toward the surface, most risks related to CO_2 storage are the result of the unforeseen migration of the injected CO_2 along faults or abandoned wells. The potential for CO_2 migration along a fault will be tested during injection of CO_2 at the Sulcis Fault Lab. Data from this experiment will be used in computer models to estimate long-term, large-scale processes at different types of sites. In addition, faults with leaking, naturally-produced CO_2 at Latera, San Vittorino and Ailano (Italy) will be examined to compare natural and experimental migration processes, to further improve monitoring strategies. Regarding wells, studies will be based on existing datasets from abandoned wells in the Czech Republic and Romania.

Collaboration with the local community for dealing with risks. The first requirement for reducing risks to a minimum is the collaboration between site operators, local authorities and the local community. An understanding of the technology and of the vulnerabilities at local and social level forms the basis of such collaboration. For this reason, local communities can play an important role in risk reduction in the technology development phase. By sharing their concerns and their knowledge of the areas in which they live,

LOCAL RESIDENTS CAN HELP RESEARCHERS TO IDENTIFY AND ADDRESS ISSUES OF SOCIAL RELEVANCE.

Later on, this can become the basis for putting in place risk management schemes that will help both operators, and the population, understand how to behave in case of risk. Within ENOS we will contribute to promoting collaboration, by creating long-term dialogue groups with local residents on the project's research. Through this exchange we aim to support the development of solutions that are both technically and socially sound, to reduce risks.

ENOS WILL CONTRIBUTE TO REDUCING CO_2 STORAGE COSTS



TECHNOLOGY TESTING TO BRING COSTS DOWN

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

ENOS WILL CONTRIBUTE TO REDUCING CO_2 STORAGE COSTS

Like all large-scale industrial processes, CO_2 storage costs money to implement. Although most of the CCS cost is associated with capturing the CO_2, issues related to storage are also expensive. For example, site selection and characterisation, infrastructure development and operations or long-term monitoring, are expensive undertakings. Clearly, any reductions in total costs, without compromising safety or site effectiveness, will make the technology more attractive.

ISSUES ADDRESSED IN **ENOS**

Reducing the cost of site characterization. ENOS will optimize the selection and evaluation of potential storage sites by developing methods to support decision making. The initial stage of CO_2 storage involves determining whether a potential site has the characteristics that would make it safe and cost-effective for long-term storage. Operators need to estimate the storage capacity of a reservoir, the quality of the cap-rock, and if there are any potential leakage pathways such as untight faults or poorly abandoned wells. To answer these questions a large amount of geological, geophysical, hydrogeological, structural and engineering data must be collected. In ENOS the characterization procedure will be optimized, to acquire appropriate data that are more reliable, robust and cost effective.

Cost-effective drilling. ENOS will examine approaches to reduce the costs for drilling wells. Drilling deep wells is an essential part of the site characterization phase, to define the geology of the subsurface. Much of the technology proposed for storage site characterization comes from the oil and gas exploration industry. However, the type of wells drilled for the production of oil and gas are expensive. In contrast, wells for CO_2 storage characterization could potentially be simpler and smaller in diameter. In an effort to reduce drilling costs, ENOS will examine the potential of adapting the much cheaper drilling techniques used in the mining industry. This approach will lead to significant cost savings, while at the same time providing the same quality of data.

Reducing costs for long-term monitoring. ENOS is developing different types of state-of-the-art sensors which will reduce the cost of monitoring. There are many different technologies that can be applied to monitor the security and safety of a storage site, both during and after operations. To optimize costs, a group of complementary methods must be chosen, to give the best coverage over large areas, at different time scales, and over long time periods. Examples of continuous monitoring systems to be developed and tested in ENOS include:

- Fibre optic sensors for CO_2 and biosensors in water wells
- Infrared CO_2 sensors for use in the soil
- Sensors mounted on drones that fly over the injection area
- Robots that monitor CO_2 at the ground surface
- Thermal remote sensing techniques.

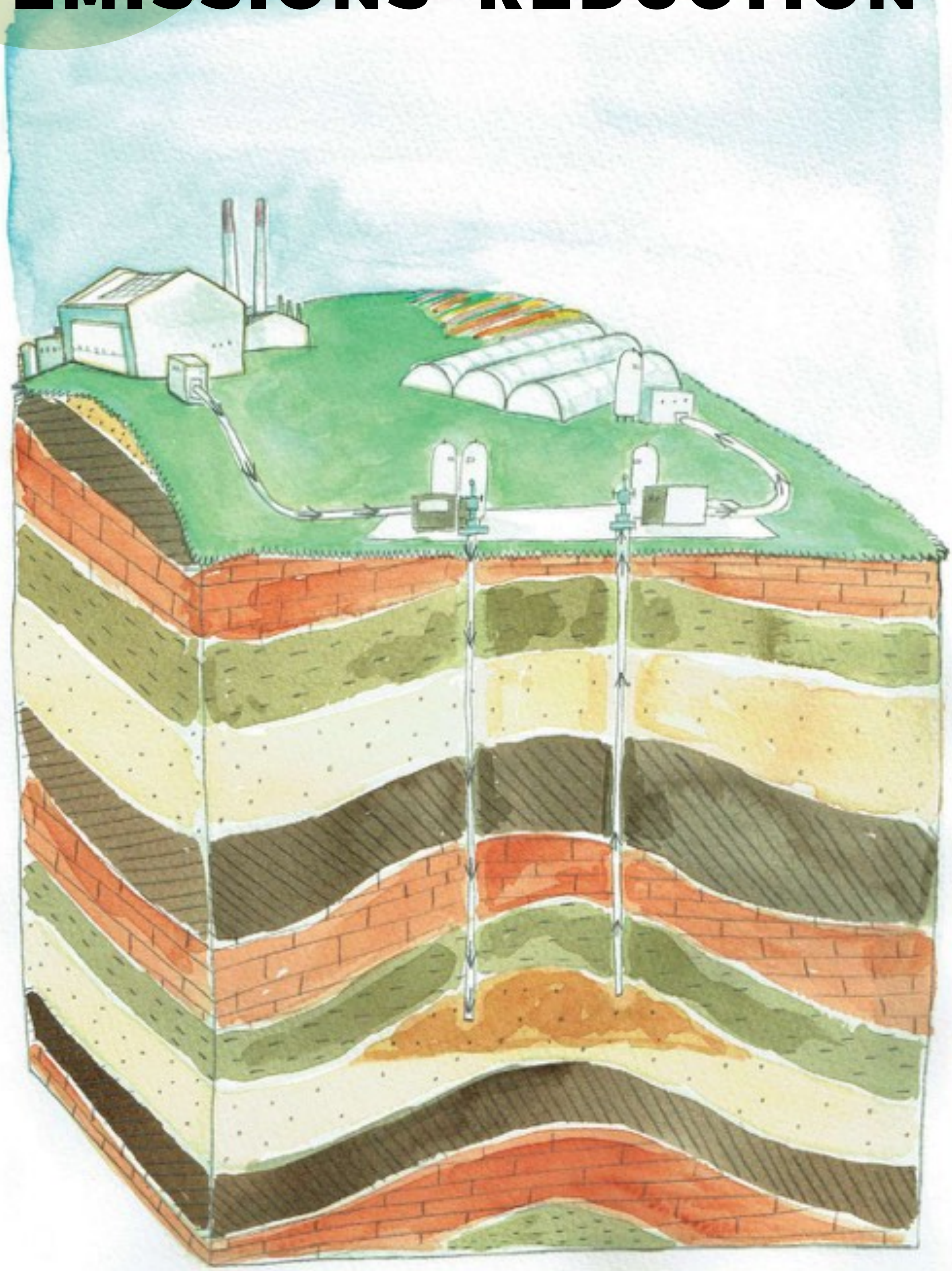
All of these technologies will be tested at one or more of the project's CO_2 injection experiments.

Safety and cost reduction. When implementing an industrial technology like CO_2 storage, efficiency and safety need to be ensured at the lowest possible cost. Decisions regarding safety can be particularly complex. Two aspects have to be considered: safety in itself and the perception of safety by the population. Striking the balance between safety measures, as defined from a technical point of view, and those made necessary for unequivocal safety demonstration to all stakeholders, will be essential. To be able to do this, a clear and transparent process, which also takes into account the point of view of the local population, can be useful.

ENOS WILL EXPLORE TOGETHER WITH MEMBERS OF THE LOCAL COMMUNITIES WHICH SAFETY ASPECTS AND NEEDS SHOULD BE PRIORITISED IN STORAGE DEVELOPMENT AND PLANNING.

Different options will be discussed, for instance regarding monitoring strategies, to identify the choices that would better ensure the protection of the communities, living near future storage sites with the lowest possible costs.

ECONOMIC BENEFIT IN ADDITION TO CO_2 EMISSIONS' REDUCTION



CO_2 STORAGE AND USE
SAPIENZA UNIVERSITY OF ROME – CERI – CC BY NC ND

THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

ENOS

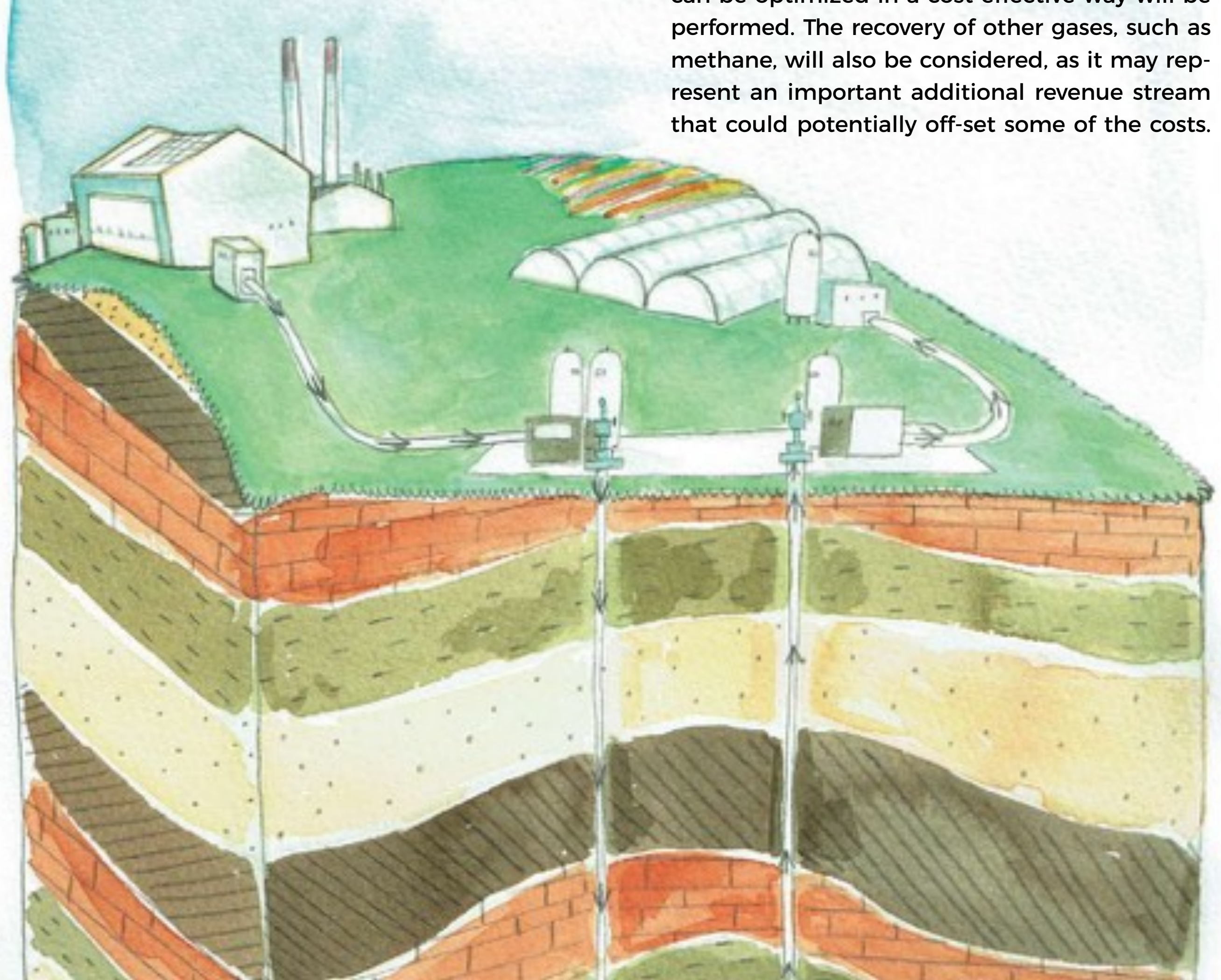
ENOS WILL EXPLORE HOW CO_2 STORAGE CAN BRING ECONOMIC BENEFIT IN ADDITION TO REDUCING CO_2 EMISSIONS

The ENOS project will address a number of possible economic benefits of not only CO_2 storage, but also the re-use of part of that CO_2 for other commercial endeavours. For example, the large greenhouse industry in the Netherlands uses CO_2 to increase the growth rate of their plants. ENOS will examine the potential of combining CCS with a scheme whereby a portion of the CO_2 injected underground is temporarily stored and then recovered for use in the greenhouses, thereby providing a needed product of value plus a reduction in the overall release of CO_2 into the atmosphere. Another possible use is to inject CO_2 in the underground to recover more oil. This method has been employed for nearly 50 years, using mainly natural CO_2. If man-made CO_2 is used instead, it will become a valuable product, while at the same time locking a significant portion of that greenhouse gas underground, in the oil field. Combining storage and use of CO_2 could help reach both climate and economic objectives.

ISSUES ADDRESSED IN **ENOS**

CO_2 storage and buffer storage for greenhouses. The agricultural industry needs CO_2 to make plants grow more quickly in greenhouses. At present, only a part of the required CO_2 is provided by industrial processes. In winter the supply by industry is larger than the demand, and excess CO_2 is emitted into the atmosphere, whereas in summer the demand by greenhouses is larger than the supply. The additional CO_2 needed in summer is currently obtained by burning fossil fuels. Coupling permanent and temporary CO_2 storage, it would be possible to store the CO_2 in winter when too much is being produced and which would otherwise be released in the air, and extract back a part of it in summer when greenhouses need it. The ENOS project will study the feasibility of this process from a technical, economic, regulatory and social point of view. In particular, the following aspects will be investigated:

- ***Quality of the CO_2 that is reproduced.*** ENOS will study chemical reactions between the gas, water and rocks within the storage reservoir, which may have an impact on the purity of the CO_2, which should be re-used in greenhouses. Data from a real-life, nearly depleted gas field will be investigated. A review of the technologies to separate the impurities from the CO_2 and how they can be optimized in a cost effective way will be performed. The recovery of other gases, such as methane, will also be considered, as it may represent an important additional revenue stream that could potentially off-set some of the costs.



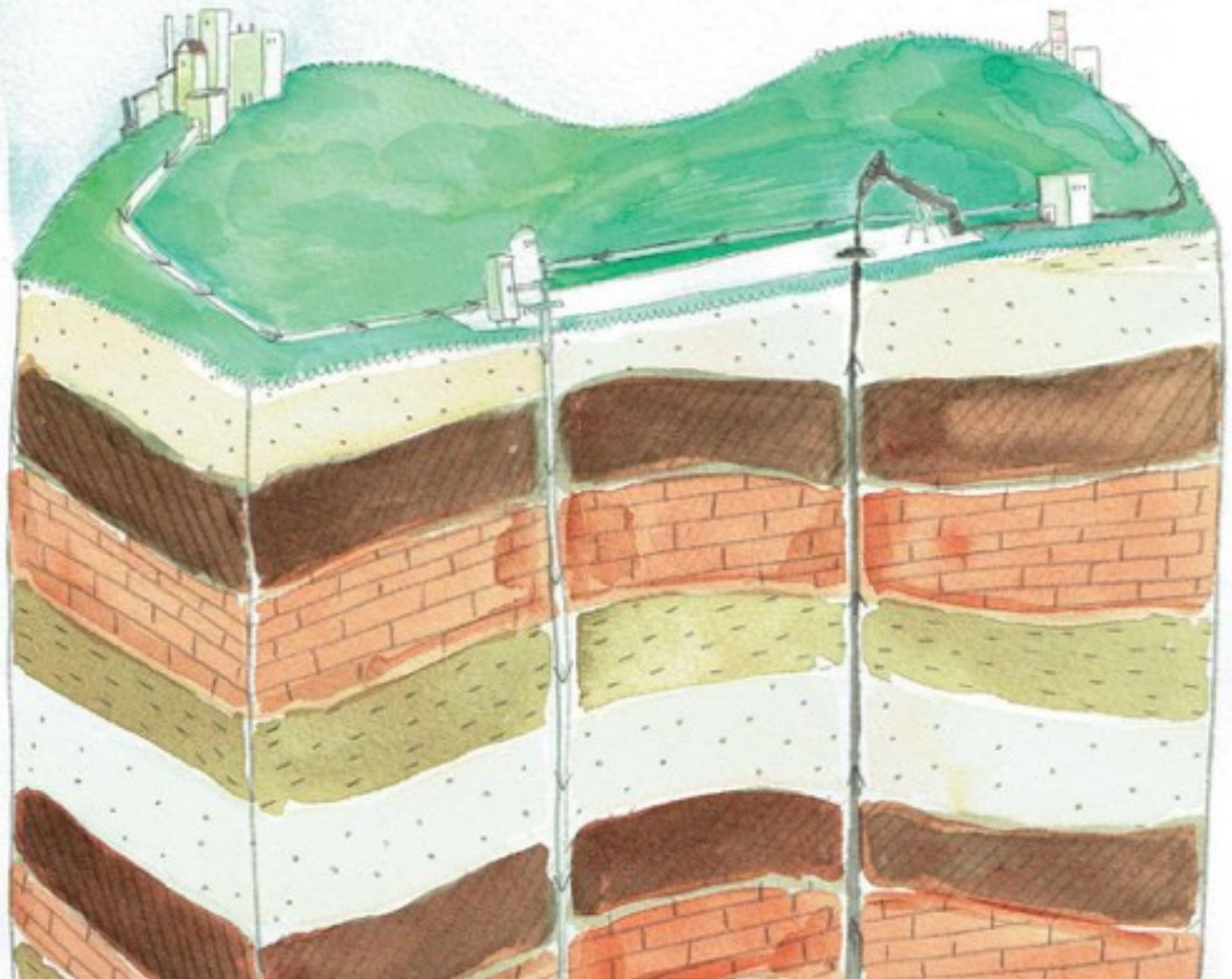
CO_2 STORAGE AND USE
SAPIENZA UNIVERSITY OF ROME – CERI – CC BY NC ND

- ***Regulatory issues.*** Many issues related to permitting, licenses, and carbon credits of sites used for both permanent and temporary storage have to be resolved. Within ENOS work will focus primarily on the Dutch legislative and regulatory framework, with a brief comparison with that in the UK and Denmark. ENOS will also design a system for monitoring the specific volumes and the chemical composition of CO_2 injected, reproduced and stored, which is needed to satisfy regulatory requirements.

- ***Economic issues.*** ENOS will consider the various costs and make recommendations, regarding feasible methods for seasonal CO_2 storage for greenhouse use. These costs will include injection and production, CO_2 purification, and pipeline transport, from the storage location to the greenhouses.

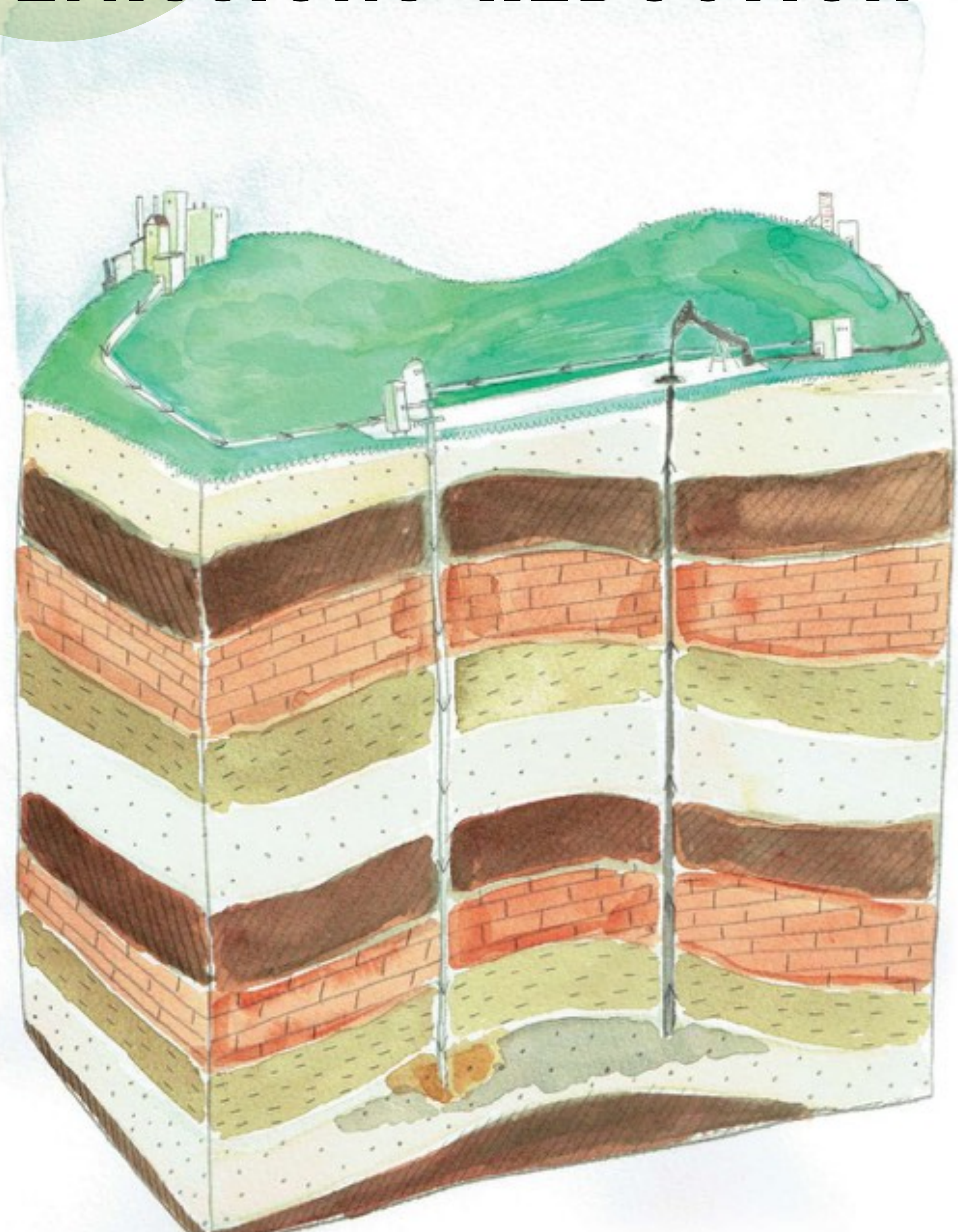
- ***Social issues.*** The ENOS project will seek input from local residents and other civil society stakeholders regarding the concept of coupling permanent and temporary storage for greenhouse use. Both environmental and economic benefits and downsides will be considered, to understand whether CO_2 storage associated with CO_2 use can be considered a good option by the population and under which conditions.

CO_2 storage and Enhanced Oil Recovery (EOR). ENOS will investigate how the use of CO_2 to enhance oil recovery can reduce the cost of CCS projects. The injection of CO_2 into oil reservoirs can largely increase the amount of oil that can be pumped out, because the oil becomes more liquid and flows easier through the rock towards the production well. Pure CO_2-EOR projects are not designed specifically for CO_2 storage, and thus research is needed to optimise the oil recovery, while, at the same time, maximizing the amount of CO_2 that remains in the reservoir. The Czech LBr-1 site will be used as an example for developing technical-economical evaluations of this concept. EOR processes will be modelled using real data from the site and lab experiments. Different options for the necessary infrastructure, including inexpensive flexible wells, will be considered. A detailed plan for a field-scale CCUS (Carbon dioxide Capture Use and Storage) pilot at LBr-1 field will be developed. Economic issues and challenges will be studied to identify value ranges of costs and benefits, taking into account a wide range of factors that come into play in real world projects. Finally, regulatory aspects will be investigated in the context of national legislation, with a focus on the definition of the storage complex, and cross-border issues, since the LBr-1 site is situated close to the Czech-Slovak border.



CO_2 STORAGE AND EOR
SAPIENZA UNIVERSITY OF ROME – CERI – CC BY NC ND

ECONOMIC BENEFIT IN ADDITION TO CO_2 EMISSIONS' REDUCTION



THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

ENOS

CO_2 STORAGE MONITORING STRATEGIES

MONITORING TOOLS COMBINATION

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

ENOS WILL IMPROVE THE CONCEPT AND PRACTICE OF CO_2 STORAGE MONITORING

When a storage site is in operation, it is essential to demonstrate that the storage mechanism is working as expected. This is achieved by monitoring the site, which is useful for many purposes: to ensure site safety, protect groundwater resources, safeguard the environment, minimise the possibility of induced seismicity, quantify possible leakage, and provide information for the EU carbon credit system. The monitoring of a CO_2 storage site is a complex process. It starts long before the site enters in operation, to determine the "initial state", e.g. to identify the amount of natural CO_2 that is normally present in the area and define the expected responses of monitoring tools before any CO_2 is injected. Then a monitoring strategy is developed, based on the geological characteristics of the site, to generate data that can be used for risk assessment and control systems. Fundamentally the aim of the monitoring plan is to check the behaviour of the injected CO_2 and to quickly identify any gas migration that could result in leakage into shallow groundwater aquifers or to the surface. Through monitoring we can detect anomalies, by comparing new data with those taken before the start of operations, and identify where and when corrective measures might be needed. ENOS will work on monitoring issues at different levels: developing new tools and testing existing ones in real life conditions and studying cost effective combinations of tools that can be integrated into a comprehensive monitoring solution.

ISSUES ADDRESSED IN **ENOS**

Detecting CO_2 and distinguishing it from naturally present CO_2. The ENOS project will develop and test cutting edge monitoring technologies, like isotope analysis, to help distinguish natural CO_2 produced by biological processes in the near surface from the injected CO_2. This is particularly important, as the misinterpretation of an observed CO_2 anomaly could result in unwarranted concern and expense (if a biological anomaly is incorrectly interpreted as being due to leakage) or increased risk (if a leakage signal is incorrectly interpreted as being the result of natural surface processes).

Measuring and quantifying CO_2. ENOS researchers will work together to assess the potential of different monitoring tools and of their combination to ensure site safety, environmental protection, and carbon credit auditing. This will address issues such as uncertainties in CO_2 quantification, method sensitivity and monitoring frequency. The project will expand on more evolved sensors, both at ground and underground level, and on remote sensing techniques to refine our ability to quickly identify even very small anomalies.

Combining monitoring techniques in a comprehensive monitoring solution. The ENOS project will integrate the innovative tools developed for monitoring CO_2 at different levels (in groundwater, soil, deep underground and at surface) to create an overall safety approach that is more rigorous, sensitive, and responsive.

THE FINAL RESULT WILL BE IMPROVED TECHNICAL GUIDELINES AS WELL AS AN ASSESSMENT OF HOW THIS APPROACH COULD BE UP-SCALED FOR POTENTIAL LARGE SCALE DEMONSTRATION SITES.

Verifying monitoring strategies with regard to the needs of the local community. Local authorities and communities need to understand how the safety of a storage site is ensured and to be informed about the performance of the storage site. This is important for them, both to feel safe and to be able to put in place behaviours or decisions that might be necessary in case of a measurement anomaly or an accident. In ENOS, we will look into how monitoring strategies can be developed taking into account these needs in addition to the technical ones, to make monitoring plans that are clear and understandable and, if necessary, adapting them to the specific requirements of local communities.

FOLLOWING THE DEVELOPMENT OF A STORAGE PILOT

PUBLIC INFORMATION TOOL

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

ENOS

ENABLING PEOPLE TO BE INFORMED AND TO FOLLOW THE DEVELOPMENT OF A STORAGE PILOT

Within ENOS, partners will be available to the public and journalists to give factual and up-to-date information regarding the research and the experimental CO_2 injection sites being studied. ENOS researchers recognise the importance for people living near a storage site, as well as the public at large, to access information about site operations. For this reason, part of the work will be dedicated to understanding how to produce end-user friendly information and how to make it easily accessible.

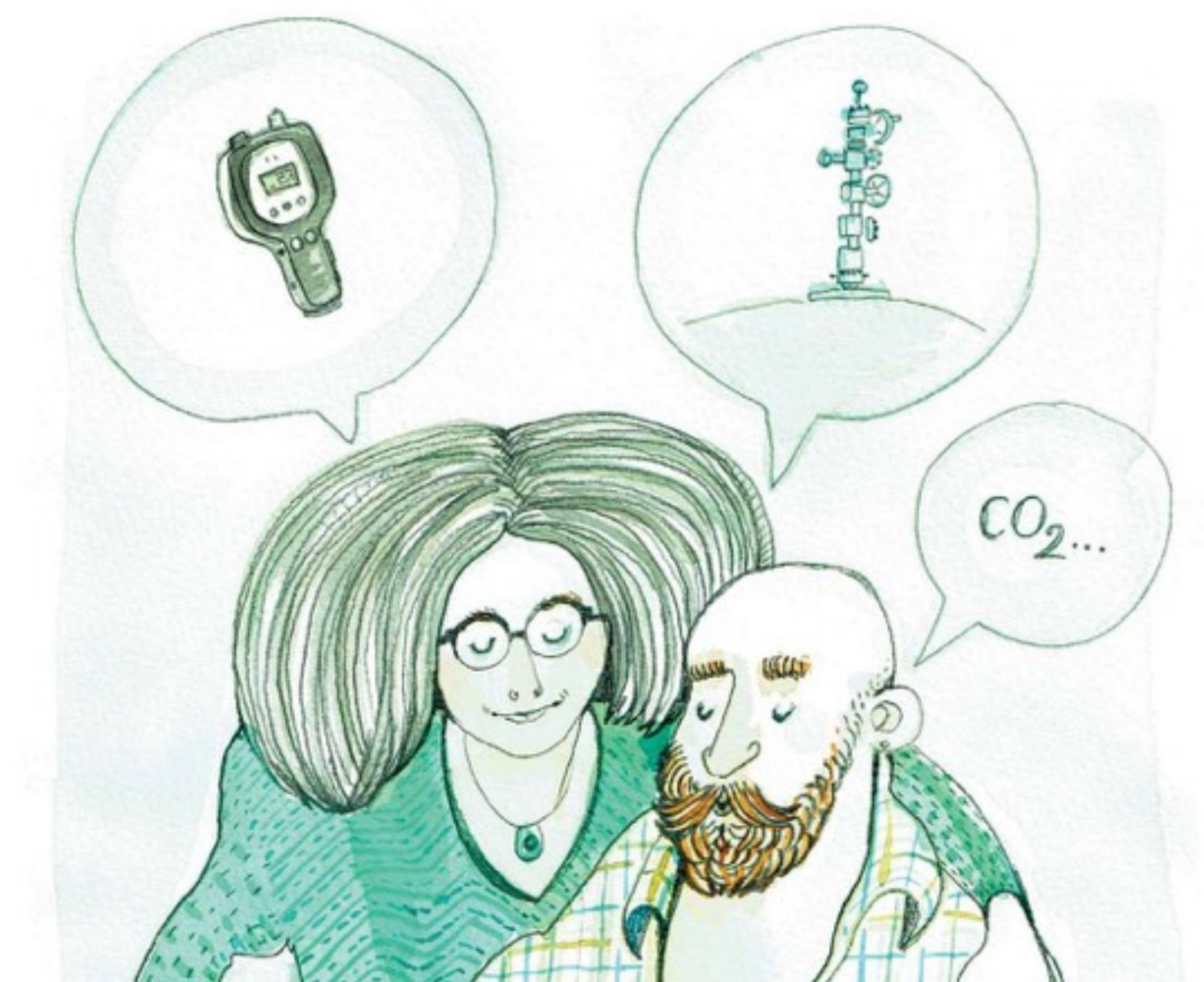
ISSUES ADDRESSED IN **ENOS**

Public information tool. ENOS will apply the knowledge gained through the relationship with the local communities to develop a dynamic and interactive online Public Information Tool of an active CO_2 storage pilot site (Hontomin). This application will allow a person to follow the progress of the activities taking place at the site. The tool will be developed so that it can be expanded in the future to include other sites. Content will be defined by interaction with the local population and other stakeholders like journalists, local and regional politicians, and regulators. It will be updated at regular intervals with news from the project and CCS in general.

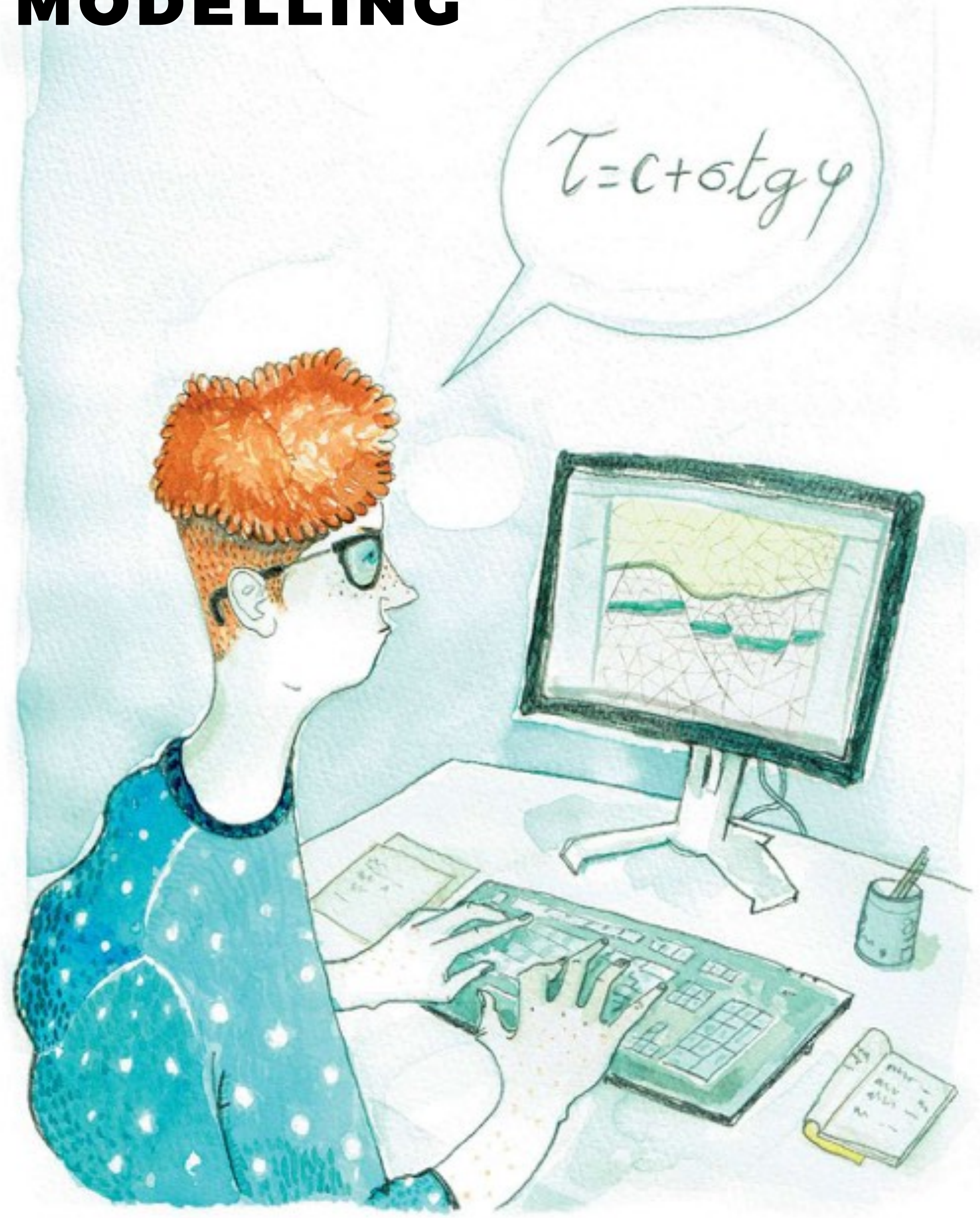
Interaction with journalists and the media. Direct exchange can provide an understanding of the research that is greater than that which can be achieved through reading documents or internet resources.

ENOS WILL ORGANISE MEETINGS WITH SCIENTIFIC JOURNALISTS AT THE EUROPEAN LEVEL

as well as local journalists working near the project's study areas in Italy, the UK, The Netherlands and Spain. Media professionals will have the opportunity for face-to-face exchanges with the researchers on important issues such as CO_2 storage safety, monitoring and site management.



MANAGING THE COMPLEXITY OF STORAGE THROUGH MODELLING



THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

ENOS

MANAGING THE COMPLEXITY OF CO_2 STORAGE THROUGH MODELLING

To manage technologies like CO_2 storage we need a good understanding of many complex processes and how they can evolve in time. To describe them we use computer models which help us to manage the huge amount of data that need to be considered. Computer models are simulations of reality which use mathematical formulae to represent specific processes, such as CO_2 migration or pressure build up in the reservoir when CO_2 is injected. As many processes have an influence on each other, the models must take into account this interdependency. Numerous models can be run to define a range of plausible scenarios that describe the process that we want to understand and predict. ENOS models will be based on real data from our sites. Model design will be modified to match experimental results, in order to improve how well they reproduce reality. This validation will be done under various changing conditions, such as before and after injection.

ISSUES ADDRESSED IN **ENOS**

Storage reservoir capacity. Understanding how much CO_2 can be injected into a reservoir is critical both in terms of the economic viability of a site as well as its safety. This information is not always simple to estimate because natural systems can be highly variable and complex. Partners in ENOS will address these issues by performing simulations to model capacity at two of the project's injection experiment sites, Hontomin and the GeoEnergy Test Bed.

Behaviour of CO_2 in the reservoir. Having a clear understanding of how CO_2 will move in the reservoir is critical to determine engineering aspects (such as how quickly the CO_2 can safely be injected), cost aspects, and safety issues. In ENOS we will calculate the directions in which the CO_2 will flow, the build-up of pressure, and the possible deformation and fracturing of the rock formations.

Behaviour of CO_2 in abandoned wells. A deep well that is no longer needed must be abandoned properly to isolate the subsurface from the atmosphere. Some old wells may have been closed using ineffective methods. CO_2 could potentially migrate along such wells, although it is uncertain how quickly or how high up. Within ENOS we will study the LBr-1 site in the Czech Republic, where there are a number of abandoned wells. This modelling will assess the potential leakage through abandoned wells, and assess the possible impact on shallow groundwater.

Behaviour of CO_2 along faults. Depending on its structure, form, and mineralogy, a fault can act either as a barrier or as a conduit to fluid flow, and can even alternate between these two extremes along its length. In addition, fault permeability can also change if pressure conditions change. Given such complexity, modelling of fluid flow along faults has received less attention than modelling of un-faulted rocks.

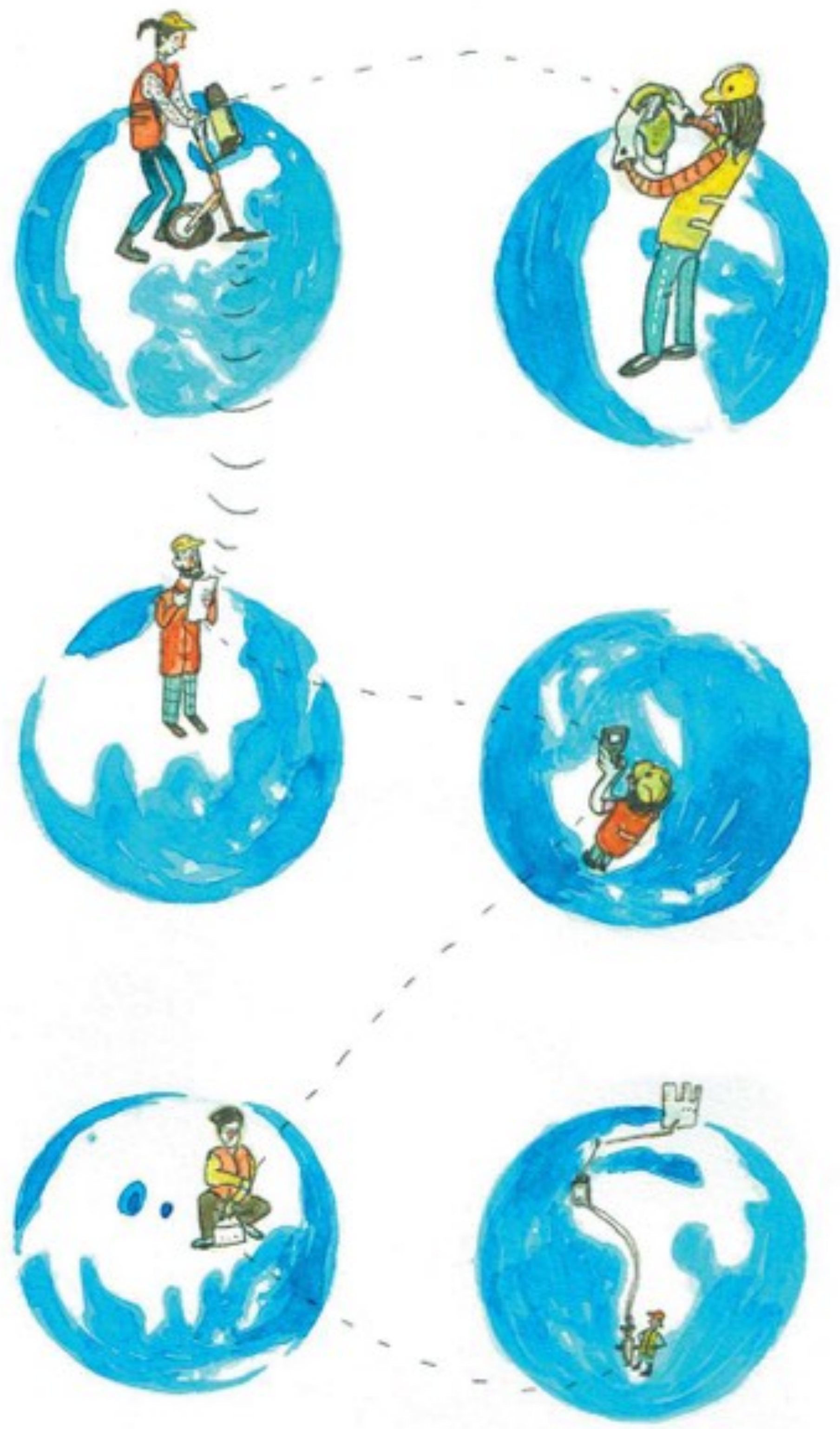
TO ADDRESS THIS KNOWLEDGE GAP, ENOS WILL USE DATA AND EXPERIMENTAL RESULTS FROM THE PROJECT'S REAL-WORLD SITES TO MODEL VARIOUS ASPECTS RELATED TO FLUID MOVEMENT AND LEAKAGE ALONG FAULTS.

For example, CO_2 will be injected into a fault at the Sulcis site, and data will be used to update modelling techniques to make them more efficient.

Influence of CO_2 on groundwater quality. The addition of CO_2 to an aquifer may result in reactions with the surrounding rocks that change the groundwater chemistry. A tool-box of computer programs will be used by ENOS partners to simulate the chemical reactions that might occur in the groundwater, using real data from the two injection experiment sites. The results will help predict potential long-term impacts on groundwater quality and will highlight the most sensitive chemical properties that need to be monitored to safeguard this critical resource.

Risk management. Complex industrial processes consist of many steps, each of which must be made as effective and safe as possible for the efficient running of the system. By assessing the potential risk of each individual step, it is also possible to understand where resources can most efficiently be used to lower the overall risk. To this end a method for estimating the probability of risk of leakage has been developed for the Hontomin site and will be applied in ENOS.

FOSTERING INTERNATIONAL COLLABORATION



INTERNATIONAL COLLABORATION
SAPIENZA UNIVERSITY OF ROME - CERI - CC BY NC ND

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

FOSTERING INTERNATIONAL COLLABORATION

Sharing experience and knowledge with other onshore storage experiments around the world is very important to enrich our knowledge of what needs to be included in best practice protocols for CO_2 storage onshore. ENOS will create several opportunities for exchange with other on-going projects in the USA, Canada, Australia, South Korea, and South Africa. Data exchange, workshops to compare ideas and results, site visits and other initiatives will support and speed development of safe and effective methods and protocols.

ISSUES ADDRESSED IN **ENOS**

Twinning. The study sites within the ENOS project will be matched with similar sites throughout the world in South Korea, South Africa, USA and Australia, with the goal of creating a close working relationship that helps speed up scientific and engineering advancements. This will consist of mutual visits, regular exchanges of information and data, and discussions on real-life issues encountered by the twinned sites operations.

Leakage simulation alliance. Worldwide there are several sites planning to study CO_2 leakage in different environments and conditions through real-life field injection experiments or by using sites that leak naturally produced CO_2. By studying leakage, we better understand how to prevent it, what its risks are, and how to monitor for it. The formation of a research alliance on this topic will foster cooperation and allow comparison and generalization of results. The initial sites proposed for the alliance are the GeoEnergy Test Bed (UK) and the Sulcis Fault Lab (Italy) sites from ENOS, as well as the CMC Field Research Station in Canada, South Korean K-COSEM and South African Bongwana Fault sites.

Experience sharing focus groups. ENOS will also create a small number of experience-sharing groups focused on specific issues that are relevant to all sites, such as site characterisation, CO_2 injection management, site monitoring strategy, or public outreach. 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.

European liaison and knowledge exchange. This work will focus on linking the ENOS project with the other onshore storage sites in Europe and the broader CCS-related community to enhance knowledge sharing and experience. This will include European pilot and demonstration projects (like Ketzin, Lacq-Rousse, Heletz, CarbFix, Longyearbyen, GETICA CCS), the European CCS Demonstration Project Network, the European Carbon Dioxide Capture and Storage Laboratory Infrastructure (ECCSEL) project, the European Technological Platform ZEP, the EURELECTRIC CCS taskforce, the Baltic Sea Region Energy Cooperation CCS Network (BASRECCS) and various national CO_2 Clubs. ENOS partners will use the knowledge obtained within the project to contribute directly to the development of the EERA CCS JP research activities.

Knowledge sharing at different levels. ENOS will also look to facilitate knowledge sharing at the national level. For example, there are countries in Europe, such as Norway, that are far more advanced in the testing of CCS than others. Forerunner countries, with their extensive experience and investment could greatly assist and speed up development in other countries. A pre-existing collaboration between Norway and the Czech Republic will be extended within ENOS, with Norway providing support for the Czech Republic in regard to CO_2 storage in depleted oil reservoirs.

ENOS WILL ALSO FORM END-USER GROUPS, REPRESENTED BY NATIONAL STAKEHOLDERS

including policy makers, energy agencies, industry and power sector, geoscientists and researchers.

INCREASING THE PREPARATION OF RESEARCHERS AND PROFESSIONALS

TRAINING IN THE FIELD LAB
SAPIENZA UNIVERSITY OF ROME – CERI –

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

ENOS

INCREASING THE PREPARATION OF RESEARCHERS AND PROFESSIONALS IN THE FIELD OF CO_2 GEOLOGICAL STORAGE

ENOS will establish specialist university programmes, provide concentrated short courses ("spring schools") for high level students and young professionals, develop distance learning tools like e-courses that will be available on the internet, and conduct workshops with scientific journalists so that they can accurately inform the general public. If Europe is to deploy CCS in the future, a highly trained workforce of specialised scientists and engineers will be needed to create the safest CO_2 storage sites possible.

ISSUES ADDRESSED IN **ENOS**

University courses. ENOS will develop cooperation between universities, with the goal of building and initially sponsoring a European Master's-level course that specifically addresses CO_2 storage practices and techniques. The course will take place over 12 months at ENOS partner Universities across Europe. It will be organized by University of Rome La Sapienza and University of Zagreb in collaboration with Heriot-Watt University, Tallinn University of Technology, the University of Nottingham, and with the participation of other partner research organisations which will host the students for their thesis. It will train graduate students for work in multidisciplinary teams in the field of CO_2 geological storage.

Postgraduate training. ENOS will develop topical CO_2 storage schools consisting of one week of intensive study and practical exercises for students, early career researchers, and young professionals. The CO_2 storage school course material will be developed and updated with the most recent results from storage pilots. Three schools will be organised, one in each country where proposed pilot storage sites are being studied by ENOS, in the Czech Republic, Italy and Spain.

E-learning. ENOS will prepare online learning materials to help educate and train a broad audience on various aspects of CCS.

THESE WILL INCLUDE GENERAL KNOWLEDGE FOR THE PUBLIC AS WELL AS SPECIFIC, COMPREHENSIVE TECHNICAL KNOWLEDGE ON CO_2 GEOLOGICAL STORAGE FOR STUDENTS OR STAKEHOLDERS.

Ten e-lectures will be created, grouped into three main topics: climate change and the importance of CCS technology for decarbonisation of energy and industry, geosciences applied to the geological storage of CO_2, and regulatory and social aspects of CCS technology. Each e-learning series will be published as a publically available e-book.

Workshops with media professionals. The ENOS project acknowledges the important role that media play to provide impartial information and to clear up misconceptions. Direct exchanges will be organised with journalists in the form of dialogue groups and workshops, where complex technical and scientific knowledge related to CO_2 storage can be illustrated and discussed. Activities will be organised in collaboration with EUSJA – the European Union of Science Journalists' Associations and other national journalist organisations. Scientific journalists as well as local journalists working in the areas studied in ENOS in Italy, the Czech Republic, UK, The Netherlands and Spain will be invited to participate to facilitate access to verified scientific information.

THE ENOS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO 653718

DELIVERABLE 5.1 OF THE PROJECT ENOS - ENABLING ONSHORE CO2 STORAGE IN EUROPE.
TEXT PRODUCTION COORDINATED BY SAPIENZA UNIVERSITY OF ROME - CERI IN COLLABORATION WITH BRGM, BGR, CGS, CIUDEN, OGS, SOTACARBO, TNO, UNOTT, GBA, GEOECOMAR, HWU, IGME, TTUGI.

AUTHORS: SAMUELA VERCELLI, STAN BEAUBIEN, SABINA BIGI, SALVATORE LOMBARDI, MATHEW HUMPHREY, GIANNI SERRA, SANDRA RAMOS, MARIE GASTINE, GILLIAN PICKUP, WILLIAM KNIGHT, PASCAL AUDIGANE, HANNEKE PUTS, TARA GEERDINK, BAREND VAN ENGELENBURG, MARIELLE KOENEN, ALLA SHOGENOVA, ALEXANDRA DUDU, VIT HLADIK, ALES HAVLIN, ISABELLE CZERNICHOWSKI-LAURIOL, GIORGIA PINNA, LIONEL LOUBEAU, CLEMENS PORPACZY, DIANA MULTINEDDU, ALBERTO PLAISANT, ROBERTO MARTÍNEZ ORIO, MICHELA ORAZZINI, STEFANO GRAZIANI, CHIARA TARTARELLO, LIVIO RUGGIERO, DALMAZIA FUMAROLA, GREGOR GÖTZL, STEFAN SCHLÖMER, INGO MOELLER, STEFAN KNOPF, ROWENA STEAD, ALESSIA CONTI, VALENTINA ROMANO.

MANY THANKS FOR READING THE TEXT AND PROVIDING PRECIOUS INPUT TO IMPROVE IT, TO:
TIM WATSON, CRISTINA RULLI, CATERINA PERELLI, ROBERTO DI BARTOLO, PAMELA VERCELLI, GRAHAM TAVERNER, PENNY MOYLE, STEVE MOYLE, SAM JONES, JAYNE HUMPHREY, LISA RYLEY, ANDREW RYLEY, PETER AUSTEN, BETH TORRINGTON, DOMENICO SANINO, GOFFREDO RULLI, VITA RUSSO, GIUSEPPINA PASCERI, LUCIANO CORDISCO, FRANCA DE ASCANIO, ANTONIO CAPPONI, MARIA TERESA MANGIONE, NINO ROMANO, CELESTINA TERZANO, SABRINA CARAMIA, MANUELA MAINELLI, ROMEA PIGNOLO, DONATO RUGGIERO, TERESA TARDIA, IVANA TUMINO, MARCO TORINO, LORELLA DE ANGELIS, ANTONINO CONTE, GRETA FRATINI, LUISA BATTOCCHIO, GISELLA LOMBARDI, TIZIANA MIONI.
A SPECIAL THANK YOU TO JUDITH BRADBURY, MEMBER OF ENOS ADVISORY BOARD, FOR HER INSIGHT AND SUPPORT.

IMAGES SAPIENZA UNIVERSITY OF ROME – CERI

ARTISTIC DESIGN AND WATERCOLOUR ILLUSTRATIONS BY GIUDITTA GAUDIOSO BASED ON INPUT FROM SAMUELA VERCELLI, SALVATORE LOMBARDI, SABINA BIGI.
GRAPHIC DESIGN: SILVIA MURACA.

ENOS:
PARTICIPATING IN CO_2 GEOLOGICAL STORAGE RESEARCH

WEBSITE
www.enos-project.eu