Storskala deponering av CO_2 kombinert med økt oljeutvinning

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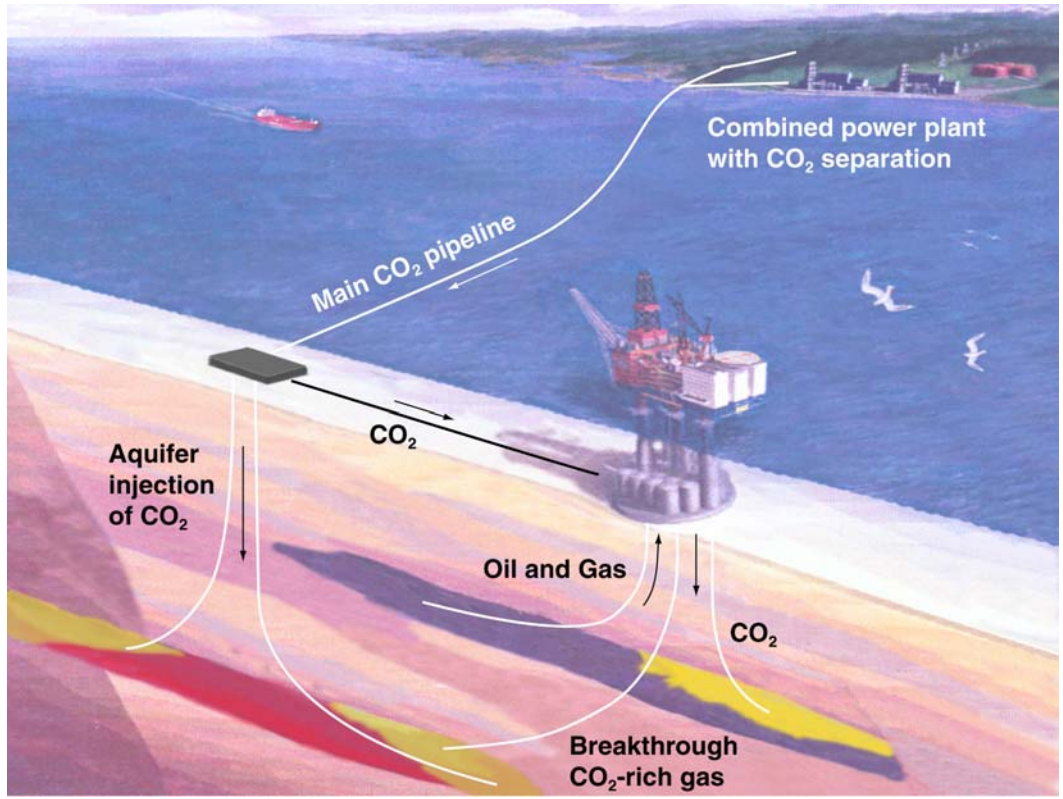
Introduction: our vision

In the future large amounts of CO_2 will be stored in underground formations in order to reduce the anthropogenic emission of CO_2. CO_2 storage will become an accepted and viable technology since petroleum reservoirs and aquifers represent large, available and safe storage sites for CO_2. Norwegian oil reservoirs and aquifers will become a major deposition site for CO_2 from North and Central Europe. **In the early phase of the CO_2 deposition era, the deposition costs can be significantly reduced by the use of CO_2 for enhanced the oil recovery.**



E2

Large scale CO_2 flooding of North Sea oil reservoirs

Main questions:

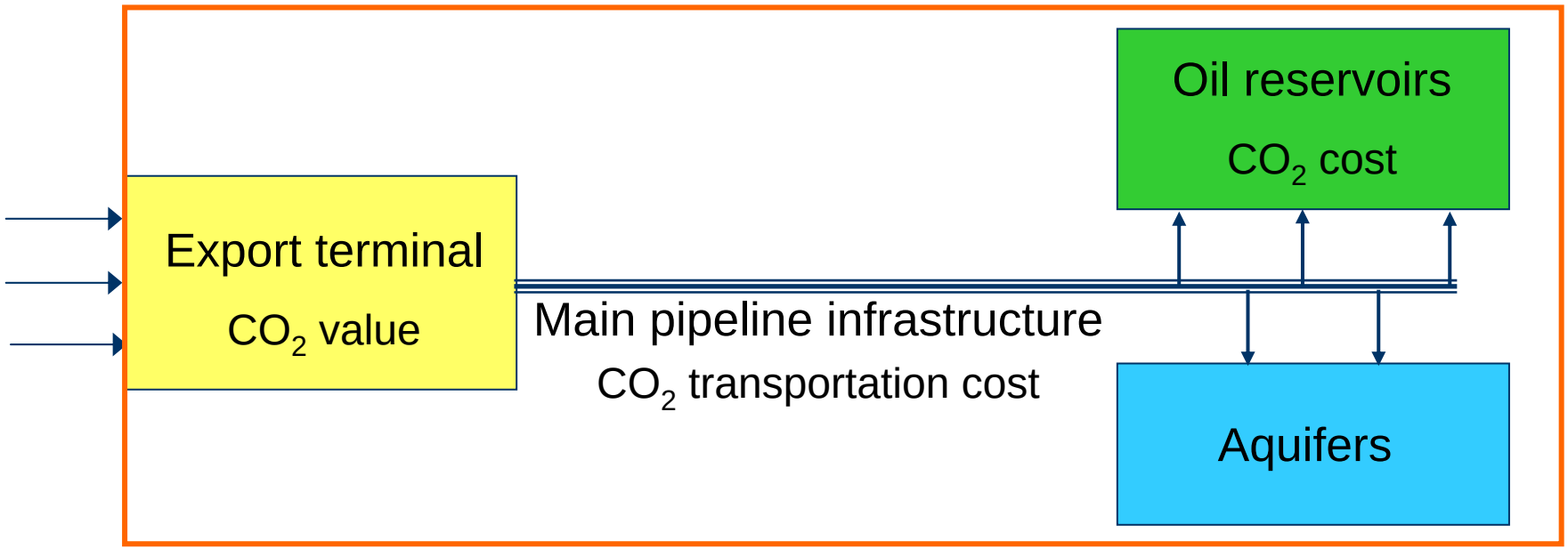
- What is the EOR potential of North Sea oil reservoirs
- How much CO_2 can be stored in the reservoirs
- What is the value of CO_2

Approach to answer the questions:

- Make a model that
  - calculates the cost for CO_2 transportation to the oil fields (**CO_2 transportation module**)
  - predicts the incremental oil recovery due to CO_2-injection (**EOR module**)
  - calculates economic quantities associated with CO_2 EOR
  - calculates economic quantities associated for aquifer deposition of CO_2

  →**The technical-economical model**

The technical-economical model



CO_2 from industrial point sources is collected, compressed and fed into main pipeline. The suppliers are paid for the delivered CO_2

CO_2 is transported through the main pipeline and distributed to oil reservoirs and aquifers

CO_2 is transported to the deposition sites through branch lines. The oil producers buy CO_2 according their needs. Excess CO_2 is deposited in aquifers

CO_2 transportation module:
Export terminals and main CO_2 pipelines

Export terminals

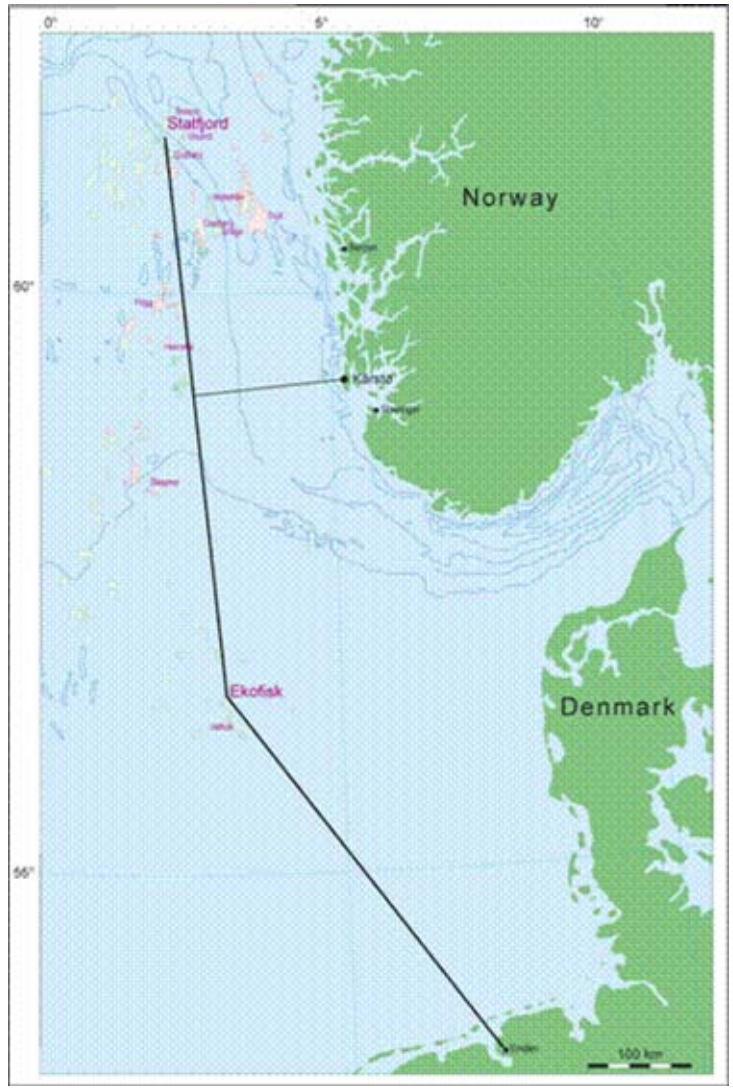
- Emden and Kårstø
- Feed: dry CO_2 in dense state
- 200-300 bar export pressure

Main pipelines

- Capacity: 10-80 mill. tonnes/year
- Kårstø line: 0-5 mill. tonnes/year
- Draw off at Ekofisk: 0-40 mill. tonnes/year

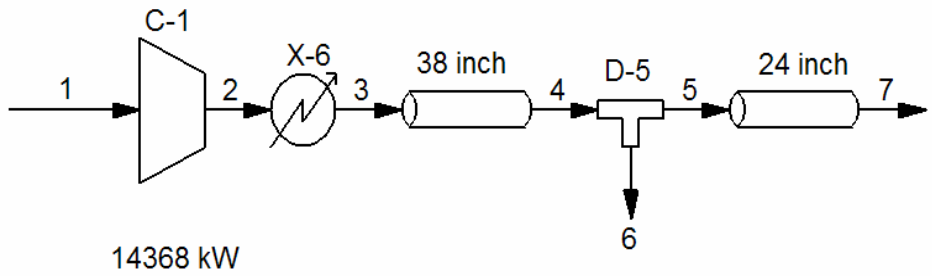
Economic parameters

- Pay back time
- Interest
- Operational costs process equipment
- Operational costs pipeline
- Energy costs



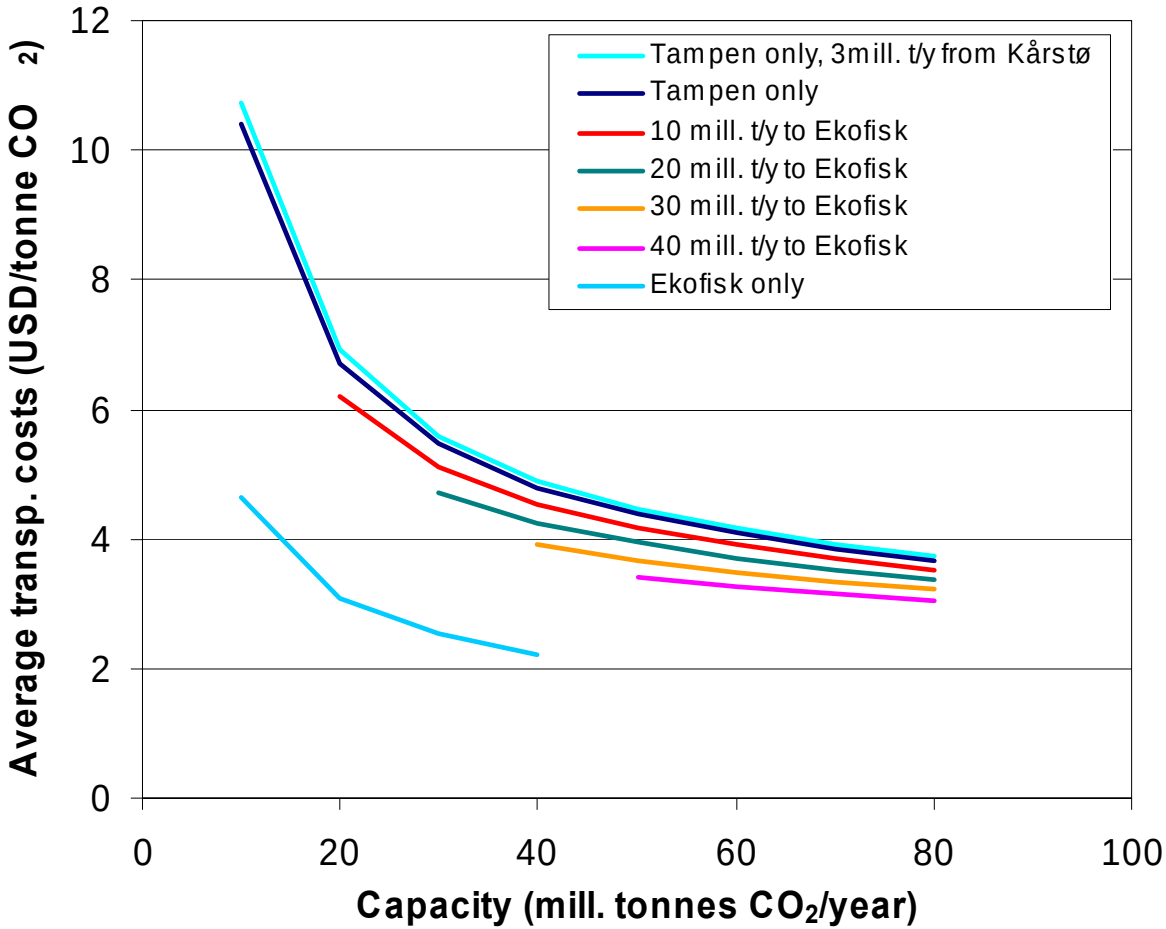
CO_2 transportation module: Cost model for the infrastructure

- Calculations done with a process simulator
- Find the tube dimensions that gives the lowest costs for given capacities and entry pressures
- The pipeline costs are integrated in a cost model that also includes process equipment



Stream Number		1	2	3	4	5	6	7
Temperature	C	20.0	42.9	20.0	7.4	7.4	7.4	4.0
Pressure	bar	60.0	200.0	200.0	179.0	179.0	179.0	104.2
Vapor Density	kg/m3	0	0	0	0	0	0	0
Liquid Density	kg/m3	772	689	942	993	993	993	958
Vapor Viscosity	cP	0	0	0	0	0	0	0
Liquid Viscosity	cP	0.070	0.078	0.101	0.113	0.113	0.113	0.105
Total Mass FLowrate	tonne/yr	19972800.0	19972800.0	19972800.0	19972800.0	9986400.0	9986400.0	9986400.0

CO_2 transportation module: Examples of calculated CO_2 transportation costs



Ship transport of CO_2: 23.6 (13) USD/tonne (1 mill. tonnes/year)

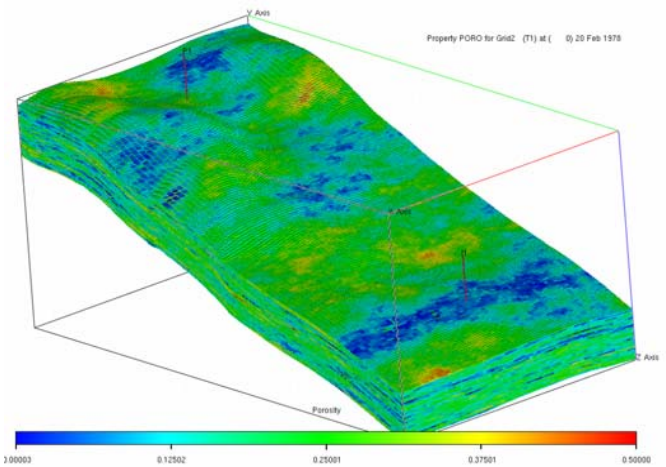
The EOR module - objective

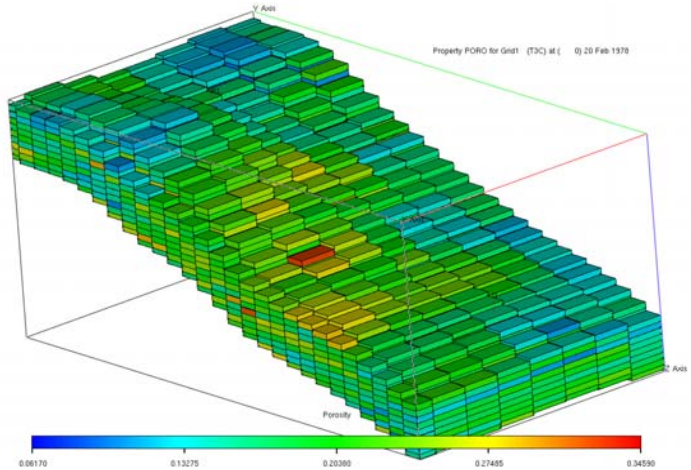
- Make a simple module to predict the incremental oil production due to CO_2-injection after water flooding depending on the state of the reservoir
- Use the module for analysis of real fields that have been under water flood

The module is developed for continuous CO_2 injection only

The EOR module - approach

- Generic reservoir model with real heterogeneities
  - $1.1 \cdot 10^6$ cells model from SPE 10th comparative study
  - stochastic reservoir model, shallow marine depositions
  - up-scaled to a 2016 cells model
- Water injection followed by CO_2 injection is simulated
  - Eclipse reservoir simulator
  - 216 different runs with varying process and geological -parameters
- Functions are fitted to the simulated production curves
  - Oil production
  - Water production
  - Gas production





Use of the EOR module

- Fit functions
  - $V_{oil}=V_{oil}(PV_{inj}, q_{inj}, PV_s, \rho_o, \mu_o, \alpha, k_z)$
  - $V_{water}=V_{water}(PV_{inj}, q_{inj}, PV_s, \rho_o, \mu_o, \alpha, k_z)$
  - $V_{gas}=V_{gas}(PV_{inj}, q_{inj}, PV_s, \rho_o, \mu_o, \alpha, k_z)$
- Find the parameters that are valid for the specific reservoir
- Use the model to calculate the CO_2 incremental oil

PV_{inj}=injected volume (PV)
q_{inj}=injection rate (PV/year)
PV_s=starting time for gas injection (PV injected at start of gas injection)
ρ_o=oil density (kg/m^3)
μ_o=oil viscosity (cP)
α=heterogeneity exponent (used at fit parameter)
k_z=vertical permeability multiplicator (used as fit parameter)

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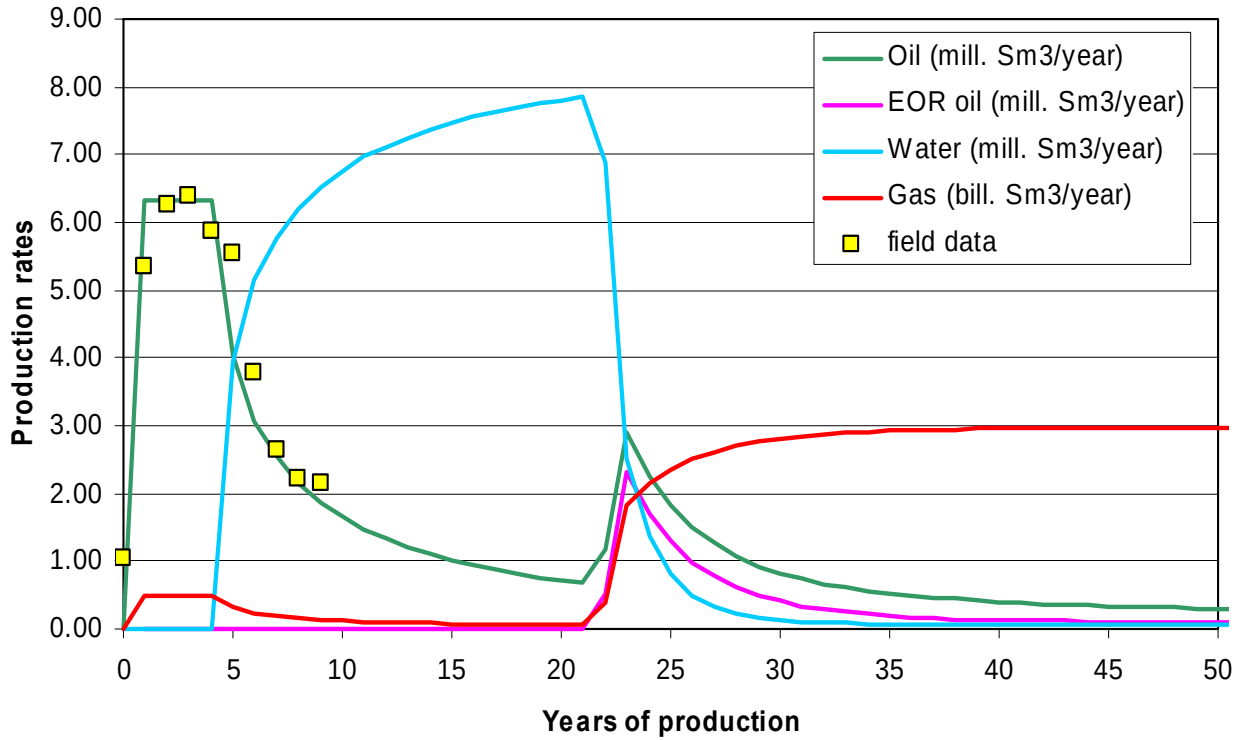
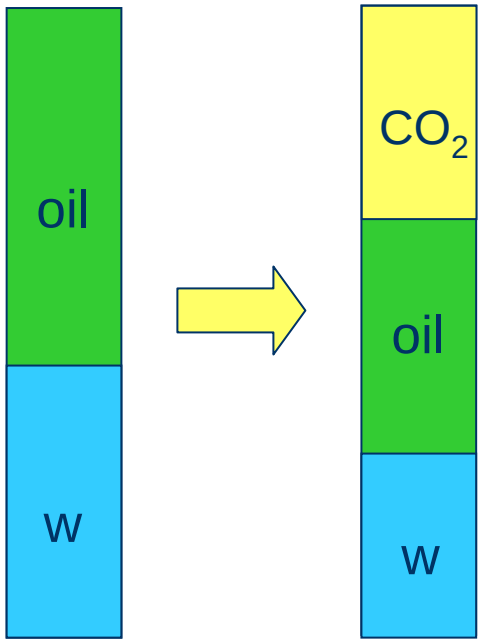
Example of production profiles calculated by the EOR module (Brage field)

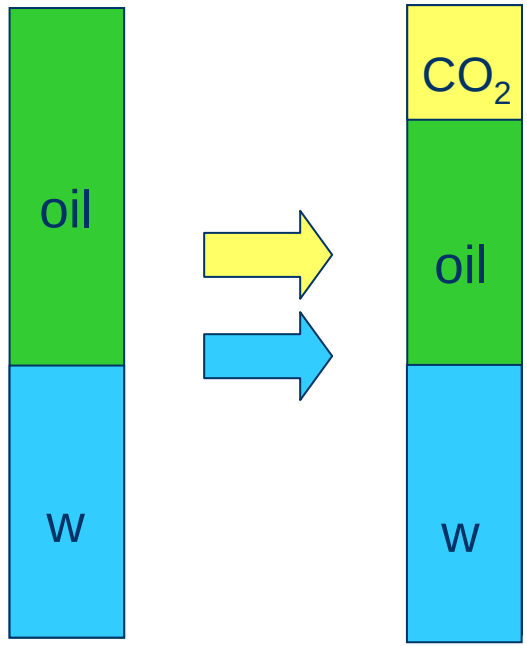


The predicted oil recovery profile is matched to historic values by use of the two geological fit parameters (heterogeneity exponent, vertical permeability multiplicator)

Continuous vs. water alternating CO_2 injection (WAG): Changes in phase saturations



Continuous CO_2 injection



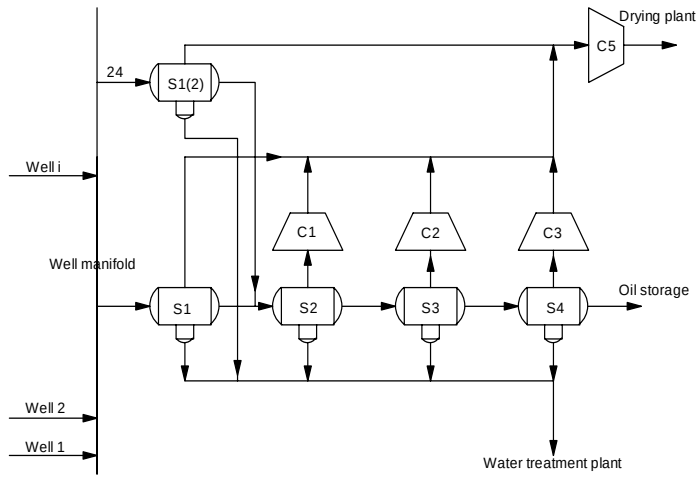
CO_2 WAG injection

The technical-economical model

- Combines the CO_2 transportation and the EOR modules to a model that calculates the economic quantities related to an CO_2 EOR/aquifer deposition system
- The model can be used to construct specific deposition scenarios for fields in the Norwegian sector of the North Sea.
- The model calculates incremental oil recovery and stored CO_2 in the oil reservoirs and aquifers
- The model also calculates a price for CO_2 that can be paid to the deliverer of CO_2 (*e.g.* the power industry)
- Each EOR project in the scenario runs as long as the net cash flow is positive
  - incomes: EOR oil (the incremental oil only)
  - costs: CO_2, investments, operating costs
- A constant amount of CO_2 is deposited during the lifetime of the scenario, excess CO_2 is injected into unspecified aquifers
- Break through CO_2 is re-injected into the reservoirs

CO_2 EOR - field specific investment costs

- Connection to main pipeline, riser
- Branch pipelines (length and CO_2 capacity dependent)
- CO_2 compressors (dependent on CO_2 capacity and wellhead pressure)
- Drying plant (dependent on CO_2 capacity)
- Modification of oil production system (depends on plateau production rate of oil)
- Well costs based on injection capacities:
  - 15000 res.bbl CO_2/day for sand stone res.
  - 7500 res.bbl CO_2/day for chalk reservoirs



Parameters used for economic modelling

Economic parameters	value	unit
Well cost	7.5	mill. USD/well
Modification of oil production	400	USD/(bbl/day)
Engineering costs	25	% equipment costs
Contingency costs	25	% equipment costs
Offshore factor	2	
Running and maintenance	5	% of equipment costs
Energy compressor	0.07	USD/kWh
Discount rate	10	%
Net present value	0	million USD
Oil price	24	USD/bbl
CO_2 cost	12.8	USD/tonne
CO_2 transport cost, Ekofisk	3.9	USD/tonne
CO_2 transport cost, Tampen	3.9	USD/tonne

The economic parameters can be varied by the user

A CO_2 deposition scenario

- The scenario includes 19 North Sea oil fields and unspecified aquifers
- Total injection rate is 67.2 million tonnes CO_2/year
- Project lifetime is 40 years
- The scenario is an example of the use of the technical-economical model and is not optimised

Results:

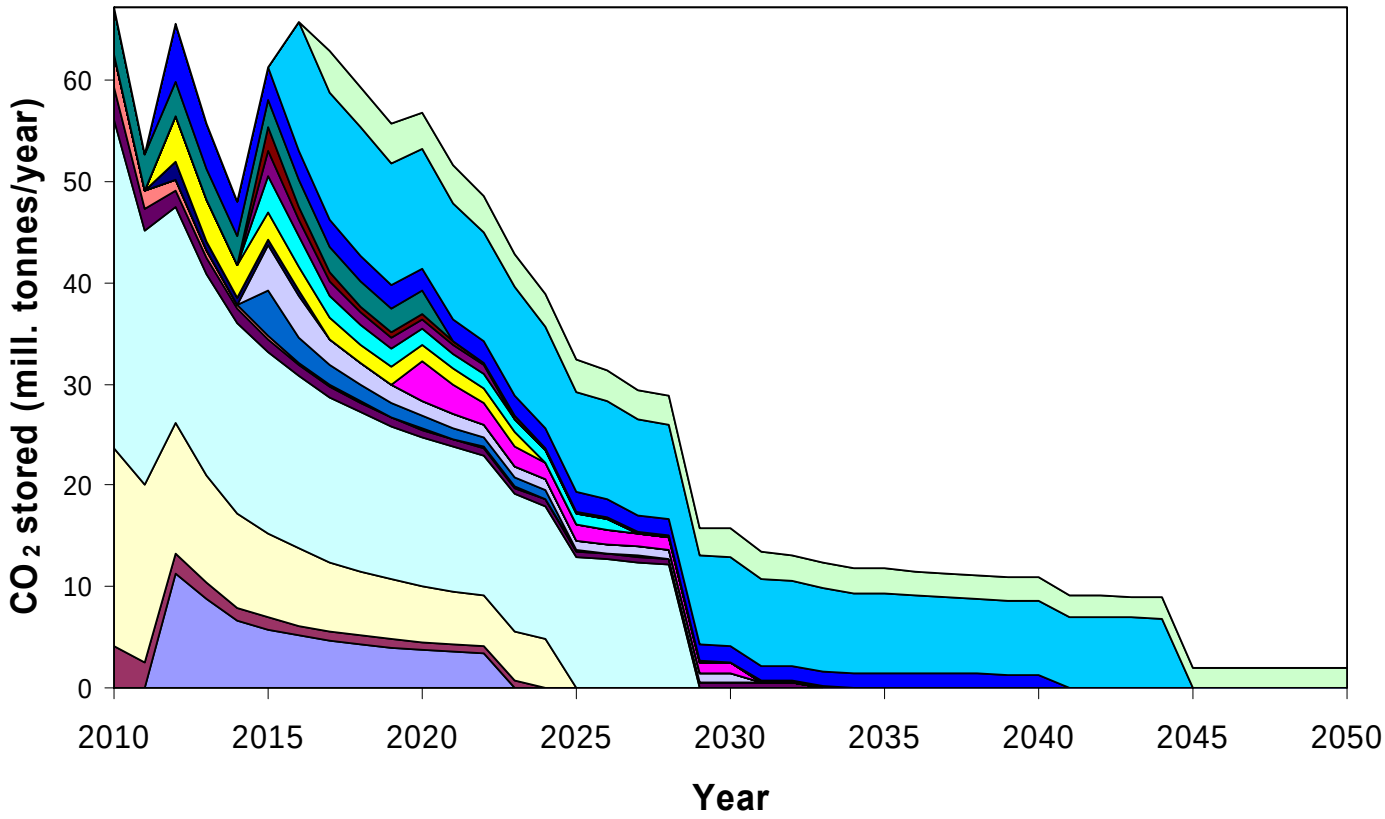
- Deposition profiles
- EOR production profiles
- Key economic figures for the scenario
- The value of CO_2 delivered to the export terminals
- Effect on power costs

Field	Start production	Start CO_2 injection
Snorre	1992	2012
Brage	1989	2010
Gullfaks	1986	2010
Statfjord Brent	1979	2010
Statfjord Nord	1995	2010
Statfjord Øst	1995	2010
Vigdis	1997	2015
Tordis	1995	2015
Sygna	2000	2012
Snorre B	2000	2020
Veslefrikk	1990	2012
Oseberg Sør	2000	2015
Oseberg Øst	1999	2015
Balder	1999	2015
Gyda	1990	2010
Ula	1986	2012
Ekofisk*)	1988	2016-2023
Valhall	1982	2017

The fields in this table are the fields presently in the database of the model. More fields can be added provided field specific data are available.

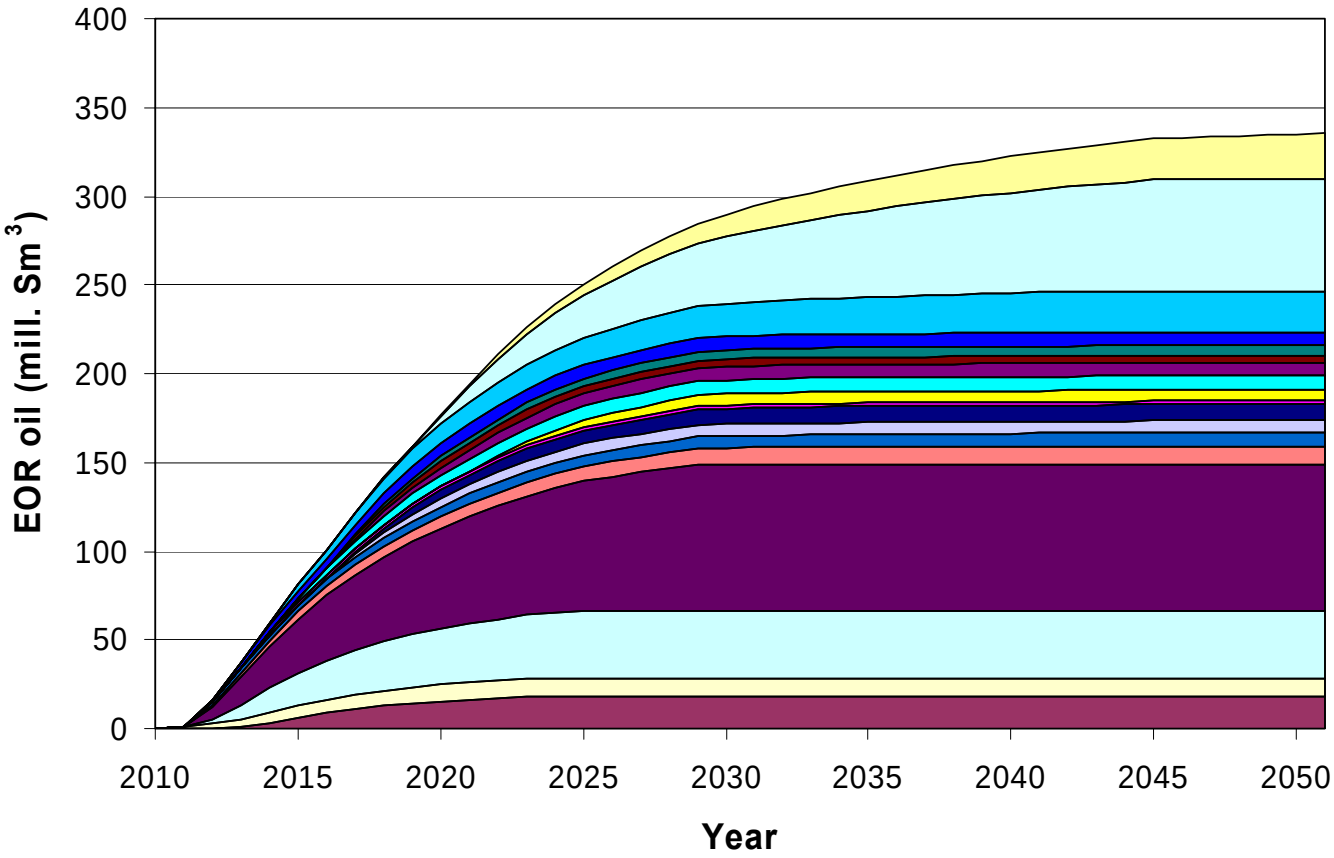
In order to make a scenario the user defines the fields to be included and the start time for CO_2 injection

CO_2 storage profiles for example scenario.



The white area represent the profile for CO_2 to be stored in aquifers

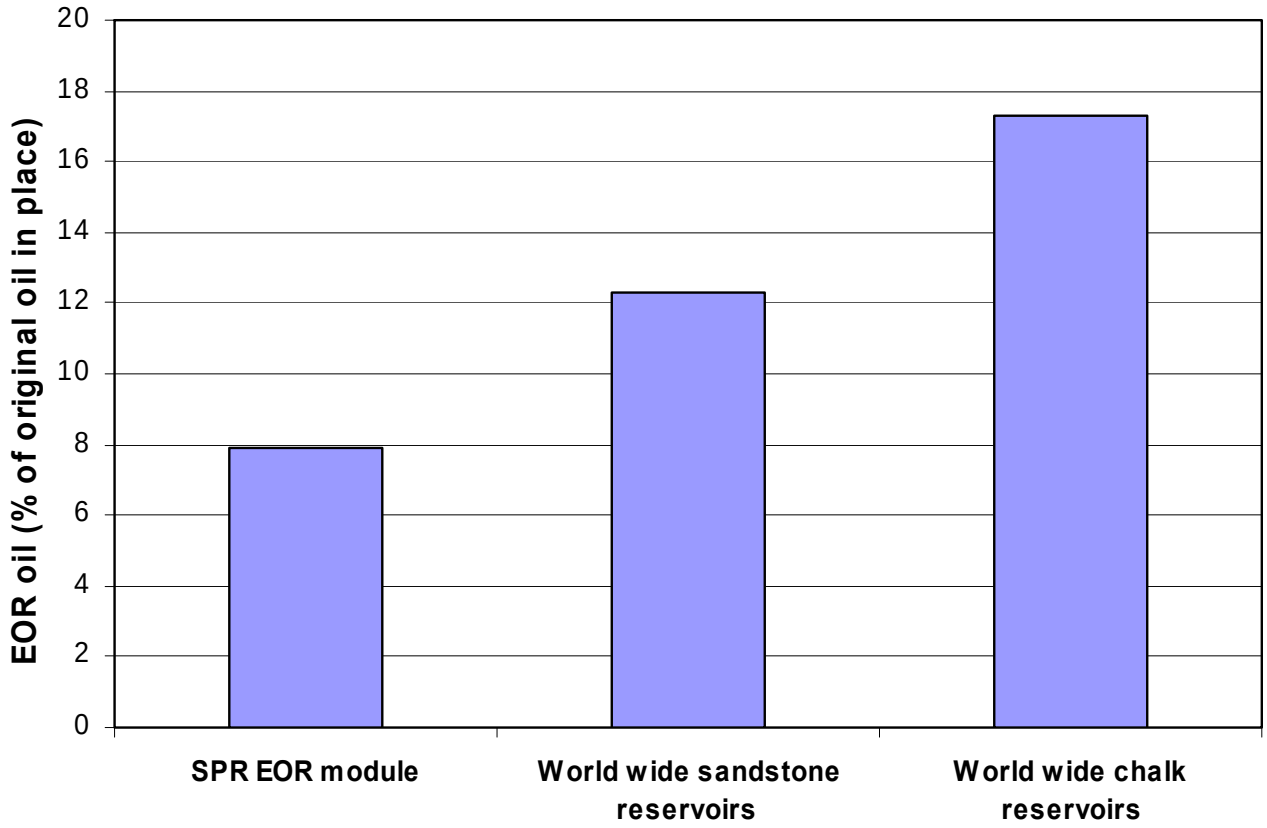
Profiles for incremental oil production



Summary of EOR project performance

Item	quantity	unit
Total oil	2269	million Sm^3
Oil rec. factor	53.7	% HCPV
EOR oil	335	million Sm^3
EOR oil	7.9	% HCPV
Stored CO_2	1153	million tonnes
Total investment costs	10398	million USD
Total running costs	490	million USD/year
Net present value	0	mill. USD

Incremental oil recovery by CO_2 injection



Summary of deposition scenario

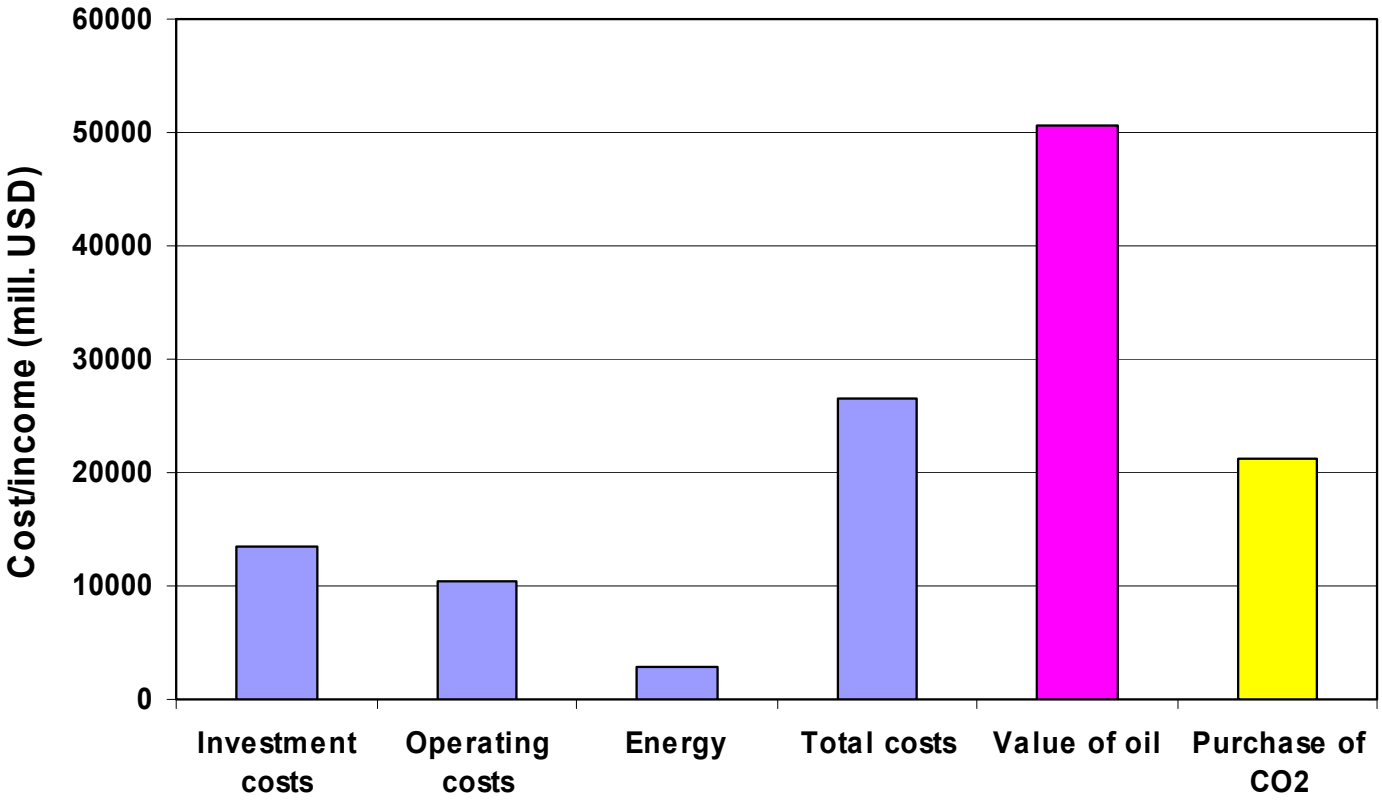
Item	Investment costs (million USD)	Operating costs (million USD/year)
Main CO_2 infrastructure	2743	34
Oil recovery projects	10398	216
Aquifer deposition	282	10
Total	13423	260

- All operating costs are averaged over 40 years and are exclusive energy
- The average project time is 17.6 years for the EOR projects
- The average oil production is 328000 bbl/day during the 17.6 years
- The average operating costs correspond of an average employment of 3000 persons for 40 years

Aquifer deposition of excess CO_2

- Technical-economical issues related to aquifer deposition of excess CO_2 is calculated as a project run by a separate unit
- The unit byes all the CO_2 delivered at the export terminals
- The unit sells CO_2 to the oil producers according to their needs. The oil producers also pays for the CO_2 transport
- The unit disposes excess CO_2 in unspecified aquifers and covers costs for transportation and injection
  - injection wells (5 million tonnes/year/well)
  - compressors (3 MW modules)
  - energy and other running costs
- Injectors and compressor modules are installed according to the injection profile
- The value of CO_2 delivered to the export terminals is found as the purchase prise that gives a zero NPV of the disposal project
- The value of CO_2 varies between 7.9 and 12.8 USD/tonne

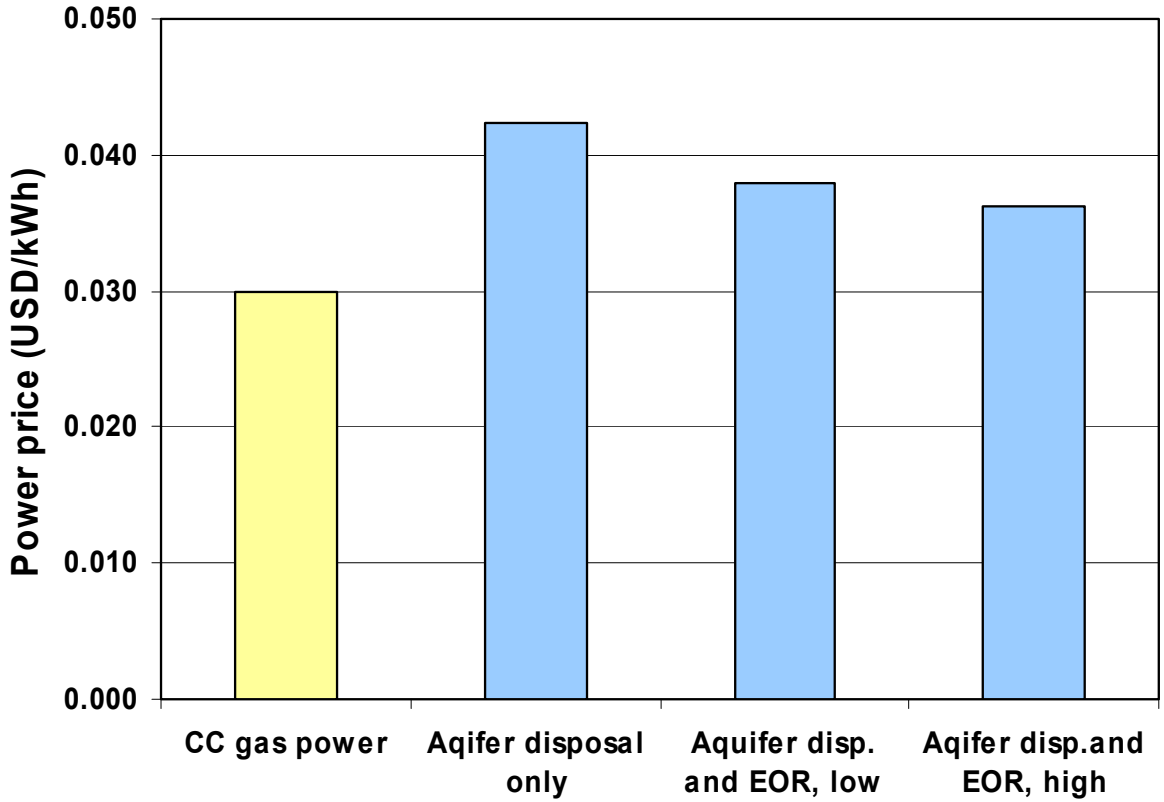
Over all economy CO_2 deposition project



Increased power cost due to CO_2 deposition

- Cost of CO_2 separation from flue gas and deposition
  - 25 USD tonne CO_2 at the power plant
  - 4 USD/tonne CO_2 for transportation to export terminals (estimate)
  - 4 USD/tonne CO_2 for offshore transportation
  - 1 USD/tonne CO_2 for injection
  - total deposition costs 34 USD/tonne CO_2
- The value of CO_2 may be in the range 8-12 USD/tonne CO_2
- The additional power cost due to CO_2 deposition will be
  - 0.013 USD/kWh aquifer deposition only
  - 0.008 USD/kWh low CO_2 price
  - 0.006 USD/kWh high CO_2 price

Increased power price due to CO_2 deposition



Further work with the technical-economical model

- Improve model user interface and functionality (some unnecessary manual operations still needed in the calculations of scenarios)
- In a complete fore the model will be a simple and general tool suited any user that want to study CO_2 deposition scenarios
- Include more fields in the database, also fields in the British sector, but within reach of the main infrastructure
- More field specific data desired (especially related to future production plans and the EOR time windows)
- Improved data for cost of process equipment and operating costs of EOR projects
- Improved cost modelling of aquifer deposition of CO_2
- Analyse more scenarios