Developing, testing and demonstrating onshore storage of CO_2: First results from the ENOS field sites

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In the H2020 project ENabling Onshore CO_2 Storage in Europe (ENOS), research and development at five field sites takes a prominent role. Each of these gives attention to particular challenges or different applications of injected CO_2. Research initiated on three of the five pilot sites gives an overview of which different challenges will be tackled and how they are approached. These include the direct geological and technical challenges of CO_2 injection (Hontomin), oil production compatible with the climate-energy nexus (CO_2-EOR, LBr-1), and the integration of geological storage in CO_2 capture and utilisation schemes (Q16-Maas).

Dans le cadre du projet H2020 validant le stockage de CO_2 en Europe continentale, (ENOS), la recherche et le développement concernant cinq sites à terre jouent un rôle prééminent. Chacun d'eux fait l'objet d'une grande attention vis-à-vis des défis spécifiques ou des diverses applications relatives à l'injection de CO_2. La recherche, initiée sur trois des cinq sites pilote, fournit une vue d'ensemble avec définition des divers défis auxquels s'atteler et comment leur faire face. Ceux-ci incluent les problèmes d'injection de CO_2 au niveau géologie locale et techniques d'injection (Hontomin), production d'hydrocarbures compatible avec les interactions climat et énergie (CO_2-EOR, LBr-1), et l'intégration du stockage géologique aussi bien pour la capture du CO_2 que pour les plans de son utilisation (Q16-Maas).

Los trabajos de investigación y desarrollo en cinco áreas de estudio in situ han jugado un papel relevante en el proyecto H2020 ENabling Onshore CO_2 Storage in Europe (ENOS). Cada uno de estos emplazamientos se centra en desafíos particulares o diferentes en la aplicación de inyección de CO_2. La investigación desarrollada en tres de los cinco areas piloto ofrece una visión general de los diferentes desafíos y cómo se abordarán. Estos incluyen los desafíos geológicos y tecnologicos directos de la inyección del CO_2 (Hontomin), la producción de petróleo compatible con el nexo clima-energía (CO_2-EOR, LBr-1) y la integración del almacenamiento geológico en los esquemas de captura y utilización del CO_2 (Q16-Maas).

The ambition of the ENOS project (Gastine *et al.*, 2017) is to study several aspects of CO_2 Geological Storage (CGS) in order to streamline the implementation of this technology as a climate mitigation measure. An additional challenge is to demonstrate feasibility and especially acceptability of CGS in on-shore settings. To make this concrete, ENOS has identified five actual pilots and near-future projects. The three field sites discussed in this paper each focus each on a totally different approach for bringing full-scale CGS to Europe.

The ENOS project is funded by the EC under H2020. ENOS is the acronym for ENabling Onshore CO_2 Storage in Europe. The project is an initiative of CO_2GeoNet, the European network of excellence on the geological storage of CO_2 (Czernichowski-Lauriol & Stead, 2014). The consortium is composed of 29 partners from 17 European countries.

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The EC remains adamant that CGS, as the final element of CO_2 capture and storage, has an essential role to play in reducing the climate impact of industry and the power sector (IEA, 2017), even when renewable energy technologies such as photovoltaic solar are reducing costs faster than anticipated. An element of increasing importance in the search for using CO_2 as a feedstock is so-called CO_2 capture and utilisation schemes, and two of the discussed field sites look into the geological aspects of such realisations.

At Hontomin (Spain) the first injection tests with CO_2 have been carried out in order to test reservoir, equipment and monitoring systems. Injection will be scaled up from this point onward. Research on the currently abandoned gas and oil field LBr-1 in the Czech Republic it is aimed at bringing it back online, with a specific focus to develop it for CO_2-enhanced oil recovery. A particular challenge will be to integrate reservoir and techno-economic modelling to determine the best development strategies from economic and environmental points of view. In the Netherlands, the currently producing but small Q16-Maas natural gas and condensate field will soon be depleted. It will then be suitable for development as geological CO_2 buffer storage, allowing the reuse of industrial CO_2 in horticulture to be scaled up.

Hontomín

The Hontomín Technology Development Plant (TDP) is currently the only operational on-shore injection site in Europe, located close to the city of Burgos (Spain). The main reservoir/seal pair is formed by Jurassic limestones and seal rocks belonging to the Lias and overlying Dogger formations, whilst the primary hemipelagic seals are marls and black shales of Pliensbachian and Toarcian age. The site represents a structural dome, with the reservoir and seal rocks being located at a depth from 900 (top of the dome) to 1832 m (flanks). The main seal is the Marly Lias and Pozazal formations (highly carbonated marls, 160 m thick) and the reservoir is the Sopeña Formation (limestones and dolomites, 120 m thick; Rubio *et al.*, 2014). Both have a

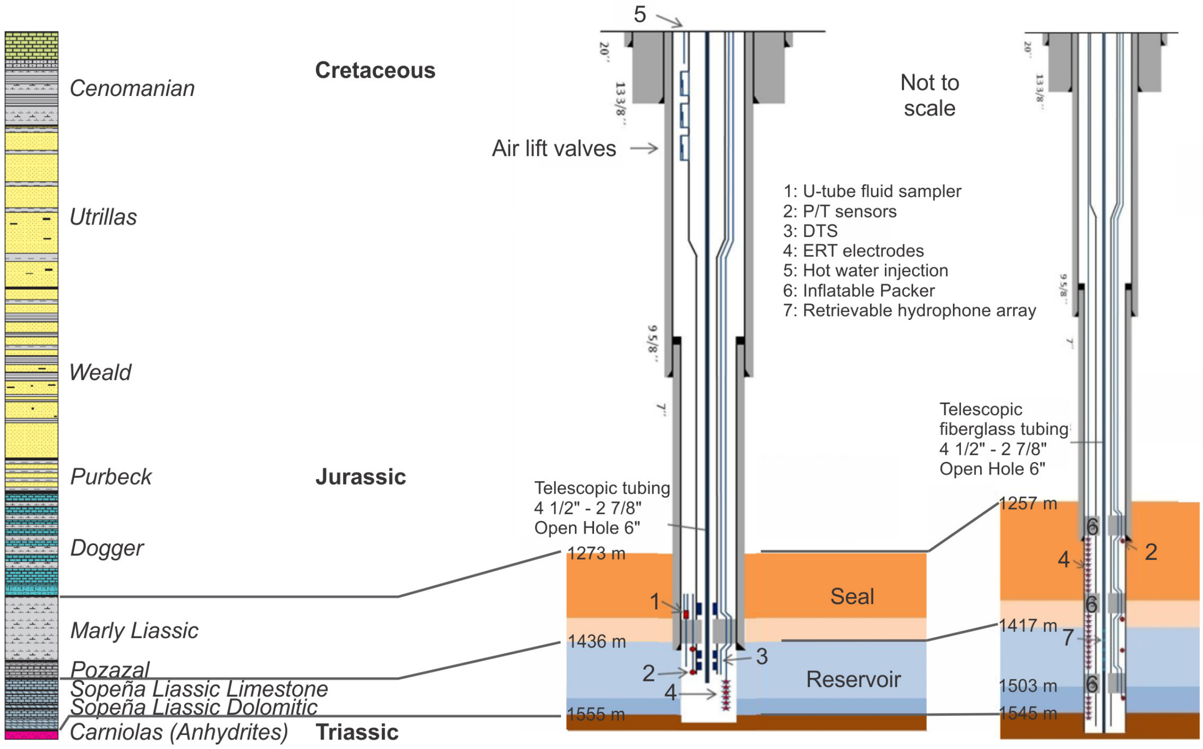

Figure 1: Lithological column on left side describes geological formations of the seal and reservoir. Injection well (middle) and observation well (right) with their deep monitoring devices form part of the Hontomín TDP.

high level of fracturing in different geological blocks, but this does not affect the seal integrity.

One injection well (HI) and one observation well (HA) form part of the pilot (***Figure 1***), with the facilities for CO_2 injection and water conditioning (to adjust brine pressure, temperature and salinity). Both vertical wells have been drilled to the depths of up to 1,600 m on the flank of the domed reservoir, with a distance of 50 m between them at surface (de Dios *et al.*, 2017).

The HI well is equipped with super duplex tubing anchored to the liner by a hydraulic packer (at 1433 m Measured Depth), two P/T sensors located below the packer, one Distributed Temperature Sensing System (DTS) and one Distributed Acoustic Sensing System (DAS) joined along the tubing, six ERT electrodes and one U-tube device to sample fluids, installed in the bottom hole.

The HA well is equipped with a fibreglass tubing anchored to the liner with 3 inflatable packers (at 1275 m, 1379 m and 1497 m MD) that section the open hole into intervals with different permeability, four pressure/temperature (P/T) sensors and 28 ERT electrodes installed in the seal and reservoir formations.

CO_2 injection and water conditioning facilities, a seismicity monitoring network and hydrogeological monitoring wells also form part of the TDP. The CO_2 injection facility consists of three cryogenic tanks with a total capacity of 150 t, and three pumps with the following operating parameters: flow 0-2 kg/s, pressure up to 120 bar, and two heat exchangers for conditioning the CO_2 temperature in the range of 10–40 °C. The water conditioning facility is used to support CO_2 injection (i.e., according to the operational procedure it is necessary to inject brine before and after the injection of CO_2).

Thirty-one passive seismic stations form part of the monitoring network, covering an area of 18 km² around the TDP. The hydrogeological monitoring network comprises eight wells, three of which have been specifically drilled for the project (150–400 m depth) into the Utrillas Formation overlying the top seal where the freshwater aquifers are located, equipped with instrumentation for remote control of groundwater composition and level monitoring.

Three different types of injection strategies will be performed at the Hontomín TDP in the ENOS project:

- **Discontinuous strategies.** Focusing on gathering knowledge to improve the hydrodynamic stability at the fractured reservoir.
- **Continuous strategies.** Handling the operational parameters to control storage integrity in long-term injection.
- **Alternative strategies.** Cold injection will be designed and tested, with the aim of finding the most efficient operational parameters.

The results from injection campaigns are expected to provide solutions to the following technical gaps, in order to define a safe and efficient industrial procedure:

- Monitoring the CO_2 phase at the well head, its evolution along the tubing and the fluid density at the bottom hole;
- Energy consumption for each injection scheme, determining the associated performance;
- BHP evolution and its influence on the pair seal-reservoir integrity;
- BHT evolution and the analysis of thermal effects during injection;
- Alteration of the operating process (e.g. hydrates formation).

At this preliminary stage of ENOS project, first discontinuous injections of CO_2 and brine have been conducted on site in

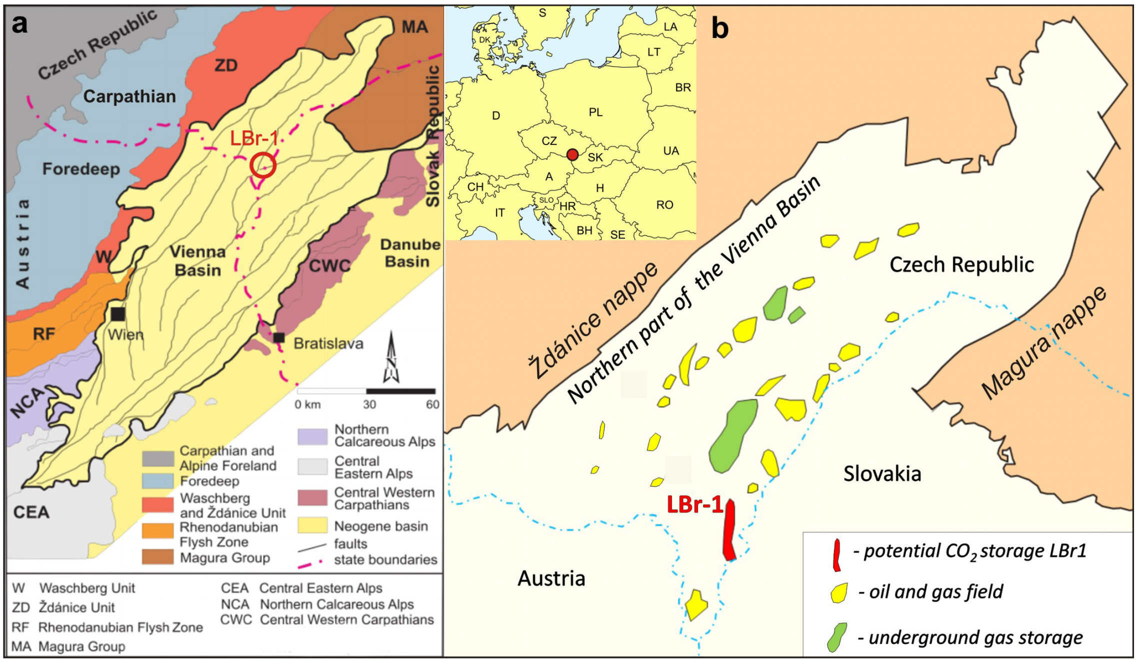

Figure 2: Sketch maps of the whole Vienna Basin (a) and its Northern part (b) with the location of the LBr-1 field (Francu et al., 2017, adapted from Kováč et al., 2008).

order to determine the reservoir behaviour during the injection and shut-in periods. Deep sampling of reservoir water to analyse its chemistry evolution and tests to perform first 3D VSP campaign for plume tracking are other activities that have been performed at the Hontomín TDP in ENOS.

CO_2-EOR as a business case for Europe

While the North Sea Basin has been long identified as a possible large-scale storage site for the whole of Europe, it is important to engage local stakeholders (policy makers, population and industry) to enable CCS in Europe. LBr-1 is a relatively small abandoned hydrocarbon field in the Czech Republic that is located close to the Slovakian and Austrian borders. Based on earlier work carried out in the REPP-CO_2 project (Hladik *et al.*, 2017), the field has indeed been confirmed as a very good pilot site for this exercise. As a small field it is representative of the mature Vienna Basin oil province, which stretches across Austria, Slovakia and the Czech Republic. There are positive indications of good potential for CO_2-EOR for this field, and production schemes will be further optimised during the ENOS project, taking into account economic considerations.

For exploitation of this site, cross-border coordination is also needed. The field itself is close to state borders (***Figure 2***), which means that the storage complex boundaries need to be carefully evaluated, including, among others, the pressure footprint and risk scenarios of possible leakage of fluids from the storage reservoir below spill points. Moreover, the closest suitable industrial point source of CO_2 is in Slovakia, at a distance of ca. 120 km from the storage site.

Based on the existing understanding of the LBr-1 field, CO_2-EOR followed by storage is not only capable of generating more oil. Such a combination can actually result in more CO_2 stored in the field than is generated from utilisation of hydrocarbons that have been and will be produced from this field.

Figure 3 shows the CO_2 balance for one of the simulated CO_2 injection scenarios (called "combined case") at LBr-1. The scenario starts from the current status quo situation that takes into account the historical hydrocarbon production from 1957 to present and the corresponding CO_2 emissions produced by combustion of the oil and gas produced. In 2020 pilot CO_2 injection will start and then continue until 2026. This will be followed by three years of oil production, until 2029. The three-year production period was selected based on the results of other simulations for this reservoir, that show that approximately 50% of the additional oil will be recovered during first three

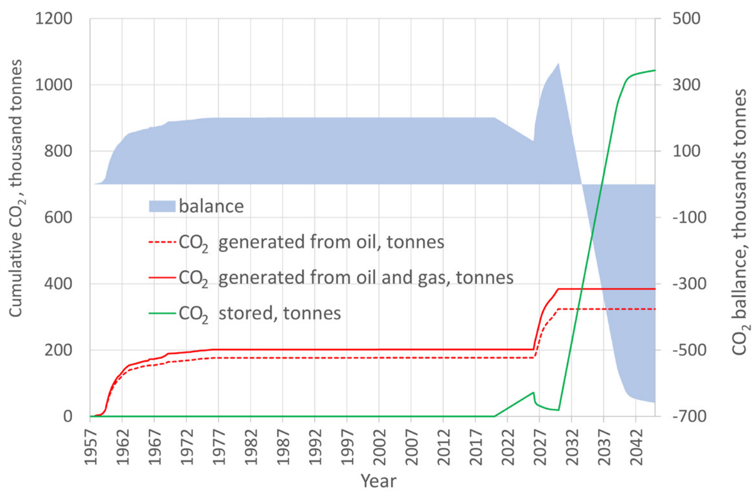

Figure 3: CO_2 balance of one of the initial simulations for the LBr-1 field. On the horizontal (time) axis we can identify the historical phase of conventional oil production, the long relaxation period after site abandonment, and the potential future CO_2-EOR and CO_2 storage phases.

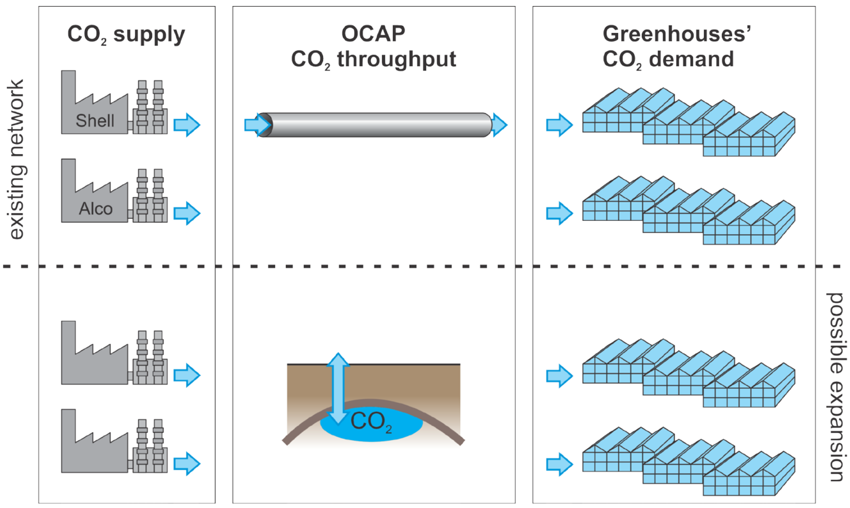

Figure 4: The existing network includes two CO_2 suppliers in the Rotterdam harbour area that deliver CO_2 to a pipeline, which transports it to several areas to be used in greenhouses (top). The lower illustration shows potential elements for expanding the network, such as additional suppliers and consumers, but the current bottleneck is the buffering capacity of the network.

years, followed by production decline. After the three years of oil production the reservoir is to be closed and the pure CO_2 storage phase will be started, which is scheduled to last until 2040.

The CO_2 balance (blue shaded area in the graph) is expected to improve quickly after the oil production is stopped and the field starts serving as a pure storage site. Five years after production termination the overall balance is predicted to be zero (= no net emission), after which it becomes markedly negative.

The importance of carbon negative solutions, extended here to hydrocarbon fields that over their lifetime can be carbon neutral or even negative, has been stressed since the CCOP 21 in Paris for meeting the 2°C climate change mitigation target. While hydrocarbons could be phased out as an energy source in the years to come, they will remain a vital resource for the petrochemical industry.

Q16-Maas

In the Netherlands, a utilisation network for CO_2 for reducing the CO_2 emissions from the horticulture is operational. The standard practice of Dutch greenhouses that are not connected to the CO_2 grid is to produce CO_2 through burning natural gas in co-generation units. In winter both heat and CO_2 are used, while in summer only CO_2 is needed.

These emissions are partially avoided by distributing CO_2 from the industrial area around Rotterdam to the greenhouses, using a reconverted pipeline as backbone. The CO_2 is obtained from two industrial sources, the Shell Pernis refinery and the Alco bio-ethanol plant, which have dedicated scrubber installations in place. The central body OCAP is the distributor and guarantees continuous supply (***Figure 4***). The pipeline is operated at low pressure, meaning that CO_2 is gaseous throughout the transport chain. An additional environmental benefit is that the availability of CO_2 is compatible with the use of geothermal energy to heat greenhouses, which is indeed increasingly the case in this area.

The success of this network is such that it has currently reached its limits: over 400 kt of CO_2 are delivered to connected greenhouses. While the pipeline can still accommodate additional capacity, the first bottleneck is the CO_2 suppliers. During summer, which is the growth season with high CO_2 usage by the greenhouses, the limits of the capture installations are reached. In order to expand the network to additional users, temporary geological storage has been proposed to buffer seasonal demand and continuous production (***Figure 4***).

The quantities of CO_2 to be stored are too large to consider storage at the surface. A more realistic option is offered by the Q16-Maas gas and condensate field just off-shore of Rotterdam. It is one of the most recent fields, but also very small, and is near depletion. The total capacity for CO_2 is currently estimated at around 2.1 Mt, which is small for traditional storage, but possibly the ideal scale for a buffer reservoir.

Developing the Q16-Maas into a CO_2 buffer offers sufficient advantages to consider it as an investment opportunity. Integrating a geological element in an already complex chain is, however, a challenge. In this case a geological buffer with converted injection, production and potential scrubber installations would be linked to the existing distribution network through a new pipeline segment to double the capacity for delivering CO_2, including potentially new CO_2 sources and consumers. Implementation depends on assessing the reliability and economics of the upscaled project, even when there are still significant geological uncertainties that remain unresolved.

The methodological approach for studying this buffer is one of the first to be based on the principles of geological economics. The integration of a reservoir model into an economic analysis allows the intricacies of working with subsurface data to be taken into account, such as widely varying degrees of uncertainty.

Because traditional reservoir simulations are calculation intensive, these are not suitable for integration in Monte Carlo-based economic assessments. In the first step of a speed-optimised solution, dynamic reservoir models will provide results for the most important parameters, injection and production pressures and fluid composition, for a limited number of cases and parameter variations (~15). In the second step, a set of continuous reservoir response curves will be interpolated based on these data, including uncertainty ranges. These results, called reservoir response curves, serve as direct input for the economic assessment.

The economic viability of integrating the Q16-Maas field as a buffer in the existing CO_2-utilisation network will be investigated, starting from the current network configuration. The greenhouses will be presented with different options for CO_2 and heat supply, including the OCAP network, CHP, geothermal and external CO_2 supplied by truck. The choices are made on a quarterly basis with limited foresight, which allows the buffer to be addressed on a seasonal basis if desired, with a realistic outlook uncertainty (***Figure 5***). This approach allows us to determine the conditions under which buffer storage provides added value.

Conclusions

The ENOS project is a unique gathering of expertise covering all aspects needed for tackling the existing knowledge gaps concerning the geological storage of CO_2 in onshore settings. A broad range of approaches is necessary to enable onshore geological storage in Europe, which is given dedicated attention in current and realistic future pilot sites. The benefits of CO_2 geological storage are not necessarily restricted to climate and environment. In two of the cases, it is integrated into schemes that also improve the regional socio-economic matrix.

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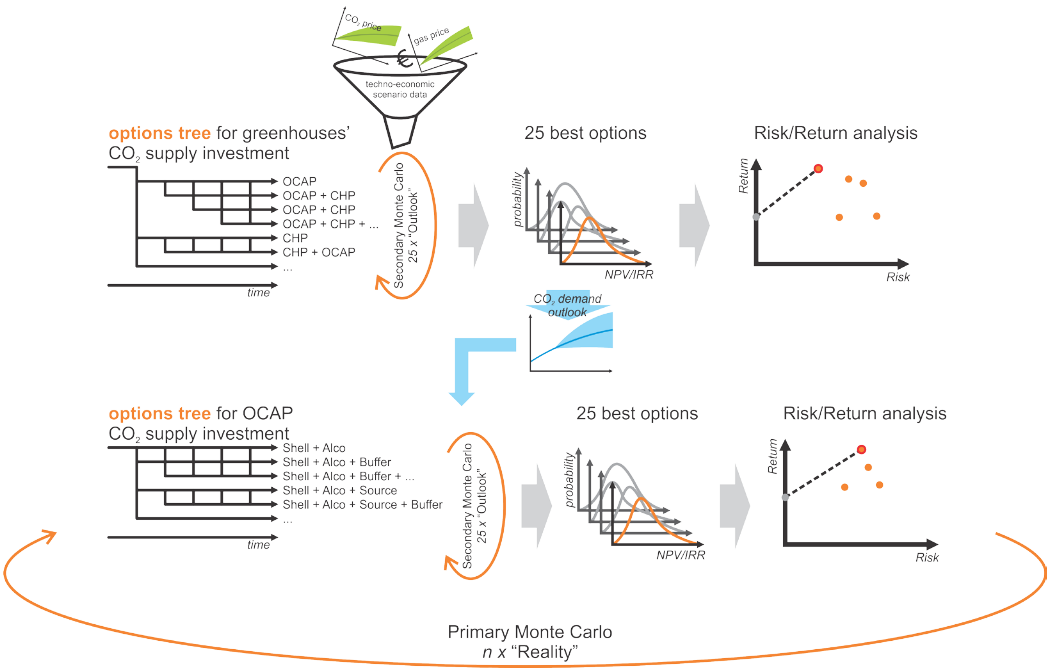

Figure 5: This schematic presentation of the techno-economic methodology shows how the predictions of the model are based on the simulating the behaviour of two actors: the greenhouse farmers (top) and the utility company OCAP (bottom). Both make realistic investment choices under uncertainty that interact with each other.

References

Czernichowski-Lauriol, I., Stead, R. 2014. Developments of CO2 geological storage in Europe and the role of CO2GeoNet. *Energy Procedia*. 63. 8107 – 8115. DOI: 10.1016/j.egypro.2014.11.846

de Di, J.C., Delgado, M.A., Martinez, C., Ramos, A., Marín, J.A., Salvador, I., Álvarez, I. 2017. Hydraulic characterization of fractured carbonates for CO2 geological storage: experiences and lessons learned in Hontomín Technology Development Plant. *International Journal of Greenhouse Gas Control*. 58C. 185-200. DOI: 10.1016/j.ijggc.2017.01.008

Francu, J., Pereszlényi, M., Riis, F., Prokop, O., Jurenka, L., Hladík, V., Krejčí, O. 2017. 3D geological model of potential CO2 storage: Abandoned oil and gas field LBr-1 in the Vienna Basin. *Energy Procedia*. 114. 2772-2780. DOI: 10.1016/j.egypro.2017.03.1393

Gastine, M., Berenblyum, R., Czernichowski-Lauriol, I., de Dios, J.C., Audigane, P., Hladik, V., Poulsen, N., Vercelli, S., Vincent, C. Wildenborg, T. 2017. Enabling onshore CO2 storage in Europe: fostering international cooperation around pilot and test sites. *Energy Procedia*. 114. 5905-5915. DOI: 10.1016/j.egypro.2017.03.1728

Hladik, V., Berenblyum, R., Pereszlényi, M., Krejčí, O., Franců, J., Riis, F., Ford, E.P., Kollbotn, L., Khrulenko, A. 2017. LBr-1 - Research CO2 storage pilot in the Czech Republic. *Energy Procedia*. 114. 5742-5747. DOI: 10.1016/j.egypro.2017.03.1712

Kováč, M., Sliva, L., Sopková, B., Hlavatá, J., Škulová, A. 2008. Serravallian sequence stratigraphy of the northern Vienna Basin: High frequency cycles in the Sarmatian sedimentary record. *Geologica Carpathica*. 59. 545-561.

IEA. 2017. Energy Technology Perspectives 2017. International Energy Agency

Rubio, F.M., Garcia, J., Ayala, C., Rey, C., García Lobón, J.L. 2014. Gravimetric characterization of the geological structure of Hontomín. In Proc. 8ª Asamblea Hipano-Lusa de Geodesia y Geofísica. Évora (Portugal), 29-31 January 2014.