EnerGizerS

CO_2- Enhanced Geothermal Systems for Climate Neutral Energy Supply

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Main objective of the EnerGizerS project

- The main objective of the project is to progress the technology of Enhanced Geothermal Systems (EGS) using CO_2 as a working fluid closer to industrial deployment.
- This process will include analysing test fields located in Poland and in Norway, respectively, and filling the knowledge gaps needed to bring the technology forward in these cases.
- An important objective of the project is also to reinforce the cooperation between the Polish and Norwegian partners involved in projects, with the goal of building cooperation in future activities.

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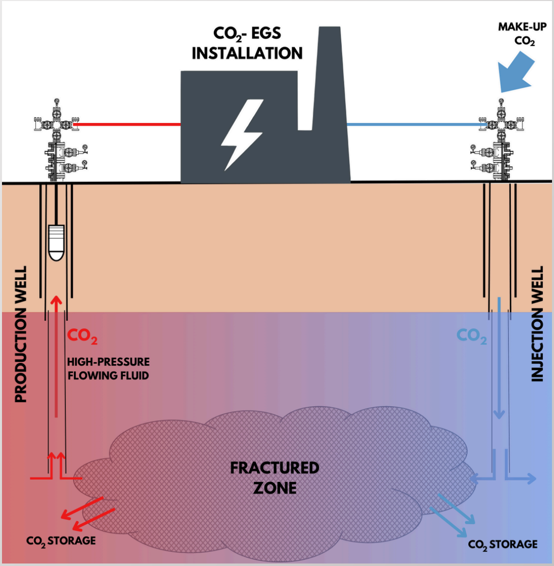
PROJECT PARTNERS

Working together for a green, competitive and inclusive Europe

CO_2- EGS SYSTEM SCHEME

CO_2-Enhanced Geothermal Systems - systems that extract energy from rock formations (dry or not containing a sufficient amount of water) by artificially increasing the hydraulic capacity of the geothermal reservoir, introducing an energy-carrying working fluid into the reservoir, and then bringing it to the surface (to the power plant) for energy purposes. The working fluid in CO_2-EGS systems is carbon dioxide. The purpose of this type of installation is primarily related to the energy aspect, i.e., acquiring energy accumulated in hot, dry rocks located at great depths, secondary - an increase in the pro-environmental effects through the geological storage of CO_2 during the energy generation process.



CO_2-EGS Scheme

Research approach

The EnerGizerS project has been divided into 6 parts

- Identification and selection of sites appropriate for CO_2- EGS
- Description of the geothermal reservoir based on the result of comprehensive laboratory rock testing
- Experimental determination of the properties anf behaviour of CO_2-EGS working fluid
- Mathematical modelling of the geological reservoir for CO_2-EGS operation
- Mathematical modelling of CO_2-based topside systems for heat and power production
- Technological, economic and environmental evaluation

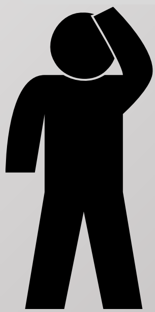
There are favourable geological conditions for developing CO_2-EGS technology - In Poland: the Gorzów Block area, and in Norway: Åre Formation in the Norwegian Sea.

The indicated test locations are characterised by different geological parameters:

- Gorzów Block (onshore location) reservoir rocks are volcanic rocks (Lower Permian) at a depth of 4100 - 4300 m a.s.l. with the approx. temp. of 145°C
- Norwegian Sea (off-shore location) - Åre formation at a depth of 4600-4800 m a.s.l., sedimentary rocks with a temperature of 166°C.

The experimental campaign delivered a new setup for accurate measurements of the phase behaviour of CO_2 mixtures - VLE results of CO_2- H_2O system at isotherm of 50°C (mole fraction from 0.3481 to 1.3075 %).

RESULTS



In Poland, two cases were considered: Case 1 - combined heat and power within the direct sCO_2 cycle - allows to achieve power of 0.4 MWel & 9 MWth for up to 18 years with electricity production of 120,235 MWh and heat production of 2,219,119 MWh. Working only with the thermosiphon effectis recommended. Case 2 - power generation only within the hybrid cycle - the power of 1.7 MWel for up to 20 years; electricity production of 369,240 MWh. The operational phase is 30 years, and 10,764,096 tons of CO_2 will be stored.

In Norway, two cases were considered: indirect ORC (at sea floor) and indirect ORC (at platform). The system can produce 10-12 MW power for decades. Higher water content weakens the thermosiphon effect, but the thermal energy content extracted is much higher. The operational phase is 30 years, and 154,723,245 tons of CO_2 will be stored. Electricity production is estimated at 2,577,987 MWh.

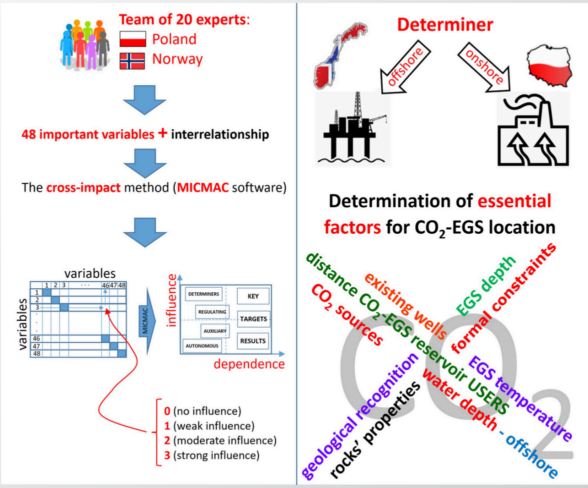
The conducted environmental analysis shows that the environmental footprint is smaller for the Åre formation, particulary for the power generation (global warming = 12 kg CO_2eq). Power generation within the Gorzów area's hybrid cycle has the highest impact (54 kg CO_2eq). For combined heat and power within the direct sCO_2, this value is 39 kg CO_2 eq. The firts phase results is the highest environmental impact, due to the energy and resources required during reservoir stimulation and well drilling.

The laboratory test results indicate that the studied rocks have suitable parameters as a geothermal reservoir for CO_2-EGS.

The economic profitability of the analyzed systems depends strongly on CAPEX, CO_2 price and heat price. Electricity production from low-temperature geothermal heat is not profitable, so the existence of heat demand is crucial. Project results indicate an investment cost of approx. 61 to 380 million Euros, depending on the selected solution. The majority of the CO_2-EGS economic profitability comes from heat sale or CO_2 storage itself. The chance for lowering the capital cost is related to a wider commercialization of CO_2- based thermodynamic cycles and potential reuse of existing wells.

Identification of key parameters for the effective use of the CO_2- EGS systems and selection of appropriate locations

Selection of key parameters, pointing out interrelationships between key parameters.



The most essential variables for the development of CO_2 -EGS systems technology:

- Formal constraints related to the local nature protection areas - this variable is essential in the case of an onshore system
- Availability of CO_2 sources
- Level of geological identification
- Distance of the CO_2 - EGS from a thermal energy consumer and electricity grid
- Existing wells and other infrastructure
- Depth of the EGS system
- Water depth if offshore, this variable is only important for offshore systems
- Physical parameters of reservoir rocks
- Reservoir temperature.

Selection of two test locations (based on the geological survey, considering the relevant parameters and relationships between them).

After a number of analyzes, the following two final locations were selected:

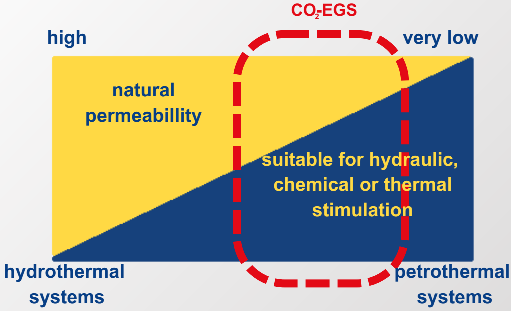
- in Poland: the Gorzów Block area
- in Norway: Åre Formation in the Norwegian Sea, Skagerrak Formation and Ula Formation (North Sea)

Both of these locations were characterized in detail in terms of the physical; and mechanical parameters of the reservoir rocks. These results then constituted an important input to numerical models of CO_2- EGS in these areas.

Selected study area

Characteristics of the geothermal reservoir based on the results of comprehensive laboratory tests of rocks

What reservoir rocks are we looking for?



Based on Blöcher et al., 2016

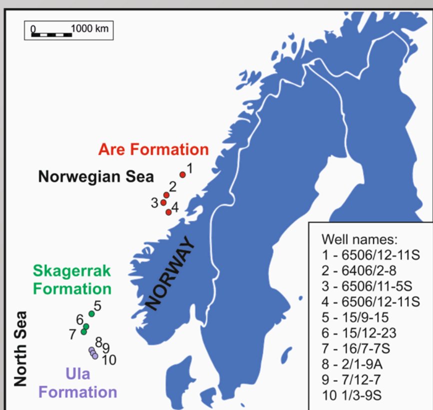
Due to the combination of these two aspects, the reservoir rock for the CO_2-EGS system should be characterized by parameters that enable it to receive energy from the reservoir zone while storing some CO_2 in the reservoir. Therefore, the reservoir rock must have a relatively low natural permeability value (energy aspect), however high enough for a part of the injected CO_2 remain permanently stored in the reservoir (environmental aspect).

To describe the CO_2-EGS geothermal reservoirs, we prepared a database containing archival petrophysical and mechanical data and collected core sample of interesting rock formations. **As a result of the activities:**

- 42 core samples were collected from the Ośno-IG2 borehole from the depth interval 3212 - 3659 m
- 10 core samples from Mesozoic reservoir formations (Skagerrak, Ula, Åre) from the North Sea region were also used for further laboratory work

Here is an example of a rock sample prepared for testing in the Polish (A) and Norwegian (B) research areas.

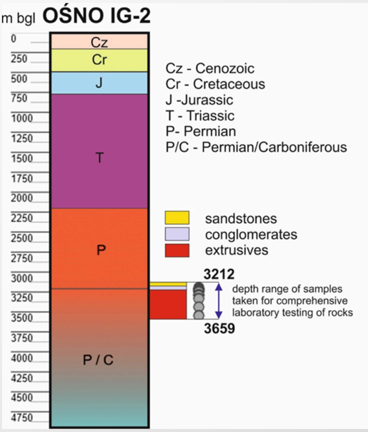
In the case of Norwegian samples, 10 core samples from Mesozoic reservoir formations (Skagerrak, Ula, Åre) were used for laboratory work. In the end, the Are formation was the most interesting. To characterise the petrogeothermal reservoirs in Norway, detailed laboratory studies were carried out on drill cores from selected locations.



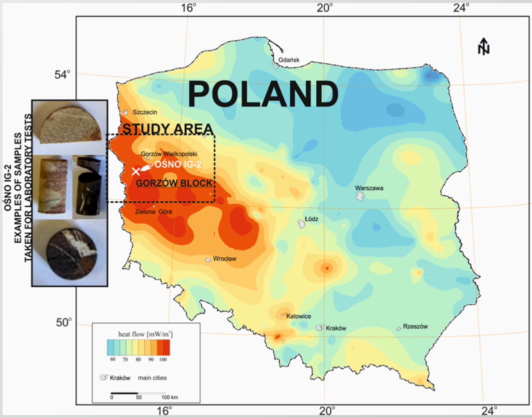
Locations of rock samples

Characteristics of the CO_2-EGS geothermal reservoirs

The Lower Permian profile in the Ośno-IG2 well located in the Gorzów Block was selected for testing. After indicating the most significant factors in the case of CO_2-EGS, 42 core samples, including sedimentary rocks and effusive rocks, were analyzed.



Chronostratigraphic profile of the OŚNO IG-2 borehole (according to CBDG) with information on the depth range of samples taken for laboratory tests.



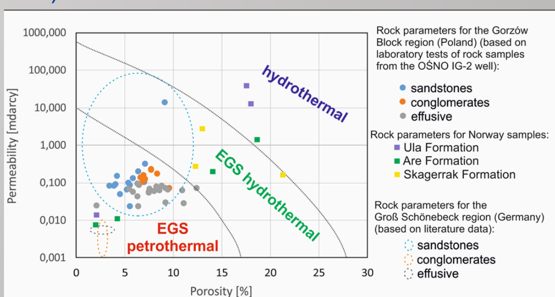
Study area on the background of heat flow map of Poland (modified, after Szewczyk and Gientka, 2009).

Laboratory tests:

- Petrophysical - pore space saturation measurements using the Nuclear Magnetic Resonance (NMR) method, pore space investigations using the mercury porosimetry (MICP) method
- Mechanical - Elastic moduli: Young, bulk and shear modulus were calculated taking into consideration P-, S-wave velocity, and density for each geomechanical test stage
- Thermal - thermal conductivity measurements using the FOX50 set
- Mineralogical composition using the XRD method

The dataset with results: https://data.mendeley.com/datasets/ch5yyg5nx8/1

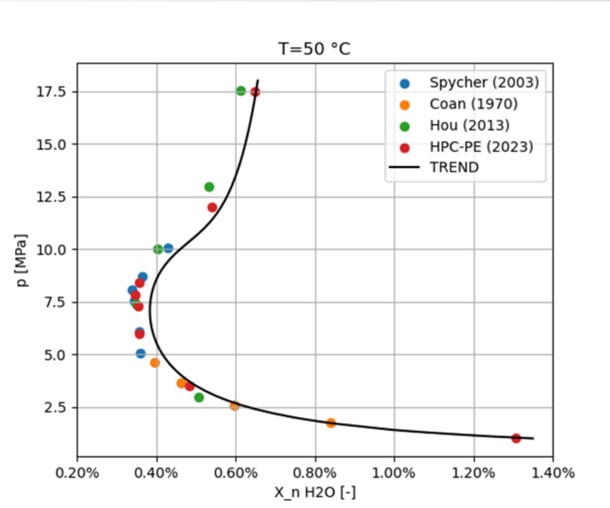
Results: relationship of porosity and permeability for different geothermal reservoir rocks. Application as EGS petrothermal, EGS hydrothermal or pure hydrothermal are presented based on (Moeck, 2014)



Relationship of porosity and permeability of different geothermal reservoir rocks

Experimental determination of properties and behaviour of CO_2-EGS working fluids

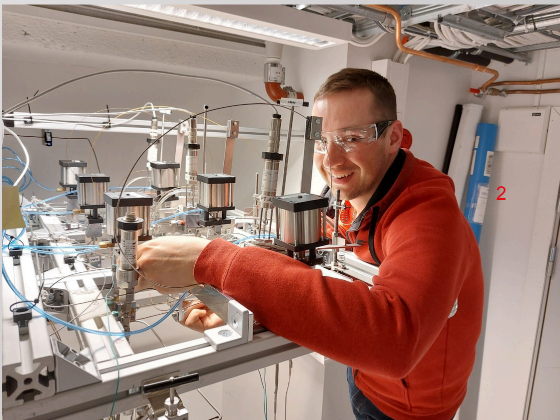
The experimental campaign was carried out using the laboratory infrastructure located at SINTEF. A Ph.D. student from AGH Univerisity of Krakow participated in laboratory experimental measurements during a six-month internship.



Experimental data compared with literature data and TREND
Legend: p - pressure
X_n H_2O - mole fraction of water in CO_2-H_2O mixture

The setup that was used for the phase equilibrium measurements - the ECCSEL ERIC High Pressure and Complex Phase Equilibrium facility (HPC-PE) is highly instrumented. The phase equilibrium behavior of carbon dioxide and water system has been investigated at temperatures of 50°C and pressures between 1 and 17.5 MPa using an analytical isothermal method, where the composition of the vapor phase has been measured.

Result: Accurate measurements of the phase behaviour of CO_2 mixture relevant for Enhanced Geothermal System working fluid.



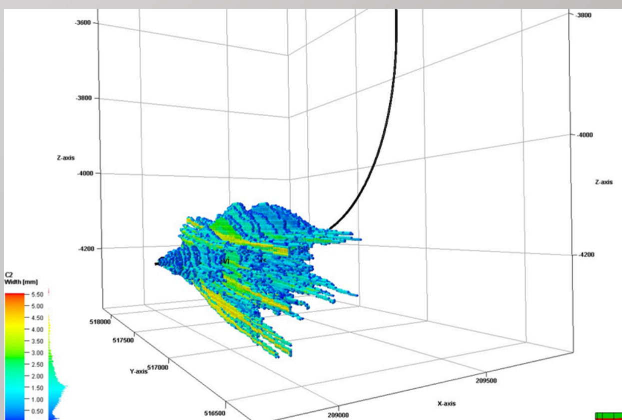
Laboratory experimental measurements

Numerical modelling of the rock's fracturing process for the selected EGS reservoir

Final case studies

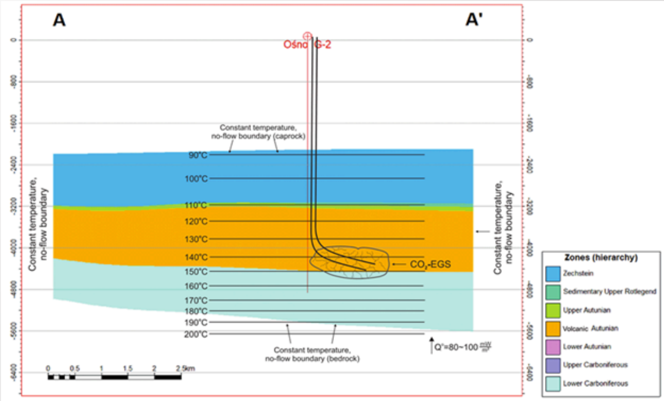
Case no	Location	Geological site	Heat demand type	Type of energy system	Type of energy cycle
1	Poland	Gorzów block	District heating systen	Combined heat and power	Direct sCO_2 Cycle
2	Poland	Gorzów block	Lack of heat demand	Power generation only	Hybrid (Direct sCO_2 Cycle witch ORC)
3	Norway	Åre formation	Lack of heat demand	Power generation only (sea floor)	Indirect witch ORC
4	Norway	Åre formation	Lack of heat demand	Power generation only (oil platform)	Indirect witch ORC

- The modelled scenarios assumed different well trajectories, fracturing fluids, and pumping patterns
- The fracturing simulations were analysed for the fracture geometry (height, length, and width) and the efficiency of using fluid for fracture propagation
- The key parameter determining the effectiveness of the fracturing treatment in EGS is the volume of the fractured zone generated
- The best result was a deviated well; water was used as the treatment fluid
- The simulation results also show that drilling a well with a production section length of more than approximately 600 meters (base case) is ineffective
- The result was a permeability distribution in the SRV zone, which was exported from the model in a format that enabled the construction of a dynamic simulation model



Hydraulic fractures geometry with width property, best variant

Conceptual model for the Gorzów Block, Poland



The conceptual model of the selected location in the Gorzów Block

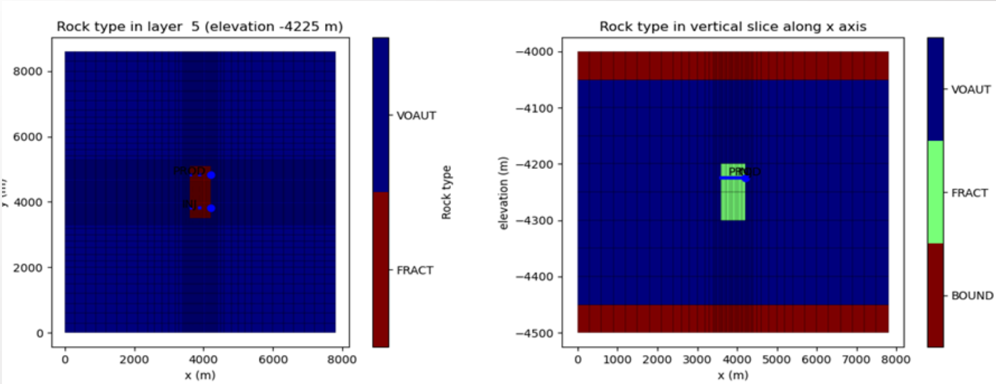
Key facts about the selected location in the Gorzów Block

Location	The Gorzów Block, with Ośno IG-2 well in the centre of the model
Host rock	Volcanic rocks and breccias/Volcanic Autunian (Permian period, Cisuralian epoch)
Cap rock formation	Volacanic Autunian itself+Zechstein
Target depth	from -4300 to -4100 m a.s.l.
Expected reservoir temperature	from 139 to 145 °C
Mean permeability before fracturing	9.87·10-17 m^2(X, Y, Z)
Mean porosity at the target depth	0.03

Pros and cons of the selected location

Pros	Cons
Low permeability formation, very thick, suitable for fracturing	Rather low reservoir temperature for typical EGS
Good sealing properties of the cap rock and bedrock	Low reservoir porosity, thus limited potential for storing CO_2
High temperature gradient compared to average geothermal conditions in Poland	Low heat demand, no DH system in close neighbourhood

Setup of the numerical model of the Gorzów Block, Poland



Mesh of the numerical model: left - top view, right - slice view

Key assumptions for the numerical model of the Gorzów Block's location

- 2 wells J-shaped: 1 production and 1 injection well, parallel to each other in the horizontal sections
- Depth: 4296 TVD, 5120 MD
- Size of the fractured zone: approximated by single cuboid 1600 x 600 x 100 m
- Volume of the fractured zone: 0.096 km^3
- Length of horizontal active section: 600 m
- Separation distance between wells: 1000 m
- Minimum pressure needed to prevent fracture from closing: 64 MPa

2 phases of CO_2-EGS development:

Phase 1 – saturation of the fractured zone with CO_2:

- injection of 139.5°C CO_2 at different flow rates;
- only CO_2 entering the production well at the end of phase 1;
- maximum duration of 2 years;

Phase 2 – full-scale exploitation:

- test different injection schemes with varying injection rates and temperatures;
- runs for up to 50 years;
- production mode: well on deliverability with a fixed bottomhole pressure limit at 64 MPa.

Injection temperature [°C]	Mass flowrate [kg/s]		
	50	100	150
45	M.50.45	M.100.45	M.150.45
60	M.50.60	M.100.60	M.150.60
75	M.50.75	M.100.75	M.150.75

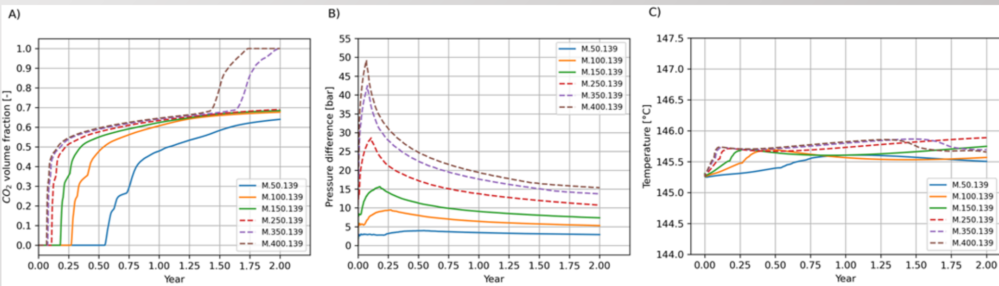
Description of the parameters

Legend: M.X.Y, where X is injection rate [kg/s] and Y is injection temperature [°C]

Numerical model of Gorzów Block, Poland - results

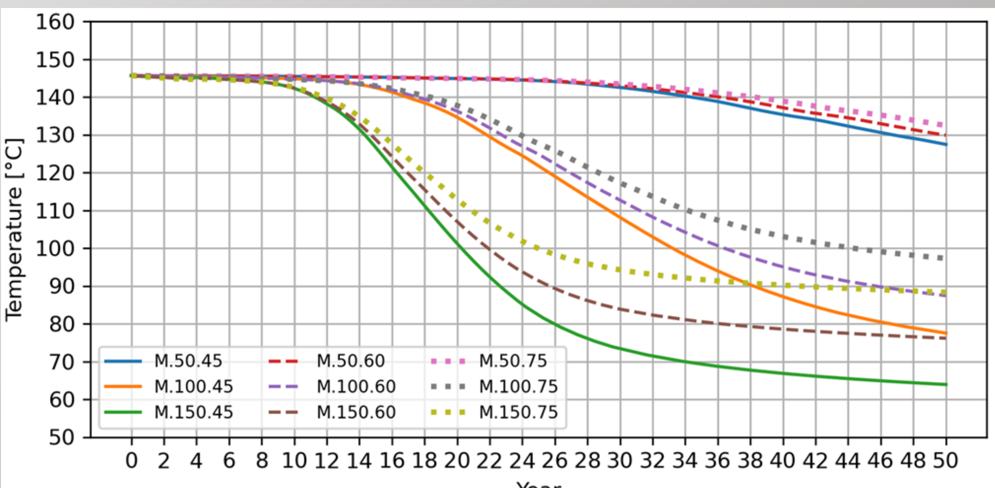
Model no.	M.50.45	M.100.45	M.150.45	M.50.60	M.100.60	M.150.60	M.50.75	M.100.75	M.150.75
Average flow rate in production well during phase 2 [kg/s]	37,69	87,47	137,36	37,75	87,55	137,45	37,8	87,63	137,54
Production temperature after 30 years of phase 2 [°C]	142,5	108	73,5	143	112,6	83,8	143,4	121,4	95,5
Production temperature after 50 years of phase 2 [°C]	127,4	77,5	63,9	129,9	87,4	76,2	132,4	97,3	88,3
Total CO_2 injected to reach full CO_2 saturation in production blocks [tons]					2,19E+07				
Total CO_2 injected in phase 1 and phase 2 (52 years) [tons]	1,04E+08	1,83E+08	2,62E+08	1,04E+08	1,83E+08	2,62E+08	1,04E+08	1,83E+08	2,62E+08
Total CO_2 stored in rocks in phase 1 and phase 2 (52 years) [tons]	2,81E+07	2,85E+07	2,87E+07	2,80E+07	2,84E+07	2,86E+07	2,79E+07	2,83E+07	2,84E+07
Cumulative CO_2 storage ratio after phase 2 (52 years) [-]	0,27	0,156	0,11	0,27	0,155	0,109	0,269	0,155	0,109
Average annual replenishment of CO_2 from the pipeline as a result of geological storage, phase 2 [tons/year]	3,88E+05	3,96E+05	4,00E+05	3,86E+05	3,93E+05	3,97E+05	3,84E+05	3,91E+05	3,94E+05

Phase 1 results



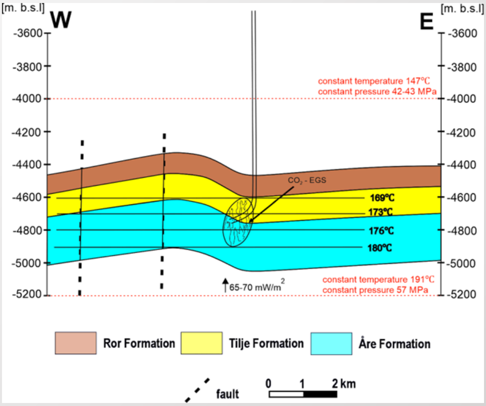
Result of modelling - Phase 1

Phase 2 results - temperature drop of CO_2 entering production well



Result of modelling - Phase 2

Conceptual model for the Åre Formation, Norwegian Sea



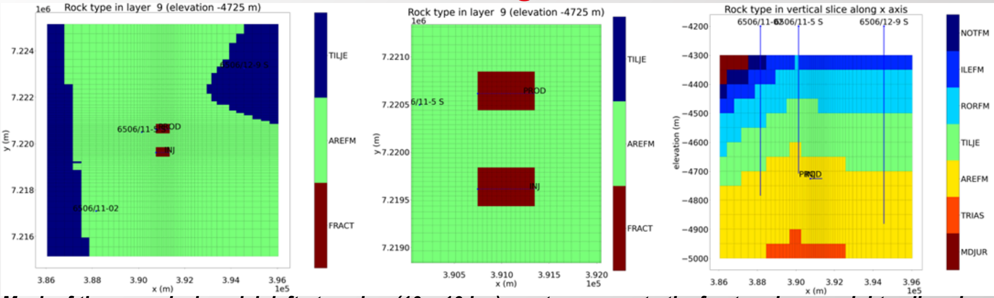
Key facts about the selected location in the Åre Formation

Location	Åsgard field in the Norwegian Sea, reservoir combining Åre and Tilje formations
Host rock/Startigrapgy	Sandstones interbedded with coals and coaly claystones (Åre Fm) or with shales and siltsones / Lower Jurassic
Cap rock formation	Ror Fm.
Target depth	from -4800 to -4600 m a.s.l.
Expected reservoir temperature	~165°C
Mean permeability before fracturing	5.0·10-14 m^2≈ 50 mDarcy
Mean porosity at the target depth	0.15

Pros and cons of the selected location

Pros	Cons
High temperature formation, at least compared to the Gorzów Block	Reservoir rocks less suitable for fracturing; fractures half-length will be limited
Good sealing properties of the cap rock confirmed by the existence of hydrocarbons	High natural permeability of the reservoir causing leakage of CO_2 outside of the fractured zone; 2-components flow in the production well
High rock porosity is beneficial for large CO_2 storage projects	Offshore location, seafloor depth at ~300 m, cooling of working fluid by seawater
Drilling infrastructure onsite	Electricity production only, no heat demand

Setup of the numerical model of Åre Formation, the Norwegian Sea



Mesh of the numerical model: left - top view (10 x 10 km), center – zoom to the fractured zone, right - slice view

Key assumptions for the numerical model of the Åre / Tilje Formation's location

- 2 wells J-shaped: 1 production and 1 injection well, parallel to each other in the horizontal sections
- Depth: 4750 TVD, 5575 MD
- Size of the fractured zone: approximated by 2 cuboids created along each well: 600 x 400 x 200 m
- Volume of the fractured zone: 2 x (0.6 km x 0.4 km x 0.2 km) = 0.096 km^3
- Length of horizontal active section: 600 m
- Separation distance between wells: 1000 m
- Estimated reservoir pressure at -4725 m a.s.l.: min. 48 MPa

Single phase of CO_2- EGS development:

- Immediate start of full scale operation shortly after end of fracturing
- Test different injection schemes with varying injection rates and temperatures
- Check impact of fracturing on the results by comparing scenarios with and without fracturing
- Runs for up to 50 years
- Production mode: forced flow from the production well equal to the injection rate
- Expected mixture of CO_2 and H_2O entering the production well

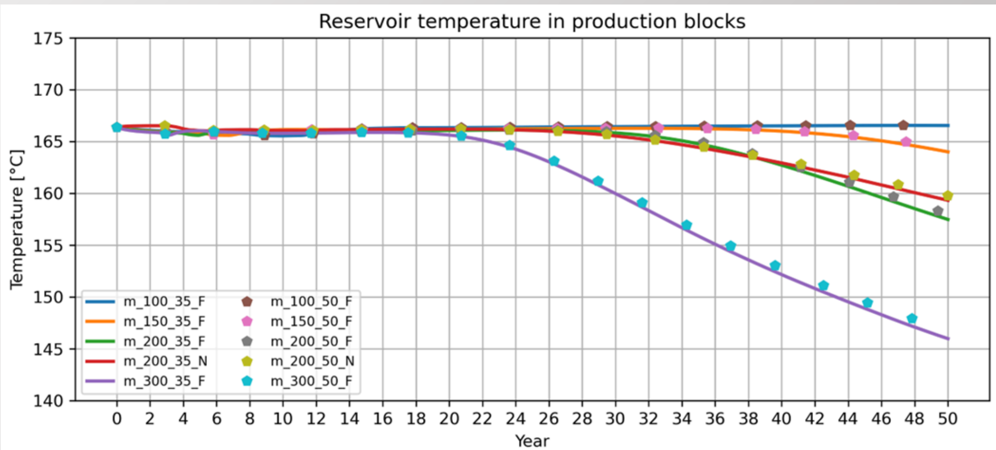
Injection temperature	Non-fractured reservoir	Fractured reservoir shape: 2 x (600 m x 400 m x 200 m) + unfractured reservoir in between			
	Mass flowrate [kg/s]				
	200	100	150	200	300
35°C	M.200.35.N	M.100.35.F	M.150.35.F	M.200.35.F	M.300.35.F
50°C	M.200.50.N	M.100.50.F	M.150.50.F	M.200.50.F	M.300.50.F

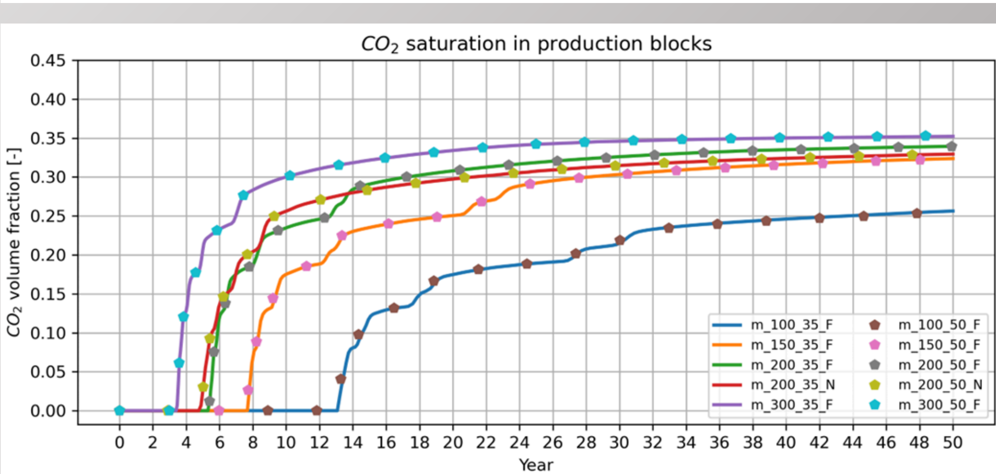
Description of the parameters

Legend: M.X.Y.Z, where X is injection rate [kg/s], Y is injection temperature [°C] and N is non-fractured reservoir, F fractured reservoir

Numerical model of the Åre Formation, the Norwegian Sea – results

Model no.	M.200.35. N	M.200.50. N	M.100.35. F	M.100.50. F	M.150.35. F	M.150.50. F	M.200.35. F	M.200.50. F	M.300.35. F	M.300.50. F
Production temperature after 30 years [°C]	165,6	165,6	166,4	166,4	166,3	166,3	165,8	165,9	160,2	160,6
Production temperature after 50 years [°C]	159,5	159,9	166,5	166,5	164,0	164,4	157,6	158,0	146,0	146,8
Average pressure difference between injection and production well during 50 years [bar]	33,73	33,31	5,49	5,54	7,17	7,20	8,92	8,8	12,64	12,34
Time passed to reach full CO_2 saturation in production well [yrs]	full saturation never reached									
Total CO_2 injected in 50 years [tons]	3,13E+08	3,14E+08	1,56E+08	1,56E+08	2,35E+08	2,35E+08	3,13E+08	3,13E+08	4,69E+08	4,69E+08
Total CO_2 stored in rocks in 50 years [tons]	2,30E+08	2,30E+08	1,33E+08	1,33E+08	1,81E+08	1,80E+08	2,30E+08	2,30E+08	3,29E+08	3,29E+08
Cumulative CO_2 storage ratio after 50 years [-]	0,735	0,734	0,846	0,853	0,772	0,767	0,734	0,736	0,702	0,702
Average annual replenishment of CO_2 from the pipeline as a result of geological storage [tons]	4,60E+06	4,61E+06	2,66E+06	2,67E+06	3,62E+06	3,60E+06	4,59E+06	4,60E+06	6,59E+06	6,59E+06





Mathematical modeling of CO_2 - based topside systems for heat and power production

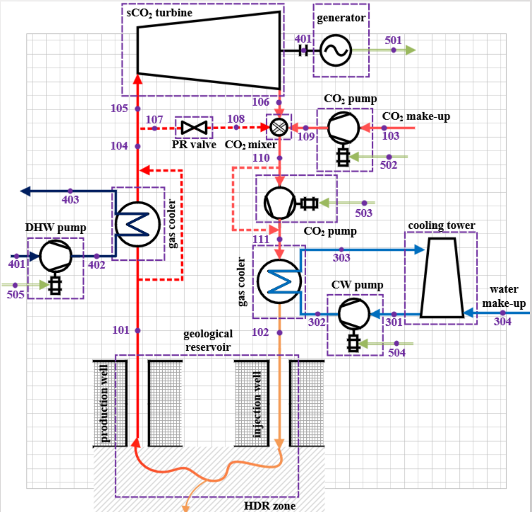
Working only with the thermosiphon effect; lower net power outputs for other approaches.
At nominal flows (100 kg/s) they can produce:

- Case No. 1 (combined heat and power within the direct sCO_2 cycle): 0.4 MWel & 9 MWth for up to 18 years
- Case No. 2 (power generation only within a hybrid cycle) 1.7 MWel for up to 20 years.

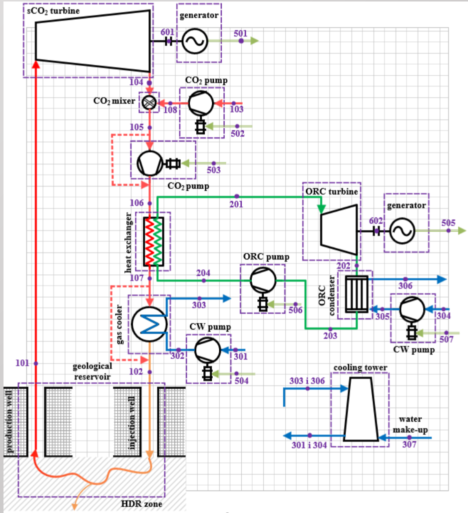
Operational phase (30 years).

- **Case 1:** Electricity production 120,235 MWh, Heat production 2,219,119 MWh
- **Case 2:** Electricity production 369,240 MWh

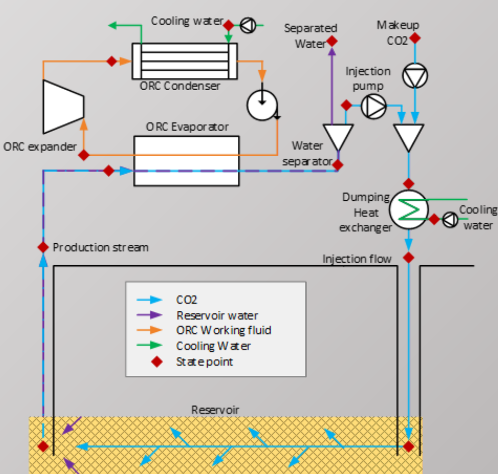
CO_2 stored: 10,764,096 ton



Polish Case No. 1



Polish Case No. 2



Norway Case

Higher water content weakens the thermosiphon effect, but the thermal energy content extracted is much higher

- Can produce 10-12 MW power for decades
- 2 cases: Indirect ORC (at sea floor) & indirect ORC (at platform)
- Operational phase (30 years)
- Electricity production 2,577,987 MWh
- CO_2 stored: 154,723245 ton

Life Cycle Assessment (LCA) results

The LCA analysis was carried out using SimaPro software.

Case 1
Poland, Gorzów Block

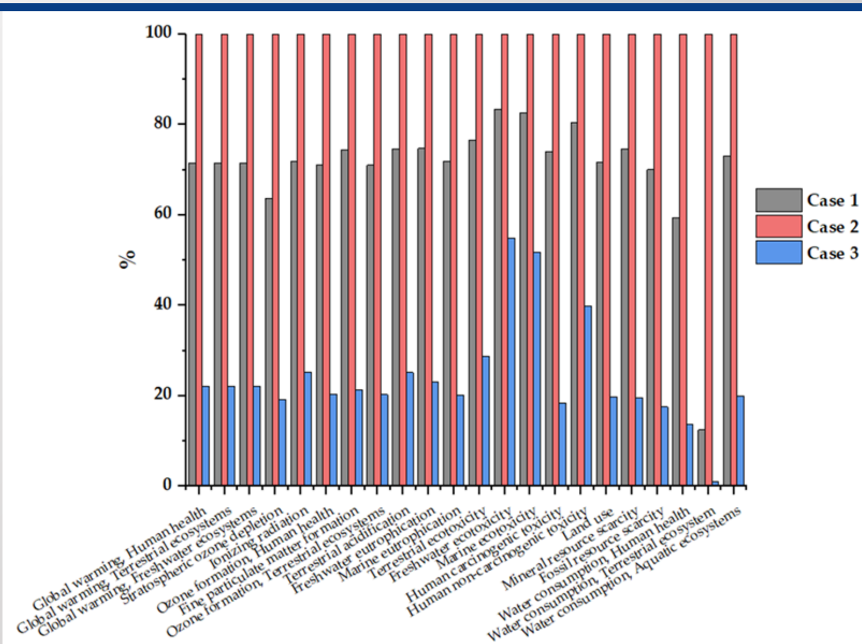
Combined heat and power with the sCO_2 cycle

Case 2
Poland, Gorzów Block

Power generation only with the indirect sCO_2 cycle witch ORC

Case 3
Norway, Åre formation (at sea floor)

Power generation only with the indirect sCO_2 cycle witch ORC



LCA results

In some categories, the lower impact due to site-specific factors, such as land use. The allocation issues were the most relevant when working on the adaptation of the LCA methodology to CO_2-EGS cases.

The Åre case is found to have a much lower environmental footprint than Gorzów cases as a result of higher energy utilisation – higher output values.

In all cases, the construction phase is dominant when environmental impact is concerned, in particular - wells drilling, which corresponds to more than 70% of environmental impacts in all cases.

End-of-life has the lowest impact, although for future work, the impact of long-term monitoring should also be considered (similar like in dedicated CO_2 storage sites).

Key results of the EnerGizerS project

- Feasibility analysis of innovative research on the development of Enhanced Geothermal Systems (CO_2-EGS) using supercritical carbon dioxide as a working medium in Poland and Norway
- Innovative solutions for reducing carbon dioxide emissions while meeting energy needs - a combination of CCUS and EGS technologies
- Cooperation between Polish and Norwegian partners and exchange of experience - joint publications, study visits, conferences
- Training of doctoral students - internship of a young scientist at Sintef, specialised training for doctoral students, working on doctoral dissertations using the results of the project implementation in an international group
- Capacity building of research teams on the national and international stage participation in numerous conferences/industry events

Norway grants

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NCBR National Centre for Research and Development

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