Tertiary CO$_2$ EOR in 23 North Sea Oil Fields - Combined CO$_2$ Storage Based in Industrial CO$_2$ Sources

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Results

- 23 selected mature water flooded North Sea oil fields was selected as candidates for tertiary CO_2 injection

- When the fields were exhausted due to water flooding, CO_2 flooding gave **307million Sm^3 EOR oil** (7 % of OOIP or 20 % relative increase in yield)

- The **operating and capital costs** of the concept (redesign of platforms, transport, capture, injection of excess CO_2) **are to large extent covered by the value of EOR** oil even low oil prices

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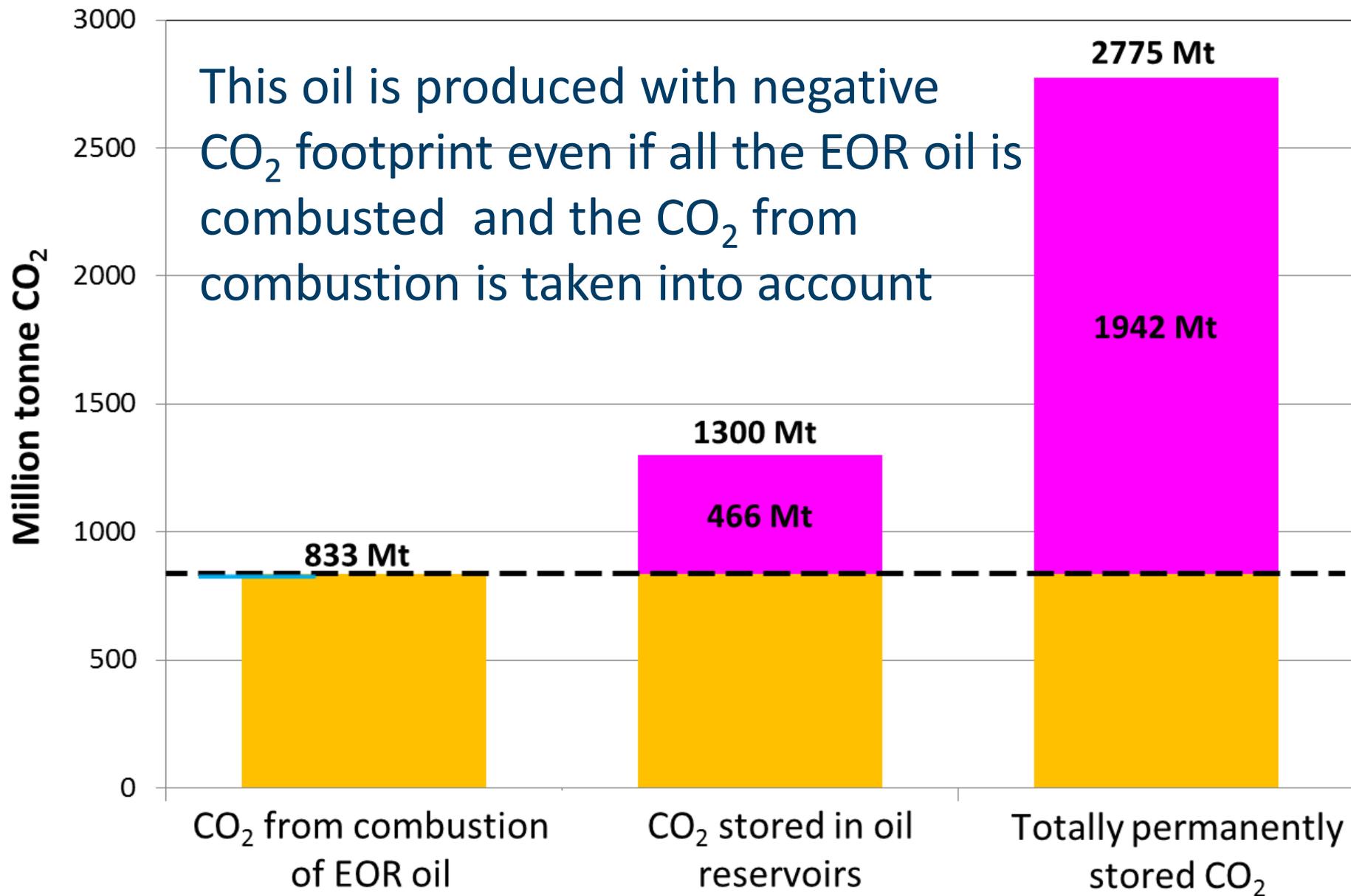
Study of CO_2 for EOR and storage in mature oil fields in the North Sea. Objective:

- The objective of study:

  - Select suitable oil fields for CO_2 flooding for EOR

  - Calculate the EOR potential

  - Find the CO_2 storage capacity in the oil fields and nearby saline aquifers which can be used as buffer capacity to obtain stable CO_2 deliveries

  - Calculate cost and economics

- Study done by SINTEF Petroleum Research, July 2012, for NPD and is an update of a study done by them in 2007 for the BIGCO2 project, Updated 2015, 2016 and 2017   (Holt, T. and Lindeberg, E. 2007: EOR and CO_2 disposal – economic and capacity potential in the North Sea. 4th Trondheim Conference on CO_2, Transport and Storage , June 2007, Trondheim, Norway). Part of BIGCO2 Phase II KMB project including 18 Norwegian and 30 UK oil fields

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Tertiary CO$_2$ in the North Sea?

Fields that are water flooded and located in the North Sea are indicated with and arrow
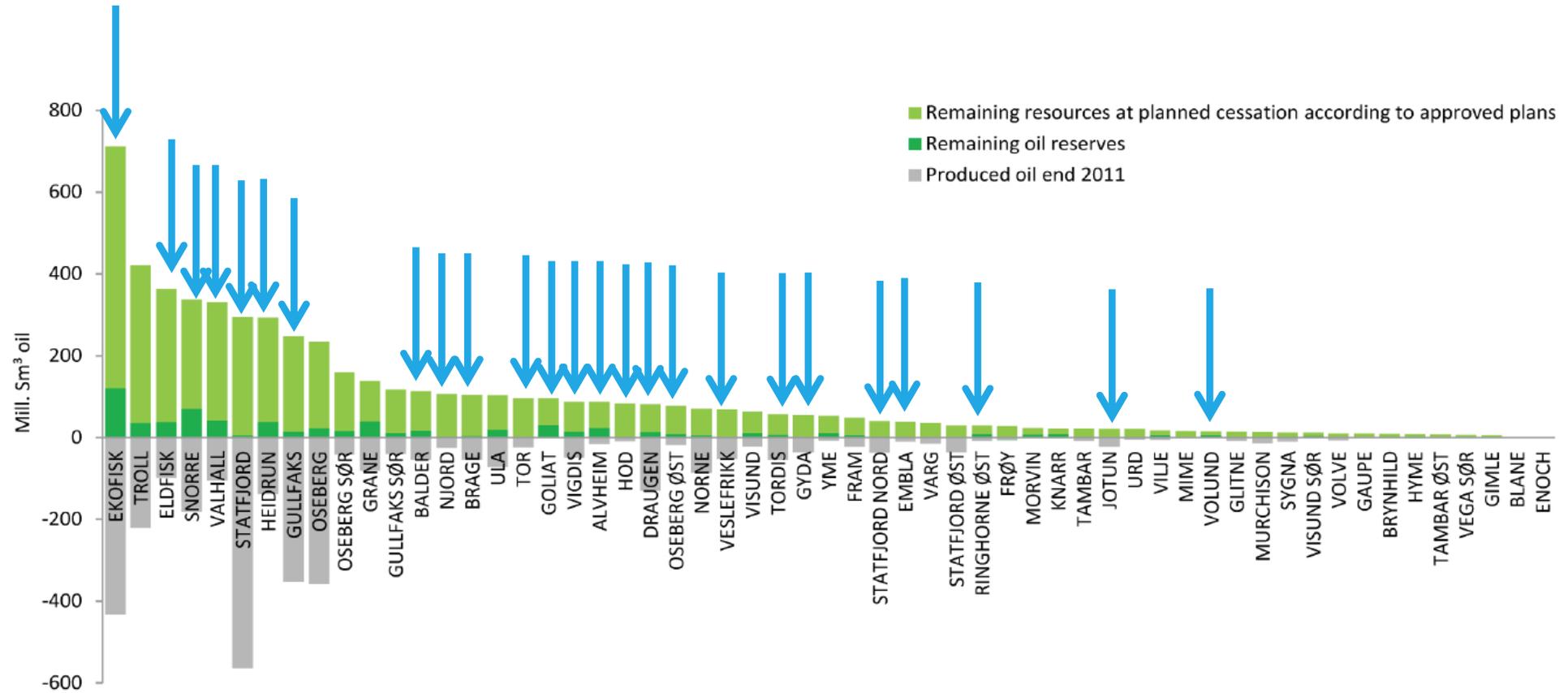
Distribution of oil resources and oil reserves in fields *(Source: Norwegian Petroleum Directorate)*
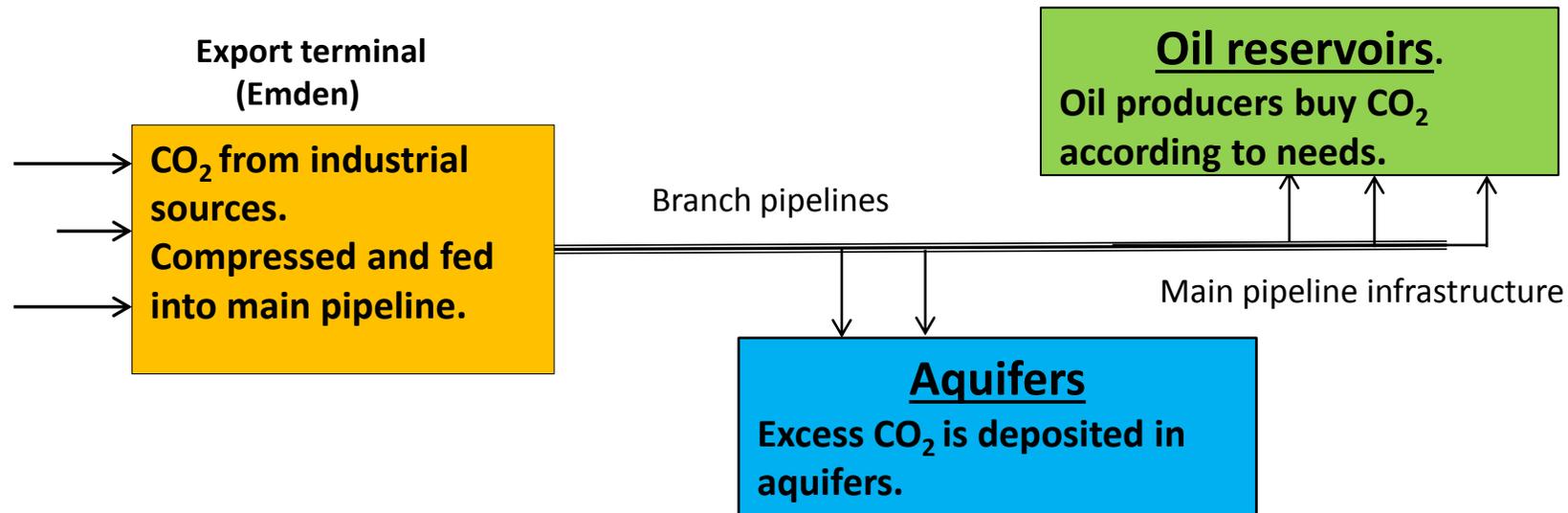
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Selection of field candidates

- 40 oil fields on production in the Norwegian North Sea were selected for screening

- 23 oil fields chosen for CO_2 flooding

- Skade/Utsira Formation and Frigg area chosen as saline aquifers for excess CO_2

- Screening criteria excluded fields due due to:
  - **Size (too small)**
  - **Initial gas cap**
  - **Earlier gas flooding**
  - **Earlier WAG (gas)**

- In some of the chosen oil fields only part of the field with was flooded with CO_2 due to that only one of the formations in the field had been water flooded

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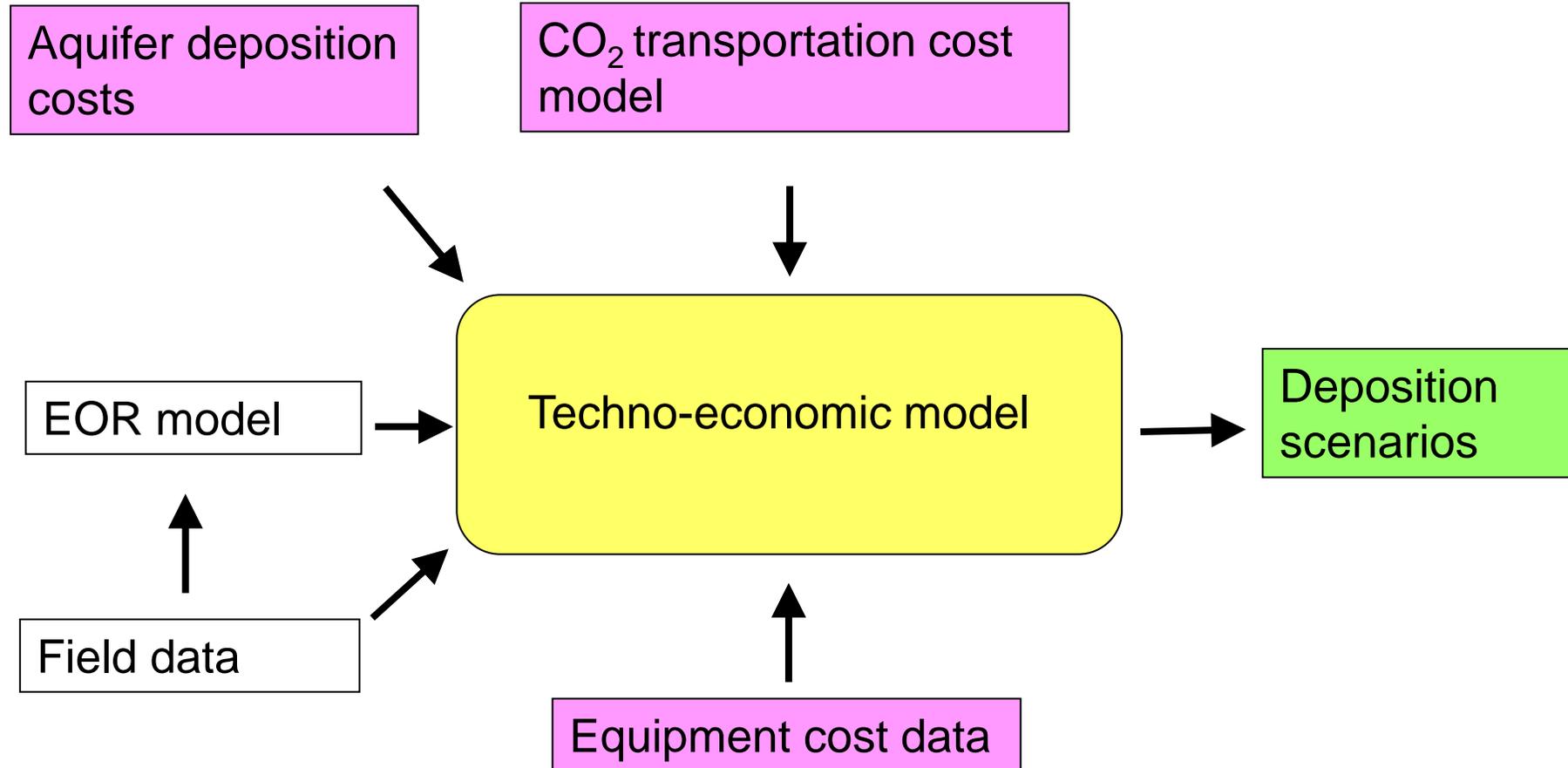| Oil field	Start Year	Remaining resources at start mill. Sm^3
Alvheim	2030	67.9
Balder	2020	96.7
Brage	2020	99.0
Ekofisk	2030	529.7
Eldfisk	2030	330.0
Embla	2020	37.2
Gullfaks	2025	218.3
Gyda	2020	53.5
Hod	2034	68.7
Jotun	2020	20.2
Oseberg Øst	2020	64.4
Ringhorne Øst	2025	22.2
Snorre	2032	222.1
Statfjord Brent	2020	291.0
Statfjord Nord	2020	36.9
Statfjord Øst	2020	26.4
Sygna	2020	11.5
Tor	2030	81.4
Tordis	2025	49.0
Valhall	2034	253.5
Veslefrikk	2020	65.8
Vigdis	2025	79.3
Volund	2025	11.4
Total		2736.1

23 selected water flooded fields with possible start of CO_2 injection and estimated remaining resources at start

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Techno-economical infrastructure model

- SINTEF has developed **a techno-economical infrastructure model** for large scale deposition of CO_2 in oil reservoirs and aquifers, which was used (Holt and Lindeberg, 2004),

Export terminal (Emden)

CO_2 from industrial sources. Compressed and fed into main pipeline.

Branch pipelines

Oil reservoirs.
Oil producers buy CO_2 according to needs.

Main pipeline infrastructure

Aquifers
Excess CO_2 is deposited in aquifers.

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A techno-economic model for predictions of CO_2 EOR in the North Sea

Aquifer deposition costs

CO_2 transportation cost model

EOR model

Field data

Techno-economic model

Equipment cost data

Deposition scenarios

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The EOR module - approach

- Generic reservoir model with real heterogeneities
  - 1.1 million cells model from SPE 10th comparat 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 and parameters
  - similar approach for CO_2 WAG

- Functions are fitted to the simulated production curves
  - Oil production
  - Water production
  - Gas production
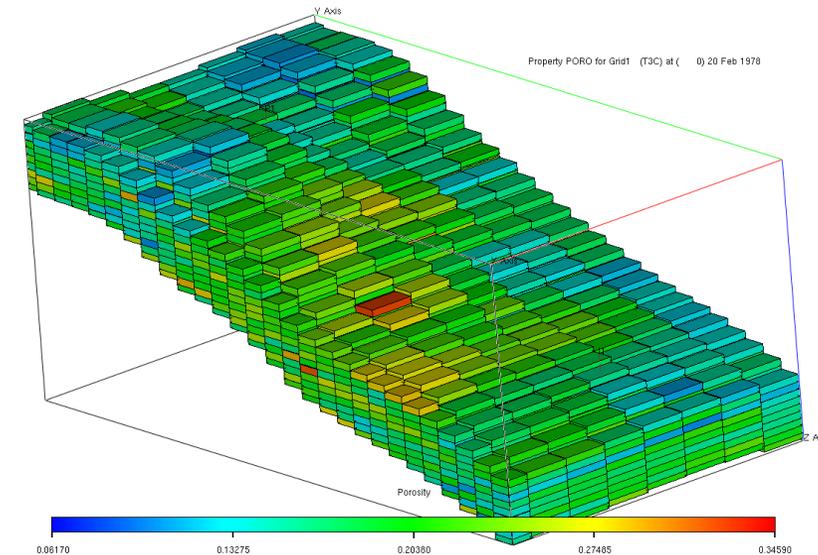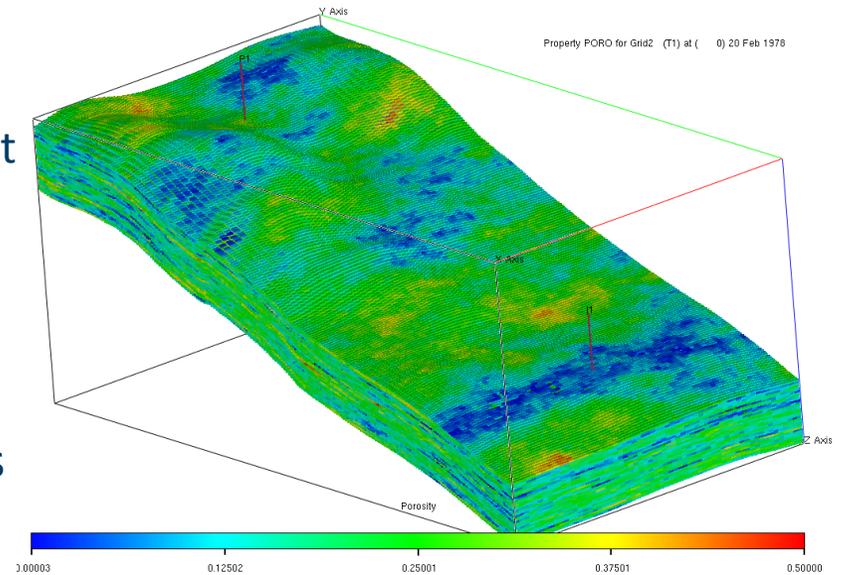
Use of the EOR module

- 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
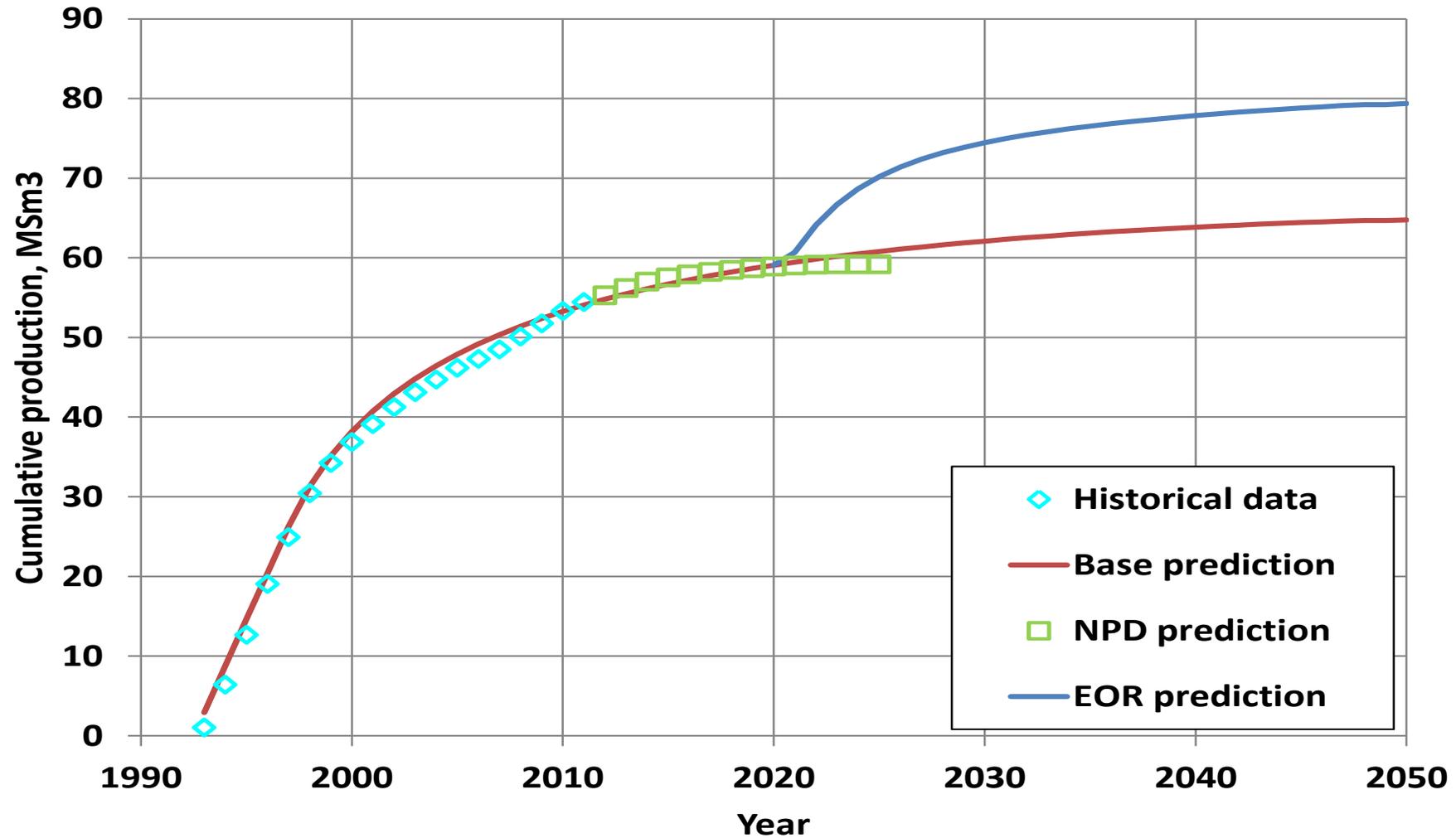μ_o = oil viscosity, cP
α = heterogeneity exponent (used as fitting parameter)
K_z = vertical permeability multiplier (used as fitting parameter)

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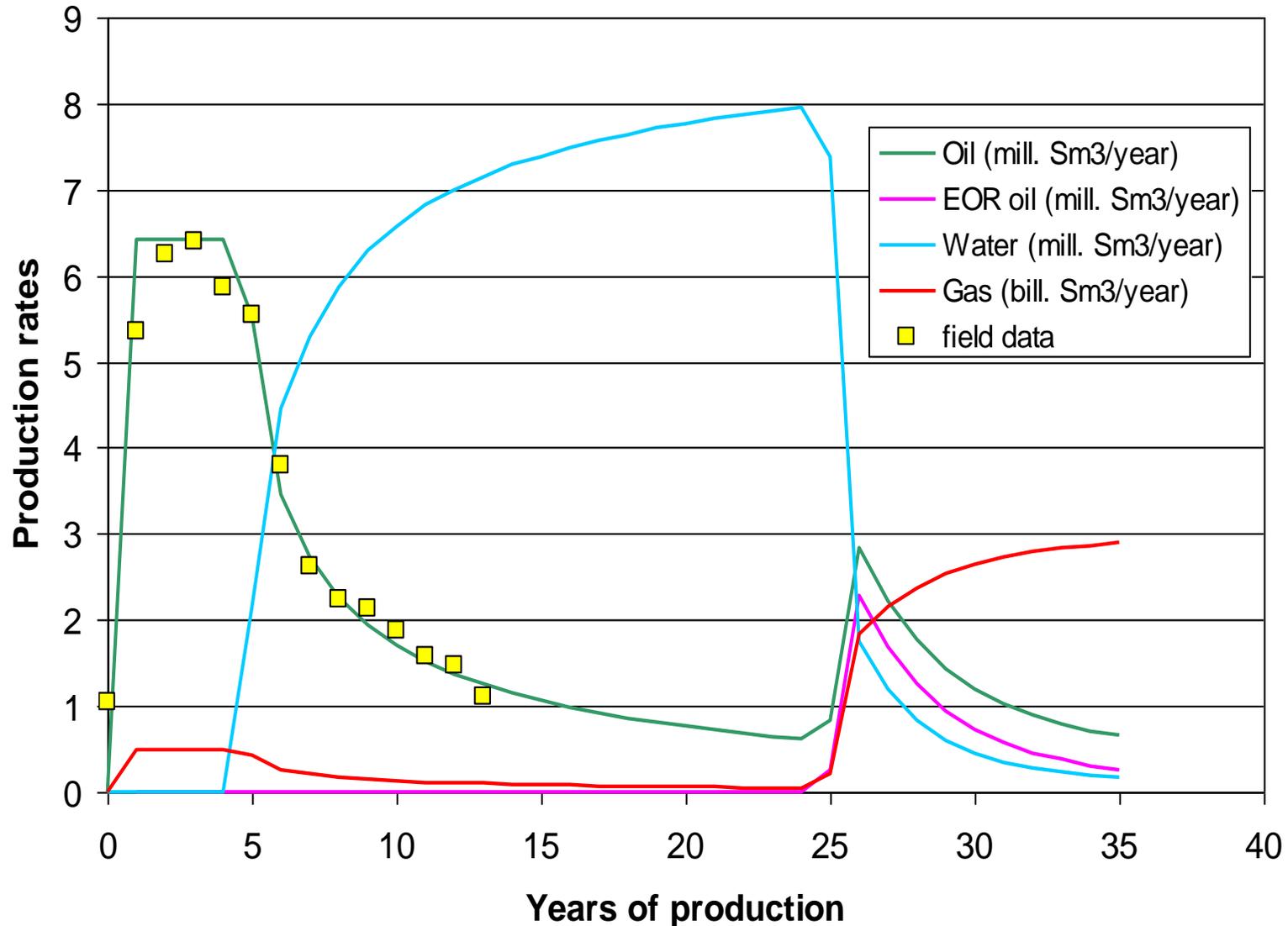# Example of production profile calculated by the module

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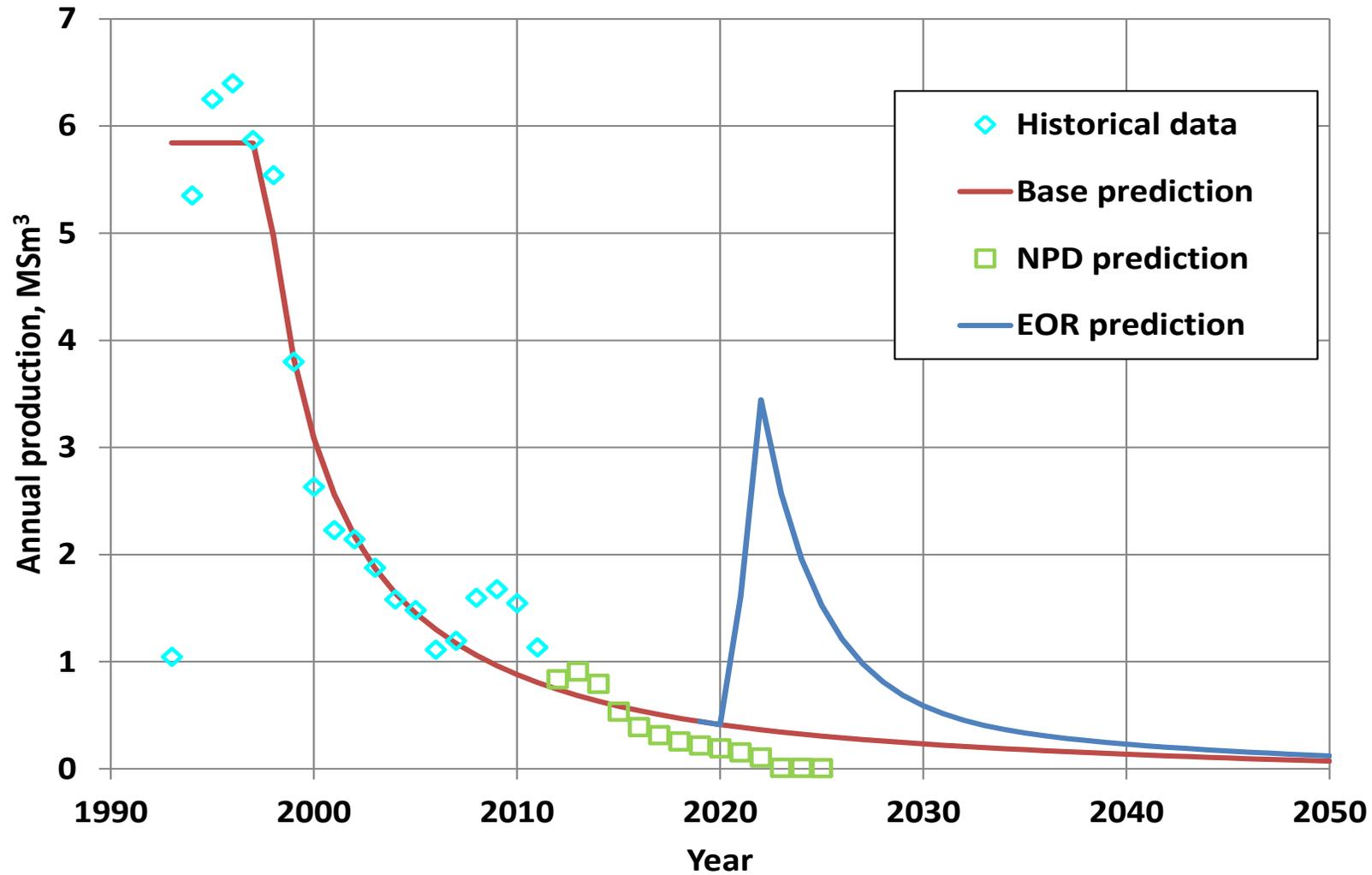
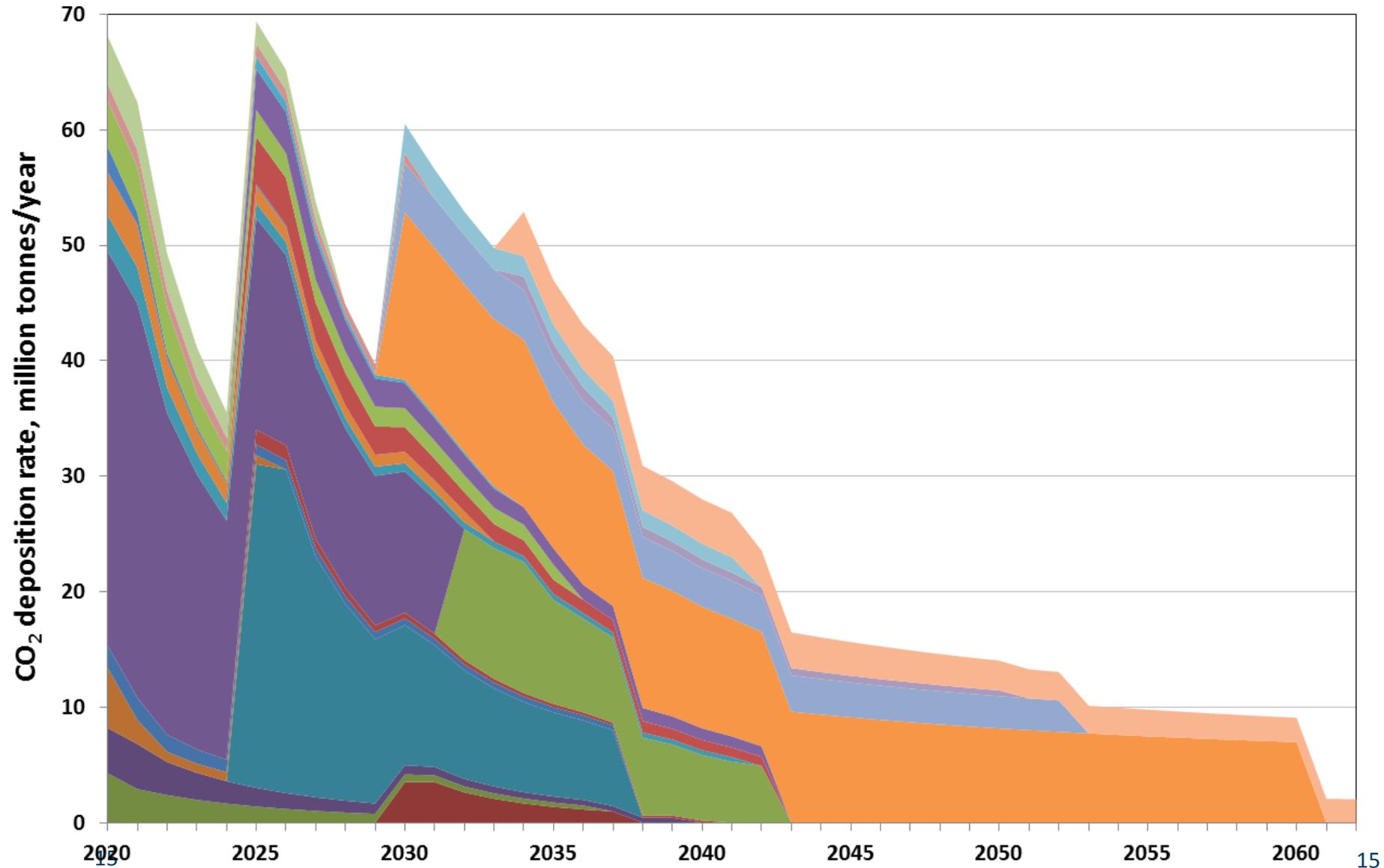# Example of cumulative production profile calculated by the module
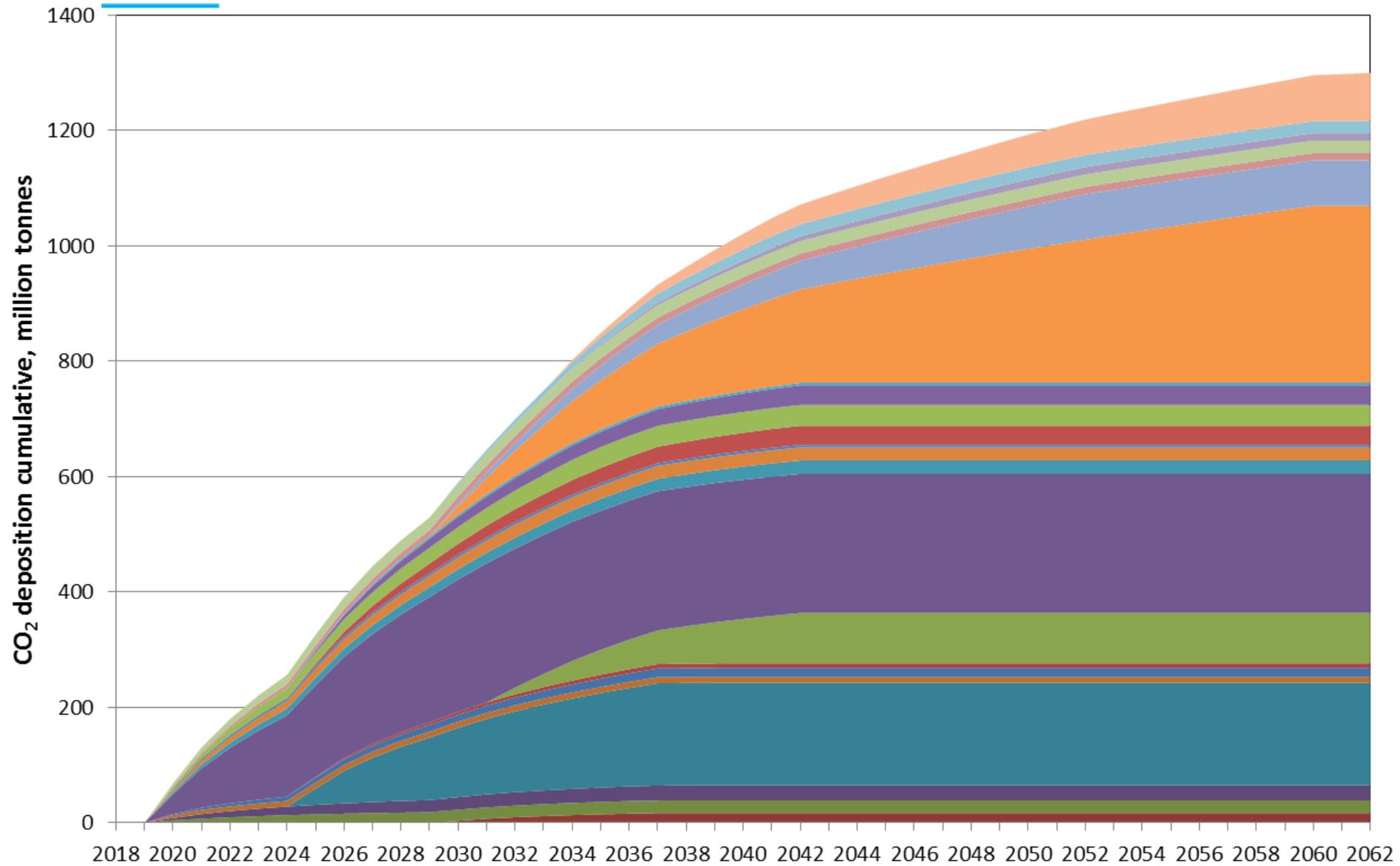
Production profile field example
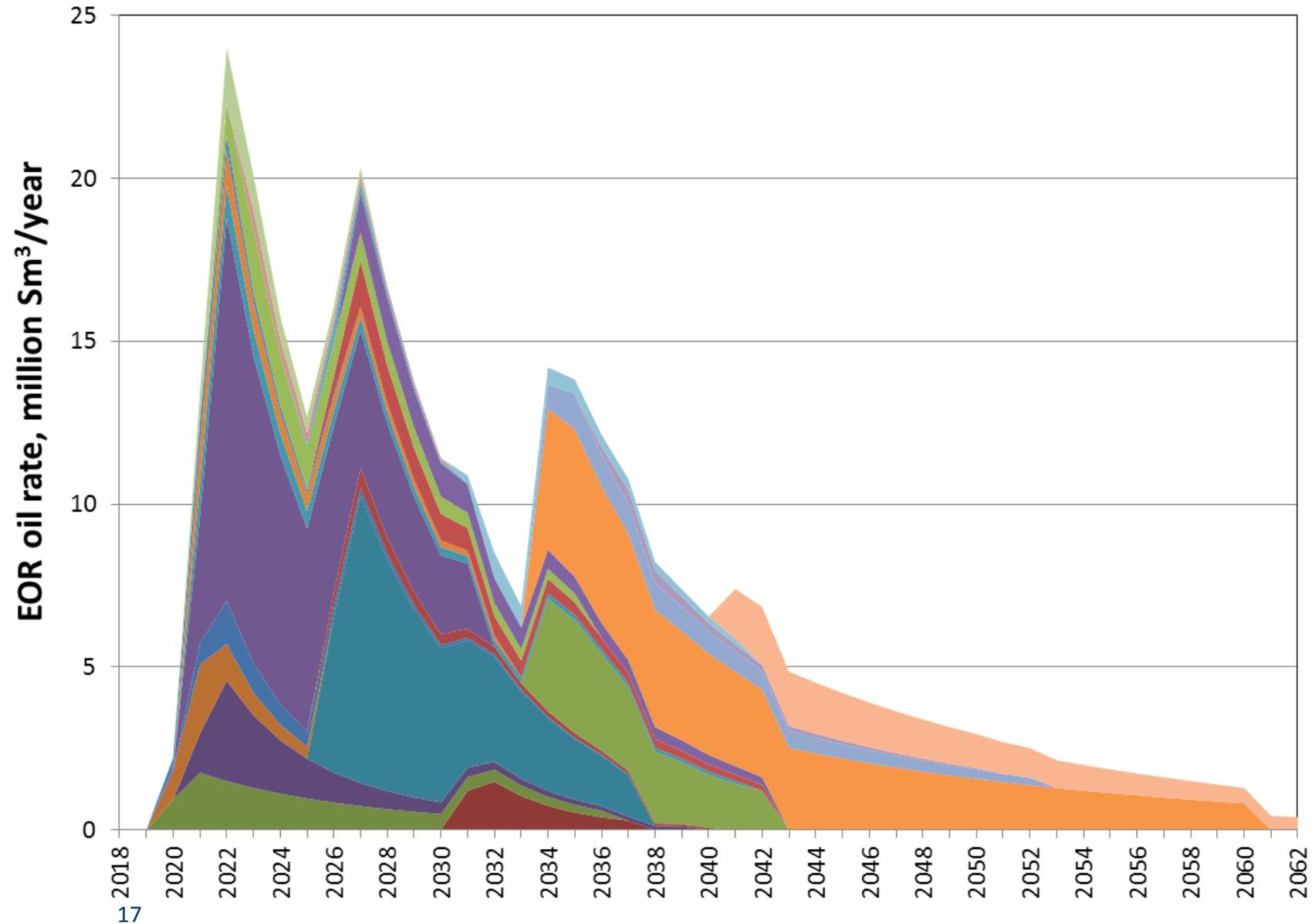# Water and gas production profiles included

CO$_2$ injection rate in the oil fields (Base case)
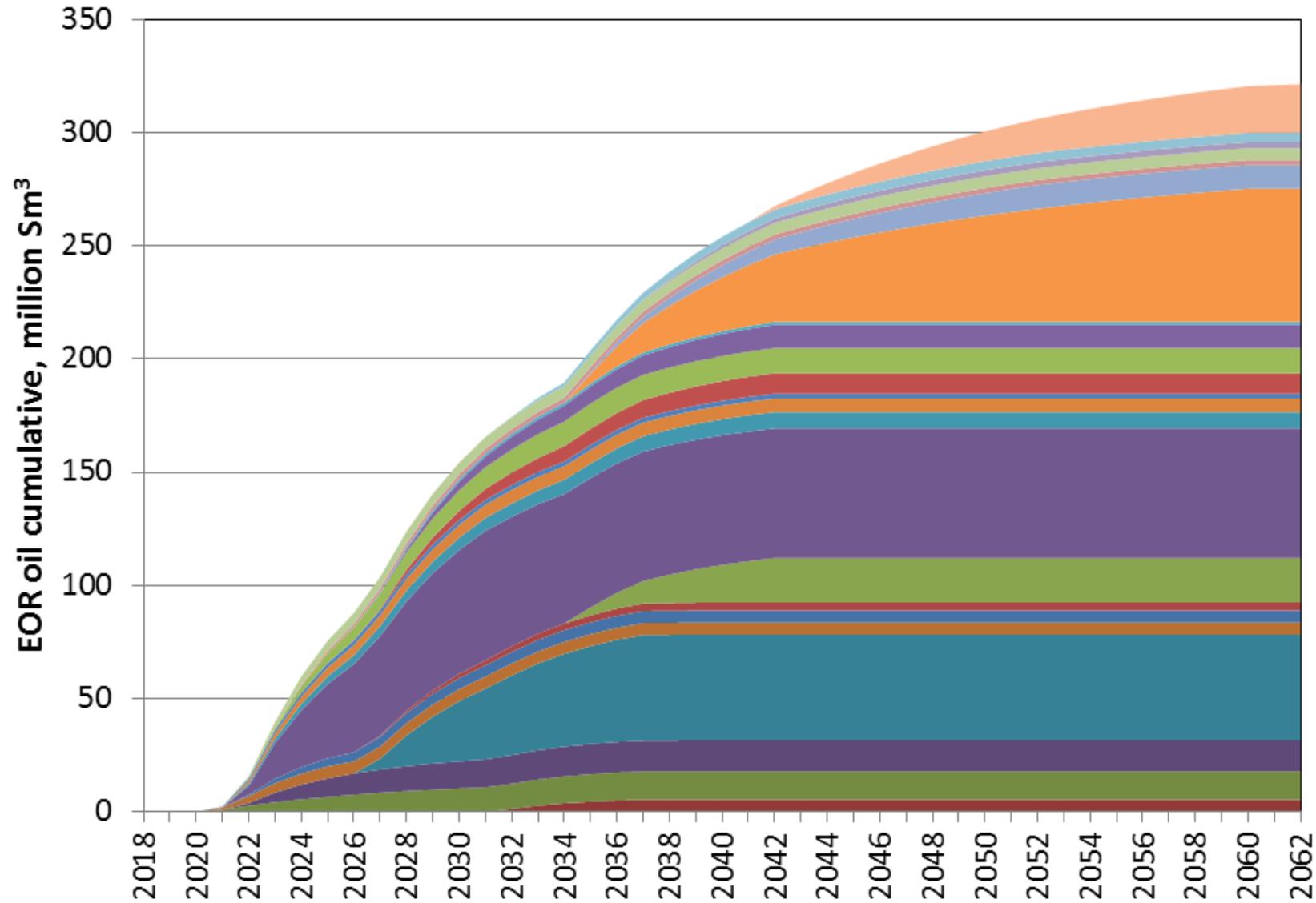
Cumulative CO$_2$ injected (Base case)

# EOR oil production rate(Base case)

Cumulative production of EOR oil (base case)

Comparing this work with previous CO_2 EOR study performed on the Gullfaks field

Study	Injection scheme	Injection rate PV/year	Injection period years	EOR yield %
Statoil (2000) Grinestaff (2000)	CO_2 WAG	0.045	22	9.7
This work	CO_2 WAG (1:1)	0.038	20	8.3
This work	Continuous CO_2	0.038	20	7.8

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Compering this work with previous CO_2 EOR study performed by the operator of Ekofisk field

| Study	Concept	CO_2 injection rate Mtonne/year	EOR yield %
Jensen et al. (2000)	CO_2 WAG	5.0	5.6
This work	CO_2 WAG (1:1)	7.3	7.8
This work	Continuous CO_2	14.5	6.5

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CO_2 balance for the Base case and WAG case
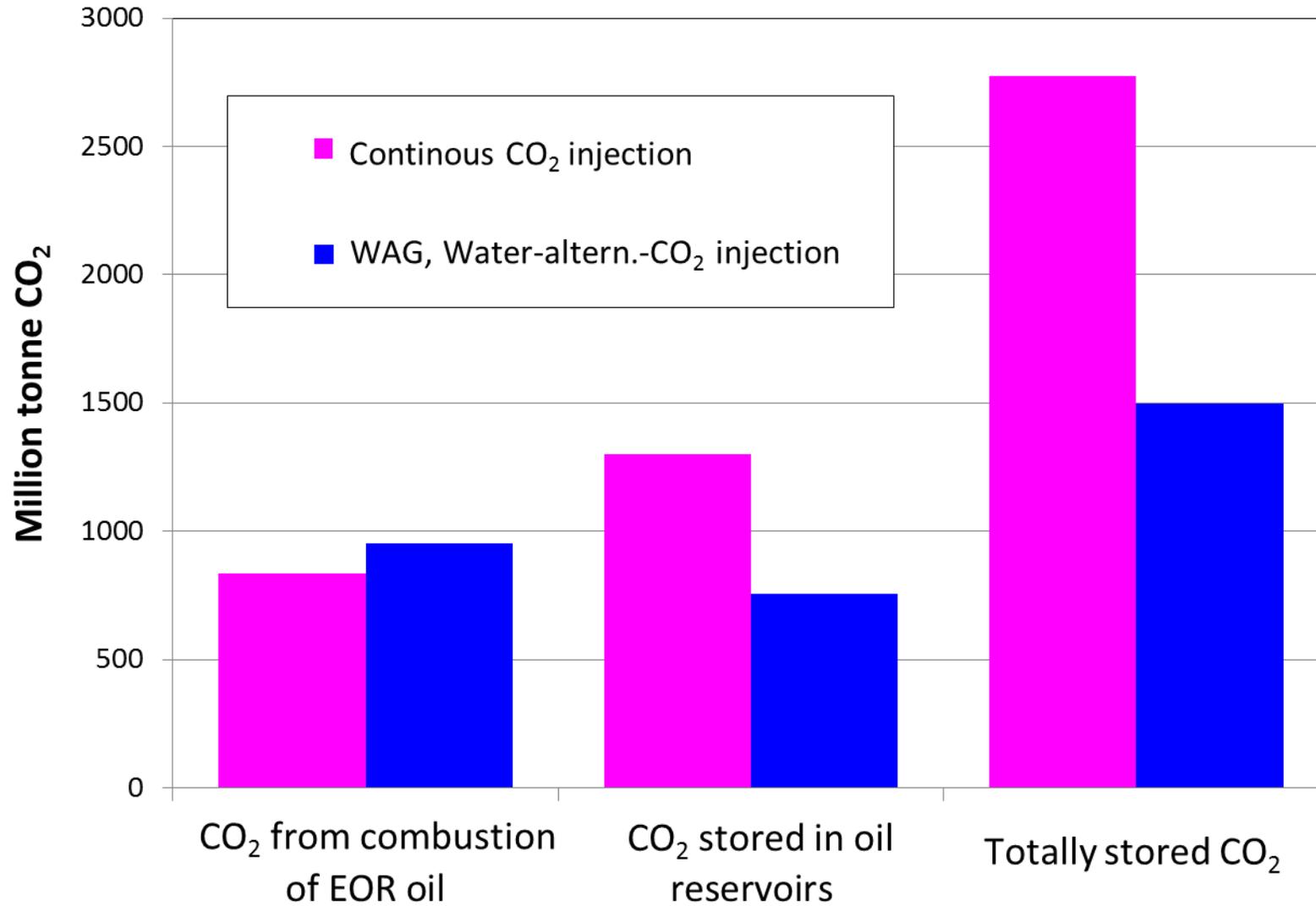
Cost module

- **CO_2 pipeline system and branches**
  - Calculated for min 100 bar in main pipeline and min 70 bar in branches.

- **Wells - New injection and production wells.**
  - No. of injection wells dependant on injection rate ; 15 000 bbl/day CO_2 per well (sandstone), 7 500 bbl/day (chalk)

- **Oil production system modification**
  - System modified to handle massive CO_2 breakthrough . Description of system described by Holt and Lindeberg (2004)

- **CO_2 compressor**
  - Investment cost related to load (corr. to injection rate and pressure, Turton *et al. 2001)*

- **CO_2 drying plant**
  - Drying after compression. Use solid desiccant. Cost calc. after Koht and Riesenfeld (1971)

- **Other cost**
  - Engineering cost and cont. (25%)

- **Aquifer deposition cost**
  - Excess CO_2 deposited in aquifers. Cost for injection wells and compressibility capacity (ZEP project 2001b)

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Incremental oil recovery for tertiary CO_2 injection
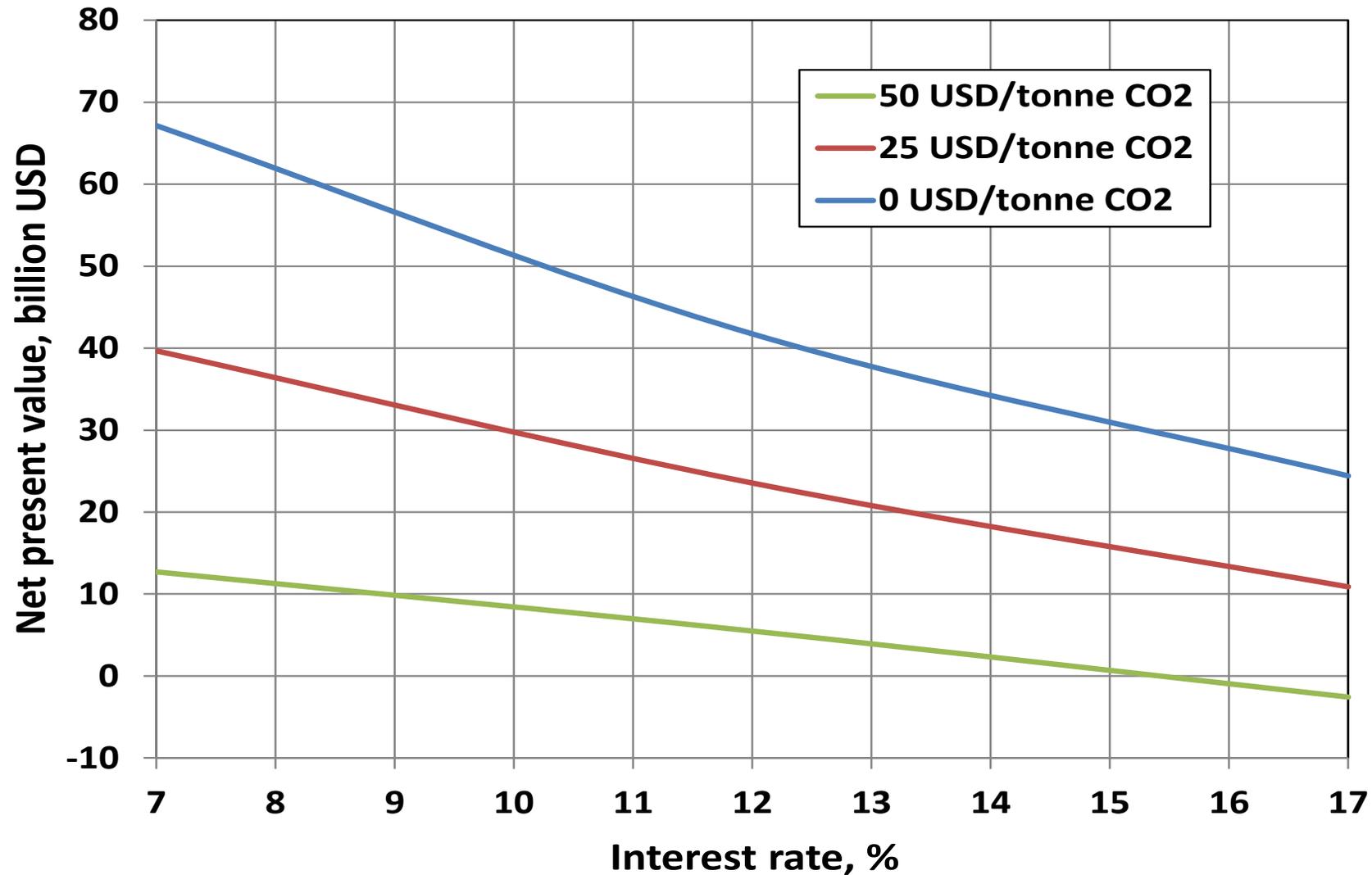
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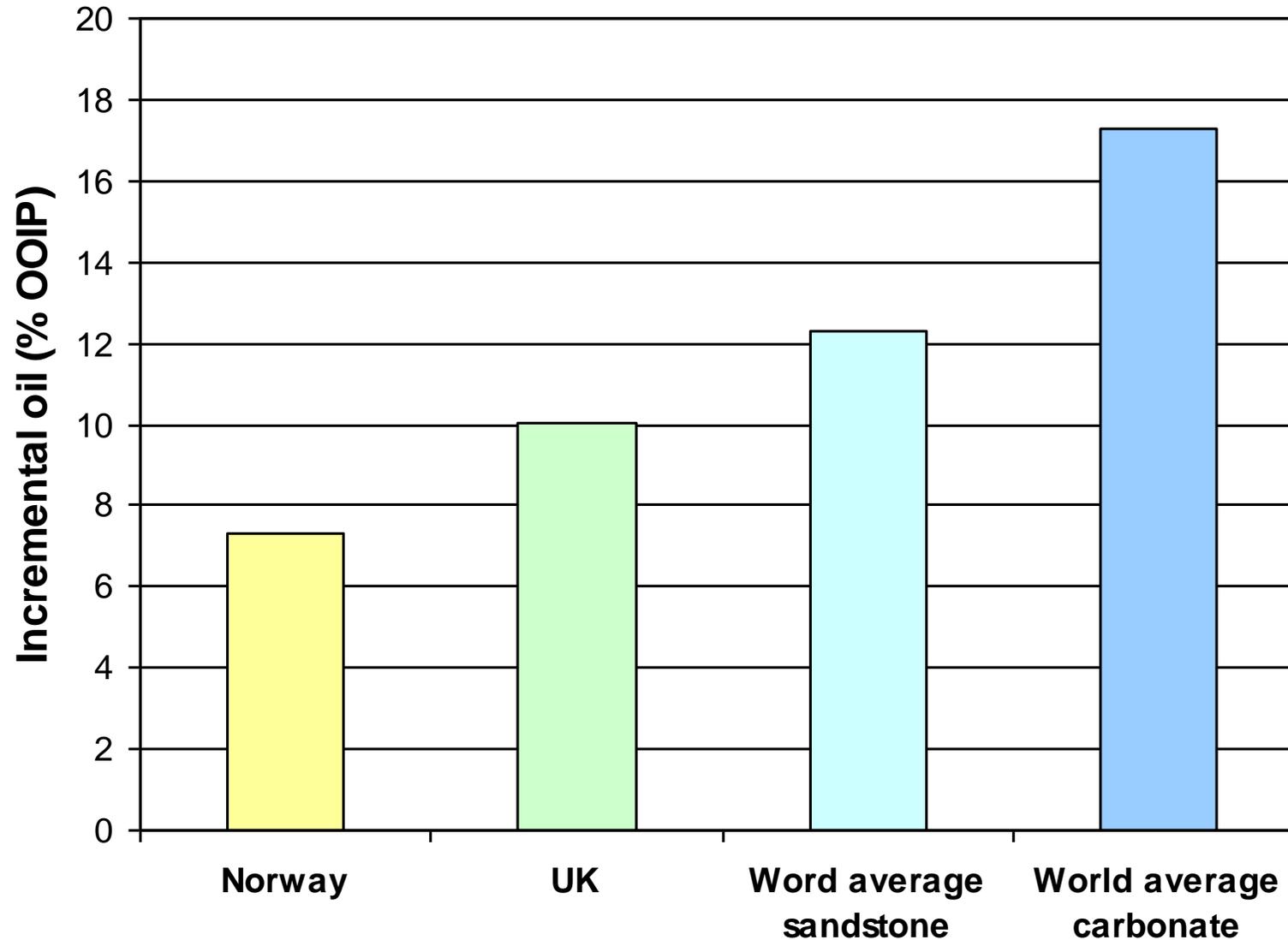
Economic analysis

- End year of field oil production is taken into account when to start CO_2 injection in the different fields (first year 2020)

- Reduced peak delivery of CO_2, by spreading out start year for CO_2 injection in the different fields (from 2020 to 2034)

- Operators pay a price for CO_2 (CO_2 cost) from the main infrastructure

- CO_2 is recycled after breakthrough, thus decreasing the amount of CO_2 imported

- EOR project is terminated when net cash flow becomes negative

Base case parameters	Value
Oil prize	80 USD /bbl
Peak CO_2 rate	70 mill tonnes/year
CO_2 cost	25 USD/tonne
Cost per well	25 mill USD /well
Interest rate	7 %
CO_2 transp. cost (main pipeline)	8.5 USD/tonne

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Base case results for 23 oil fields

Item	Value
Investment costs excluded wells, billion USD	9.9
Investment costs wells, billion USD	8.0
Operating costs, billion USD/year	2.2
Total oil, million Sm^3	2241
Oil recovery, % OOIP	6.6
EOR oil, million Sm^3	307
Incremental oil recovery, % OOIP	6.6
Total stored CO_2, million tonne CO_2	2744
Stored CO_2 in aquifers	1507
Stored CO_2 in oil reservoirs	1227
Net present value, billion USD	22.4

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NPV at 80 USD/bbl as function of interest rate

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NPV as function of oil price and CO$_2$ cost at 7% discount rate

Chart — Net present value, billion USD (y-axis) vs Oil price, USD/bbl (x-axis)

Legend:
- 0 USD/tonne CO2, modified wells
- 0 USD/tonne CO2, new wells
- 25 USD/tonne CO2, modified wells
- 25 USD/tonne CO2 new wells
- 50 USD tonne CO2, modified wells
- 50 USD/tonne CO2, new wells

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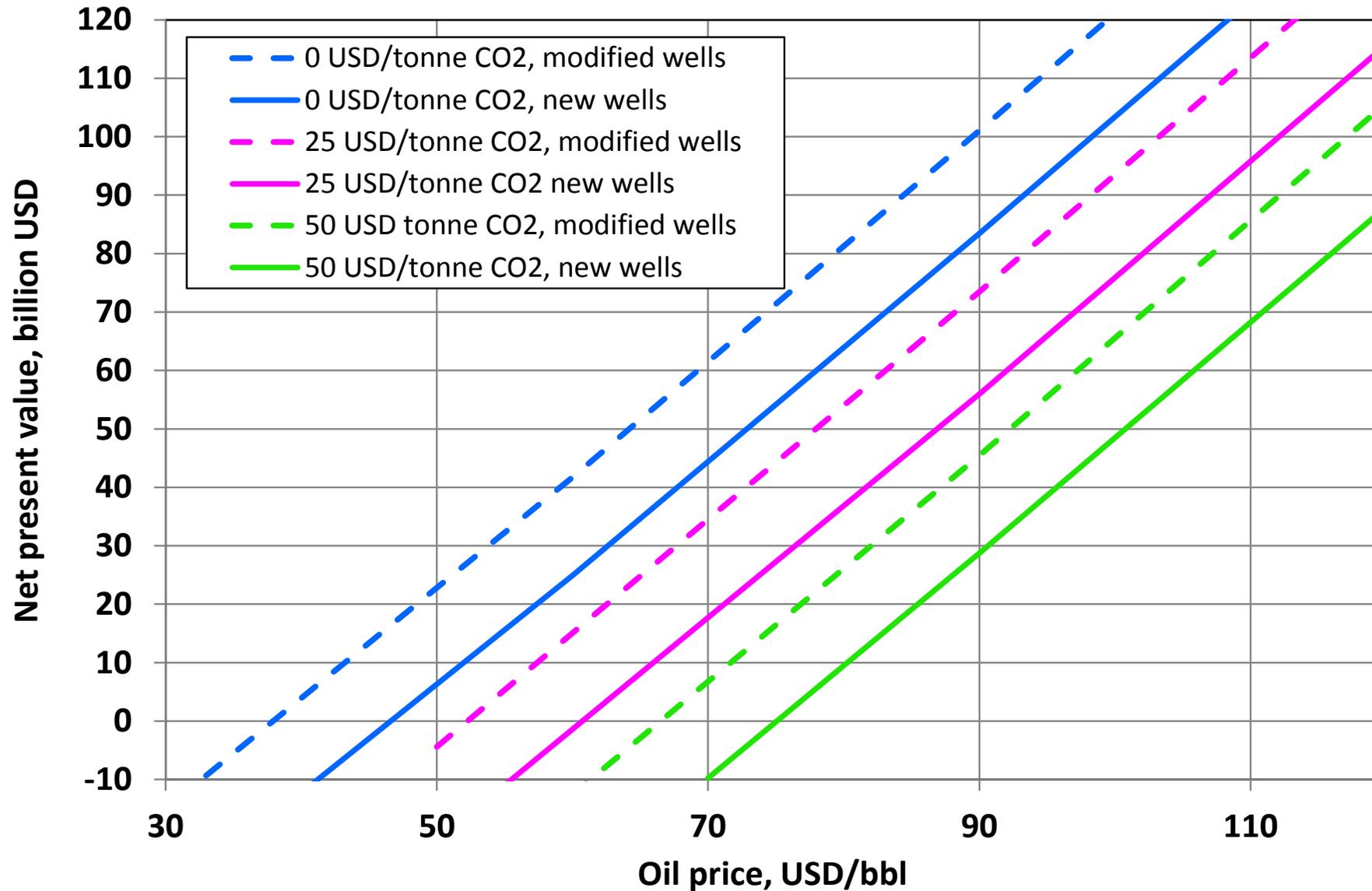
Conclusions

- Screening of oil fields for CO_2 EOR in the Norwegian North Sea has shown 23 possible candidates with a total potential of 250 – 340 mill Sm^3 of extra oil from 2020, corresponding to 5 – 7 % of OOIP.

- Total investment 17.9 billion USD

- 70 million tonnes of CO_2 injected per year for 40 years

- Net present value (NPV) 40 billion USD at 7% interest (oil prize 80 USD/bbl, CO_2 cost 25 USD/tonne)

- **1.3 Giga tonnes of CO_2 stored in the oil fields**

- **1.7 Giga tonnes of CO_2 stored in buffer aquifers**

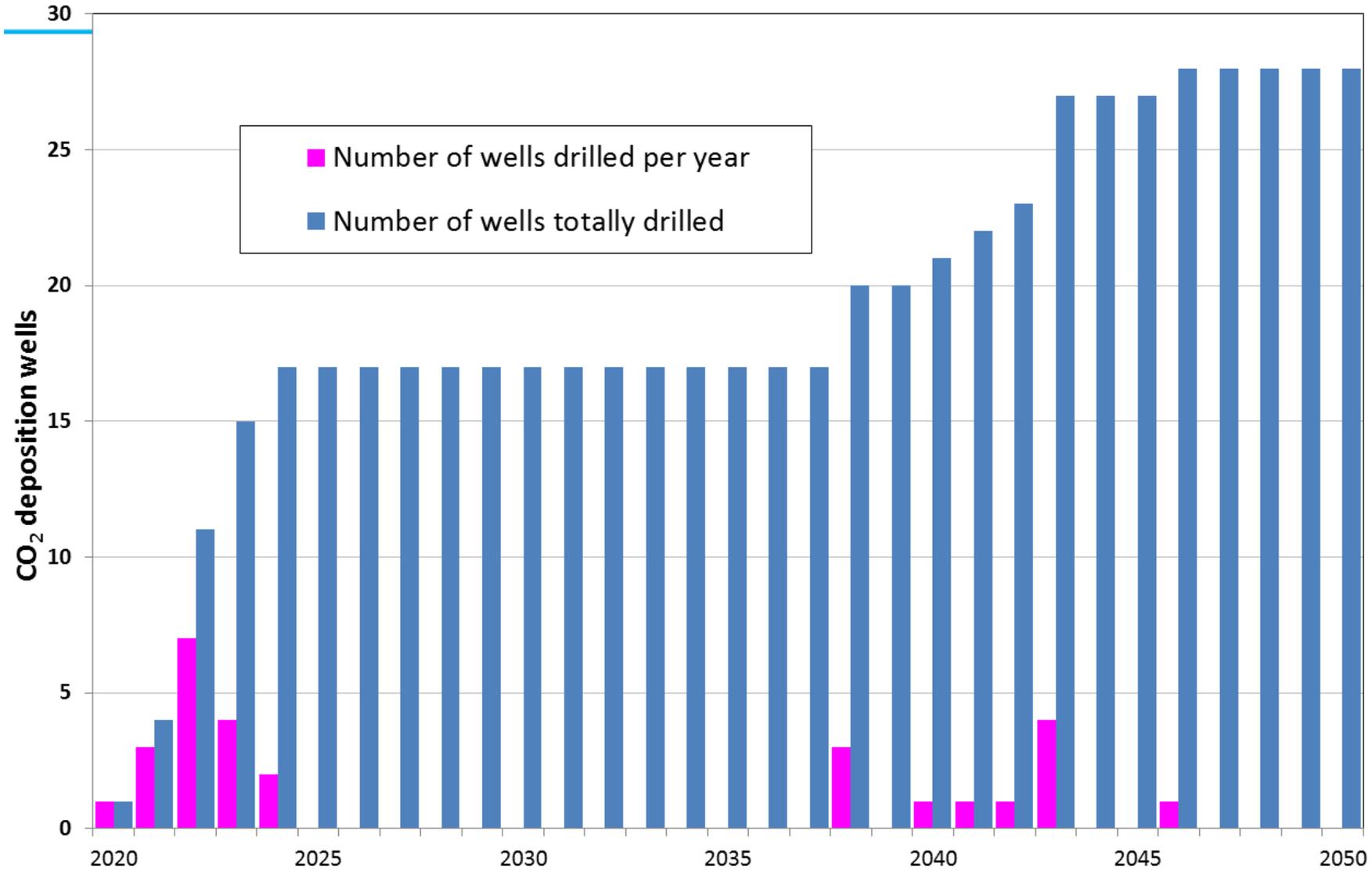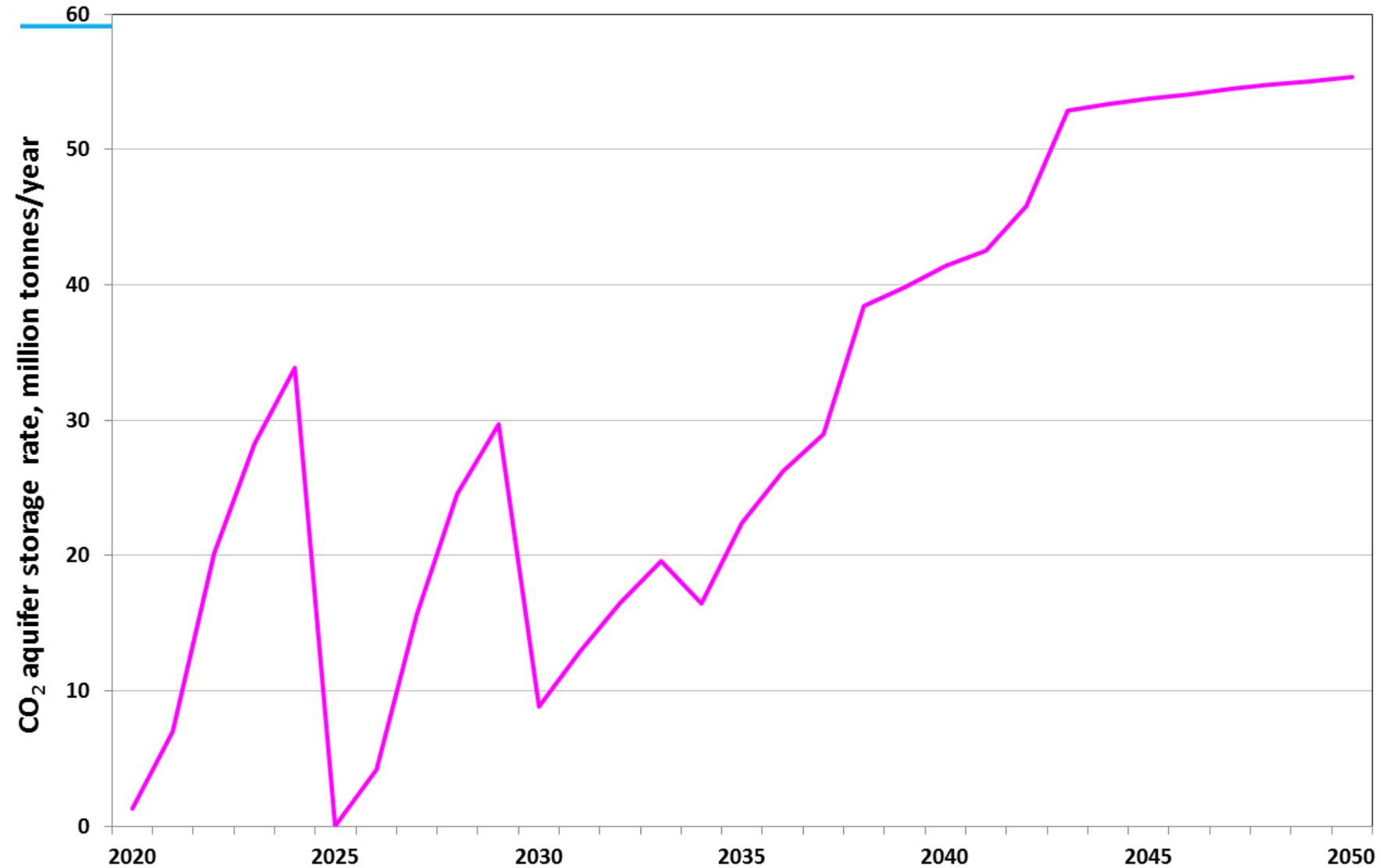- The amount of CO_2 stored is much larger than the CO_2 formed by combustion of the EOR oil

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Mapping the potential of CO2 storage
opportunities in mature oil fields...

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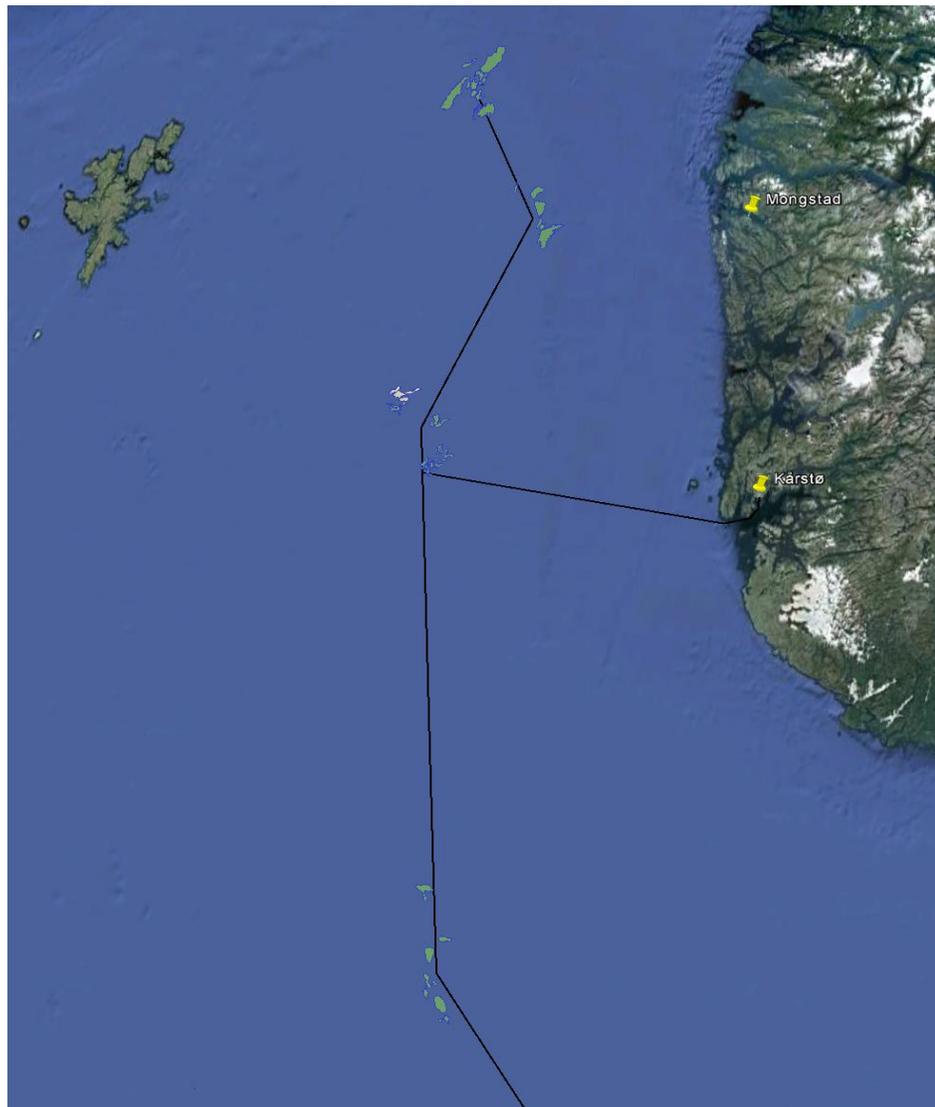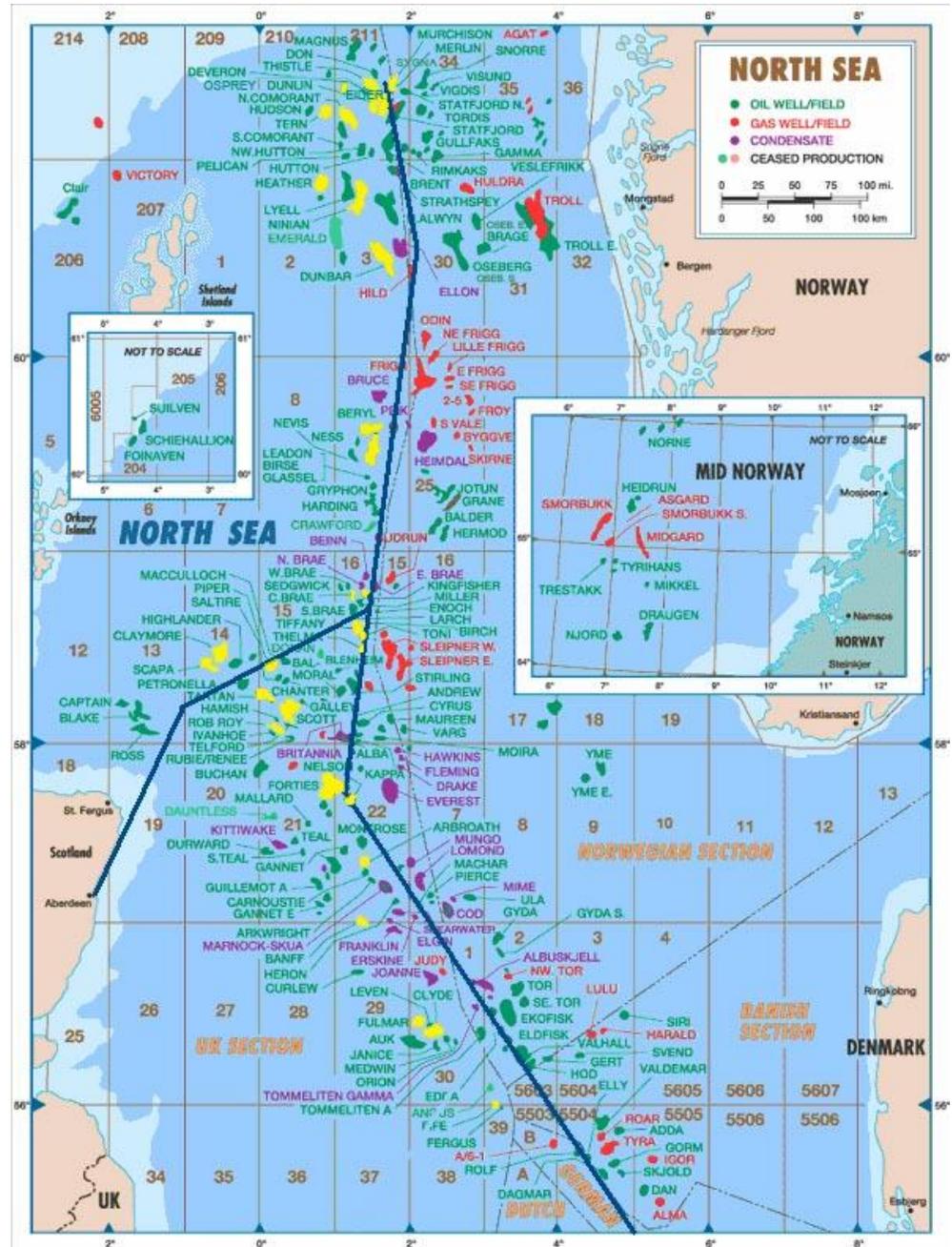
Total project economy field example
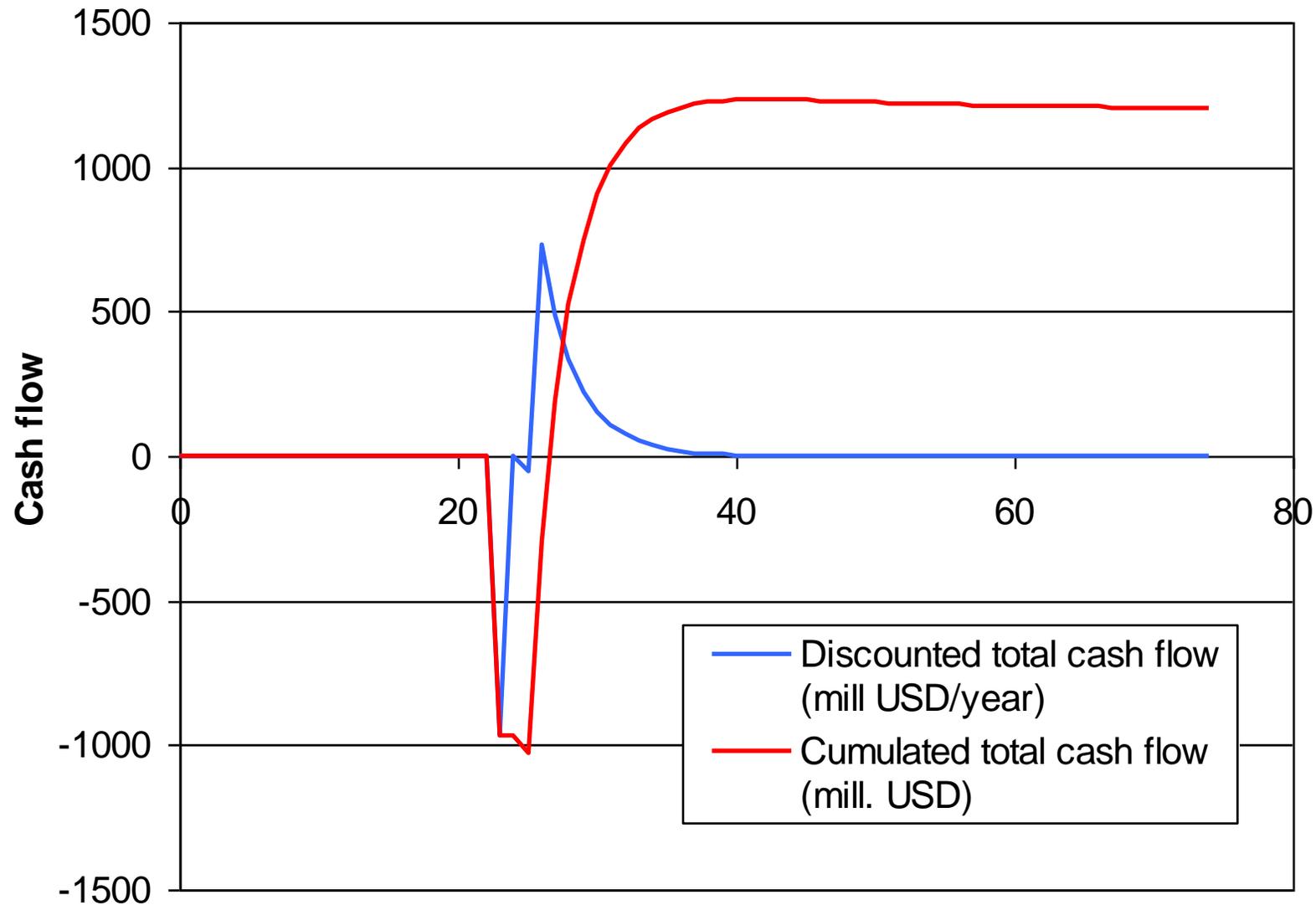
Need for wells for storing excess CO_2

Storage rate of excess CO_2 in aquifers

Aknowledgment

- Torleif Holt, Alv-Arne Grimstad, Per Bergmo, Dag Wessel-Berg, Malin Torsæter

- Norwegian Petroleum Directorate (NPD) for their viewpoints on investment cost and field data.

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