CO_2 EOR and Storage

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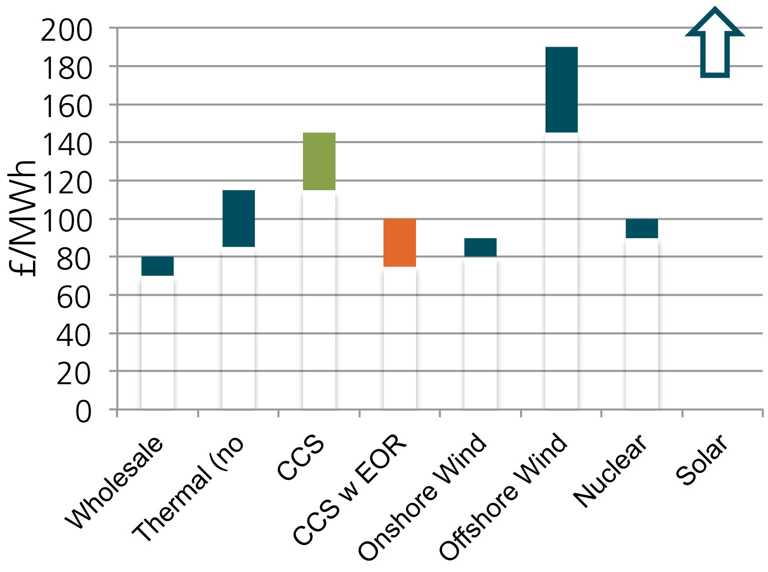
CCS and EOR – Context

CCS deployment hinges on lagging demonstrations

- *Commercial* CCS deployment is a practical necessity to meet abatement goals
- Business case for CCS remains weak, slowing demonstrations of so-called "(commercially) unproven technology"
- Principal objection is cost (esp capture), followed by storage acceptance

CO_2 EOR can be a significant catalyst for commercial deployment

- Significantly lower net overall costs
- Reduced commercial risk in storage development
- Improved acceptance of storage sites
- Reduced demand for new infrastructure

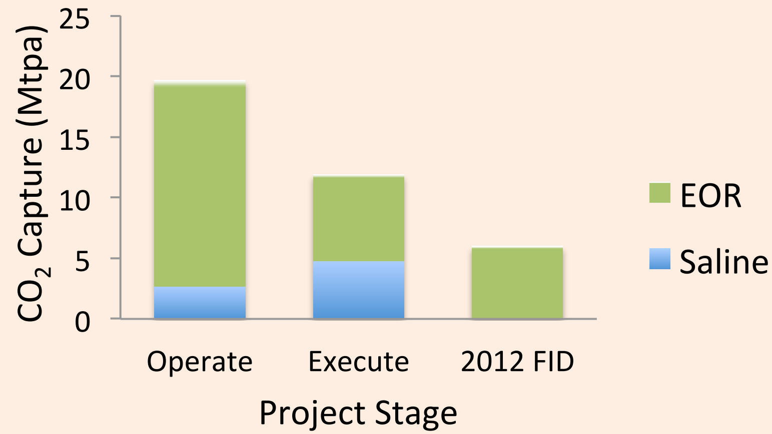


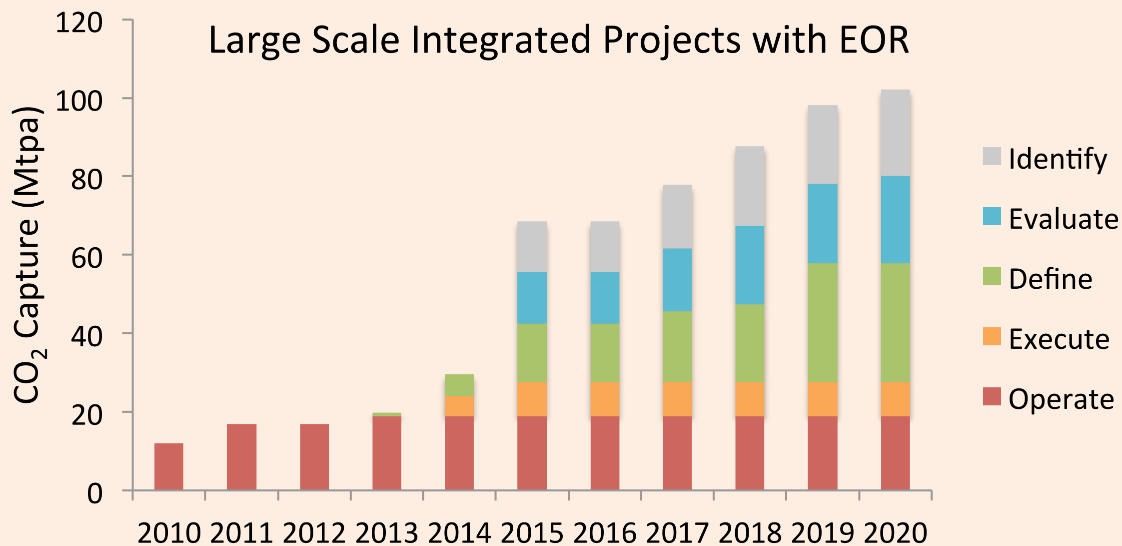
Source: Mott Macdonald for DECC, UK Electricity Generation Costs Update June 2010

CO_2 EOR and storage for CCS

Most CO_2 currently captured is stored in EOR projects

In new projects, most captured CO_2 is destined for EOR projects





CO_2 storage in EOR projects is planned to increase nearly ten-fold in this decade

data modified after GCCSI Global Status Report 2012

Commercial drivers for CO_2 storage deployment

Deployment Driver	EOR	Depleted Gas Field	Deep Saline Formation
Net storage cost	Lowest Oil revenue, lower monitoring	Intermediate No revenue, lower monitoring	Highest No revenue, higher monitoring

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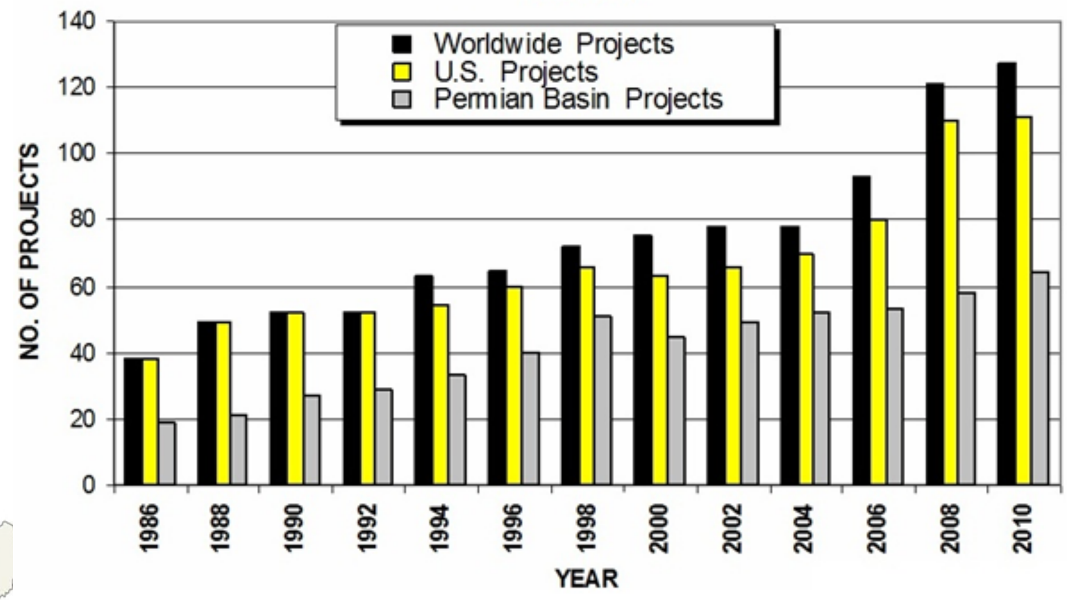
Well integrity risk	Highest More wells, some re-used, corrosive fluids	Intermediate Re-use of wells, large pressure gradients	Lowest Fewer purpose-built wells

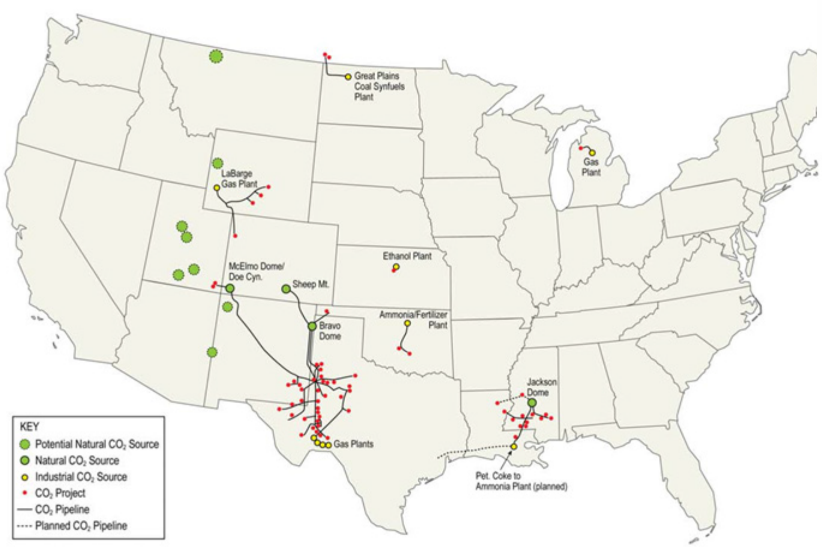
CO_2 EOR today

Number of projects has grown steadily for 3 decades

W Texas (Permian Basin) growth limited by CO_2 supply

Growth in US and other areas driven by new supplies, increasingly motivated by CCS



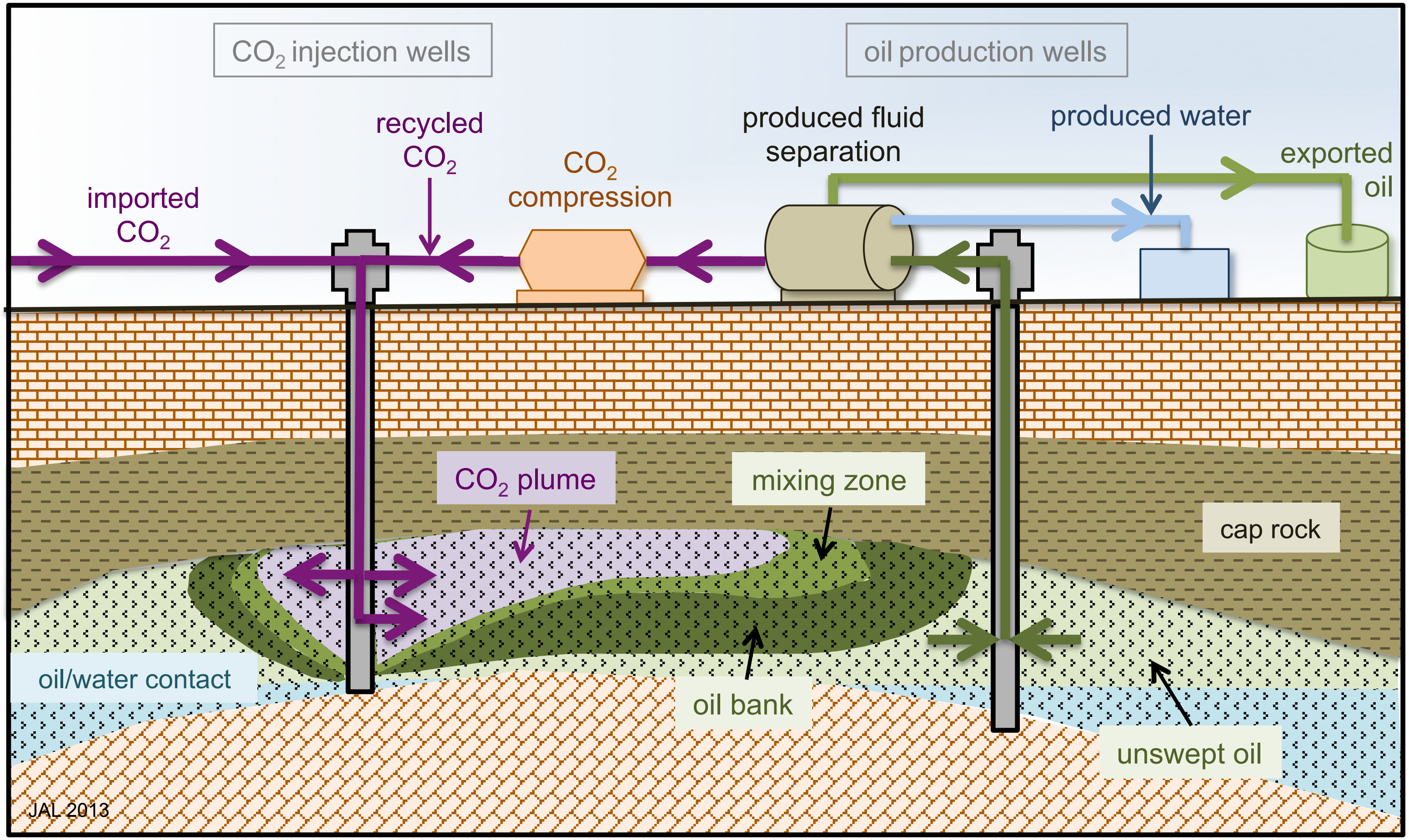


In 2011, ~72 Mt of CO_2 was injected in N American EOR projects (24% captured, mostly from gas plants) (EPSA, 2012)

US CO_2 EOR production is ~300,000 b/d, 6-8% of total

graph and map from NEORI, 2012

CO_2 EOR process overview



The CO_2 cycle in EOR

Imported CO_2 is injected into an oil reservoir, where it mixes with oil and displaces it to production wells

Some of the injected CO_2 (typically 50 – 70%) is eventually produced along with oil, water and natural gas present in the reservoir

The remainder is trapped in the rock (capillary forces or mineralisation), or mixed with reservoir fluids (oil, water, gas) that are not produced

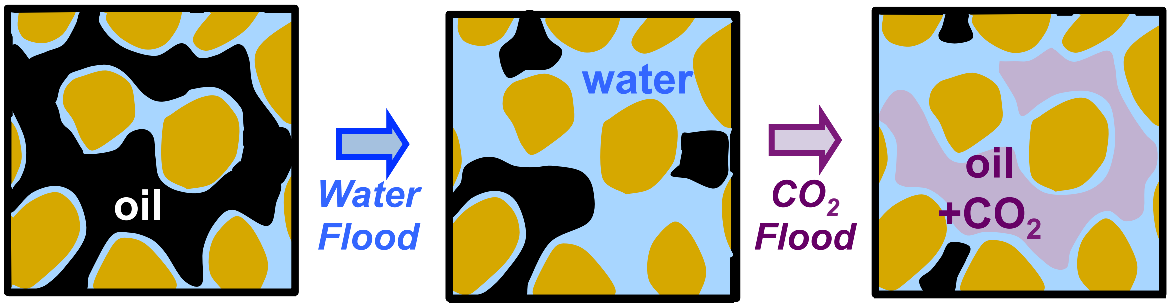
Produced CO_2 is separated from other reservoir fluids by reducing pressure

Separated CO_2 is compressed and re-injected into the oil reservoir (recycled)

Nearly all imported CO_2 remains in a closed system that is eventually sealed like any other storage

Fugitive emissions from valves and seals are greater for EOR than other storage sites, due to recycling of produced gas

CO_2 mobilises oil that can't be produced by water flooding



Oil vapourises into CO_2 and CO_2 condenses into oil, causing

- oil to swell in volume
- reduced oil viscosity
- reduced interfacial tension between oil and water
- when ***miscible***, CO_2 and oil form a single phase comprising any proportion of oil and CO_2

Some CO_2 dissolves in formation water; the amount depends on salinity, temperature and pressure

CO_2 injection for EOR

At reservoir P, T favouring miscibility, CO_2 is a dense phase (liquid or supercritical, depending on temperature)

Injectivity of CO_2 is significantly greater than water, due to lower viscosity

Degree of oil recovery at small scale is not achieved throughout the reservoir because CO_2 does not contact all of the oil

Sweep efficiency is a complex function of rock and fluid properties; buoyancy of CO_2 (gravity override) is generally the most important issue

Courtesy Bruce Hill, Clean Air Task Force

Injection patterns are adjusted over time and space to improve sweep, e.g.:

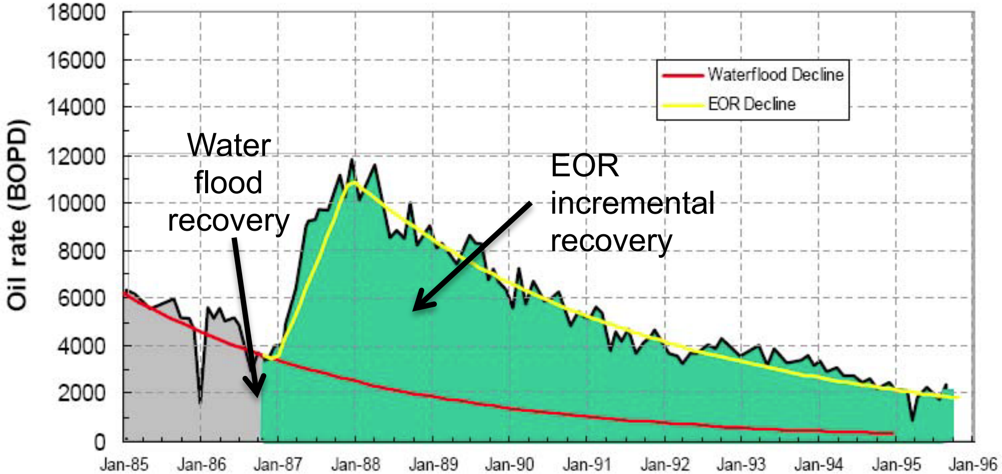
- Injection at reservoir top, to push oil downward (gravity drainage)
- Injectors aligned to create a ‘wall of CO_2’ (line drive)
- Injectors interspersed with producers to improve coverage (pattern injection)
- Water alternated with gas (CO_2) (WAG) to reduce CO_2 ‘viscous fingering’ into oil

Oil recovery from CO_2 EOR

Incremental oil recovery typically begins 6-24 months after CO_2 injection

EOR production profiles are relatively low and slow

EOR efficiency is measured by:



Wertz Field, Texas (from Lake & Walsh, 2008)

Recovery factor = incremental production / original oil in place (STOIP)

- ranges up to 30% for CO_2 EOR, typical estimates are 10-15%
- existing projects forecast average ~13%, but increasing; compare 30-60% for water flood

Utilisation factor = incremental production / imported CO_2 *(or inverse)*

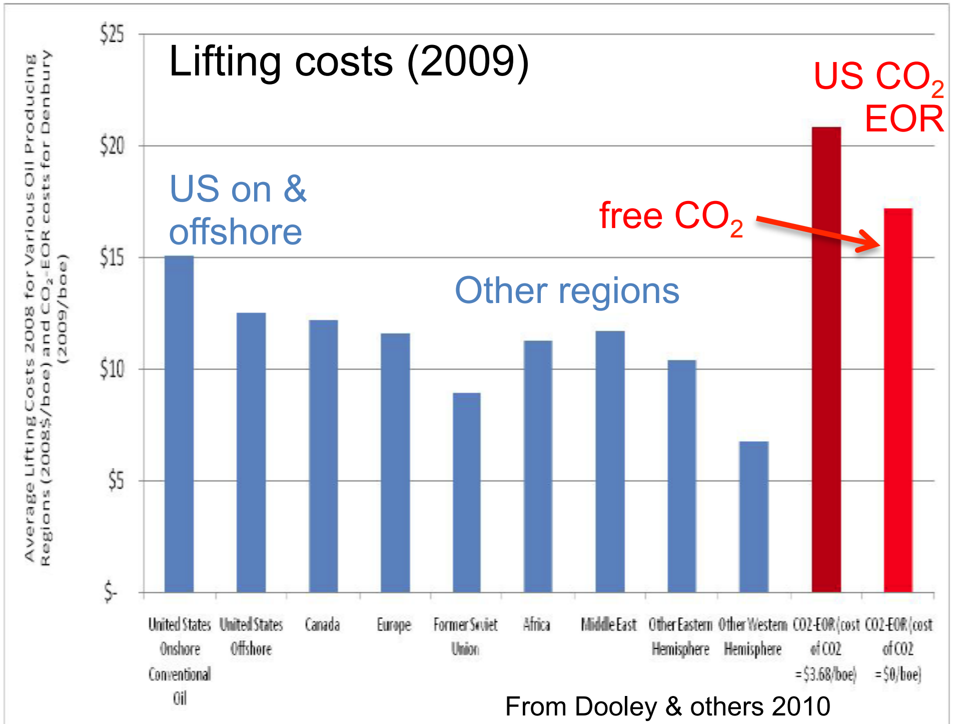
- Ranges up to 7 bbl/tonne *(2.7 mscf/bbl)*; existing projects average 3.0 bbl/tonne *(6.3 mscf/bbl)*
- Typical range 2.5 – 3.5 bbl/tonne *(5.4 – 7.6 mscf/bbl)*

1 tonne = 18.9 mscf for US oil field STP

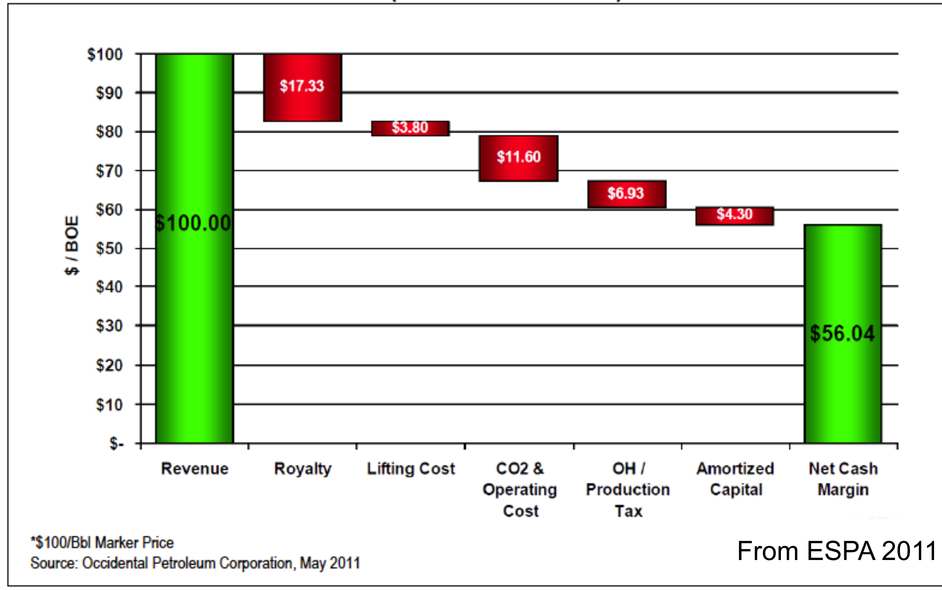
CO_2 EOR economics

CO_2 EOR is profitable in favourable circumstances (left)

But production costs are generally higher than for other recovery processes (below)



From Dooley & others 2010



From ESPA 2011

Incentives (e.g., tax) are likely needed in less favourable environments, e.g.:

- high oil production taxes
- expensive CO_2
- offshore

Where is CO_2 EOR attractive?

Oil fields prospective for miscible CO_2 flooding

- High pressure – typically 2,000-3,000 psi or more, re-pressurisation may help
- Light oil – typically > 30° API; < 25° is challenging (probably not fully miscible)
- Large remaining oil volume – sufficient to repay EOR development
- Good reservoir –rock properties and reservoir geometry good for gas injection
- Low temperature – favourable geothermal gradient or cooled by water flood

Low development and operating costs

- Old fields – typically after water flood, with few other recovery options and re-usable facilities
- Onshore – lower capital and operating costs
- Low-cost (or free) CO_2 delivered to site – generally largest controllable expense
- Low taxes – taxes are less affordable with higher capex and opex

CO_2 EOR design for storage

Pressure management and storage capacity

Production (mostly water) creates significant capacity for CO_2 and pressure management for storage integrity

Low-cost CO_2 for storage is suitable for continuous injection (vs WAG, used to reduce CO_2 purchase)

CO_2 injection manifold
Courtesy B Hill, Clean Air Task Force

Storage obligations

Capture plants require very high injection availability; possible with extra equipment (wells) or an alternative site

Monitoring obligations are broadly consistent with good reservoir management – potential to recoup incremental costs

Matching CO_2 supply and demand

Conventionally, recycle increasingly replaces import CO_2, reaching full requirement in roughly 10 years

This can be managed with no WAG, larger recycle, higher production, and lower utilisation

For some time, developing new fields may be more attractive than maximising storage

CCS value chains with EOR

CO_2 capture and EOR are complimentary, but different, economic activities

- CCS offers new CO_2 supplies suitable for EOR where demand is not met from natural sources
- EOR offers potential to offset storage and transportation, and potentially to defray capture costs
- Differing risks mean that capture and storage are likely to be separate, even with common owners
- Transfer of CO_2 (with attendant obligations and liabilities) can be mediated by a transfer price that may be positive (CO_2 storage fee), zero, or negative (CO_2 sales price)

Integrating the CCS chain is challenging, but feasible

- Supply and operations coordinated among capture plant, pipeline and EOR project
- Plant outages less than ~ 1year have limited EOR impact (deferred revenue)
- Short EOR outages managed fairly easily in large projects, long-term EOR outages could incur huge liabilities to capture plant
- Successful EOR projects are economically incentivised to develop clusters, thereby mitigating risk of long-term storage outages

Cost reductions for CCS with EOR

For other types, CO_2 storage is an inherent cost component of CCS

EOR requires more capex and opex per tonne stored, but oil revenues offset these in many diverse examples

For an average EOR project with $100 oil, gross EOR revenues are about $300/tonne over project life (typically 20 years)

Higher petroleum taxation (e.g., N Sea) leaves less to pay capture plants for CO_2

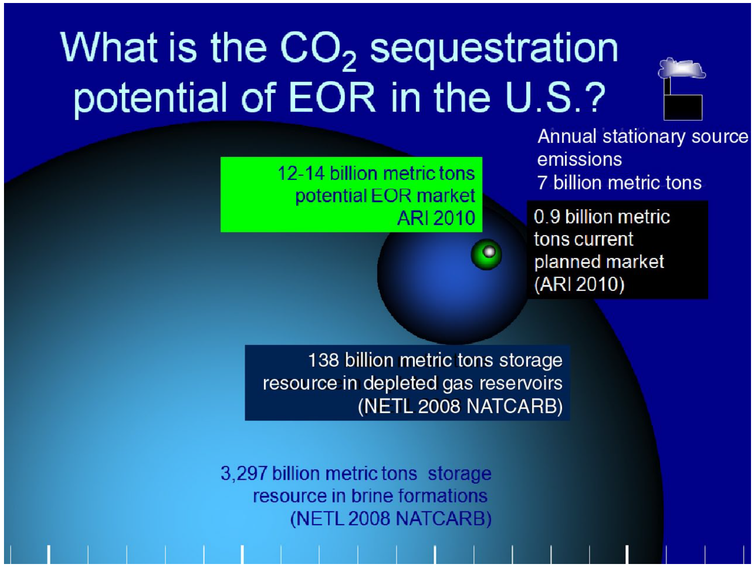
Tax may significantly offset capture incentives, in some cases eliminating the net cost of CCS to the public

In the 2011 W Texas example, roughly $30/tonne is paid for CO_2

- Current prices include commodity cost plus long-distance transport, so a capture plant could expect to transport and store CO_2 at no charge, as a minimum
- ~$160/tonne is available before EOR investment returns; a portion of this, plus the CO_2 commodity value, could defray capture costs

Currently, natural sources modulate CO_2 prices in US EOR markets, but sustained high oil prices and demand for limited natural CO_2 are driving prices higher

CO_2 EOR storage capacity – is there enough?



From Havorka, 2010

EOR storage is sometimes dismissed in context of larger, but unproven *potential* outside oil fields

Insofar as cost is a hurdle to CCS, lowest-cost storage with EOR is a priority

CCS may displace marginal natural CO_2 sources

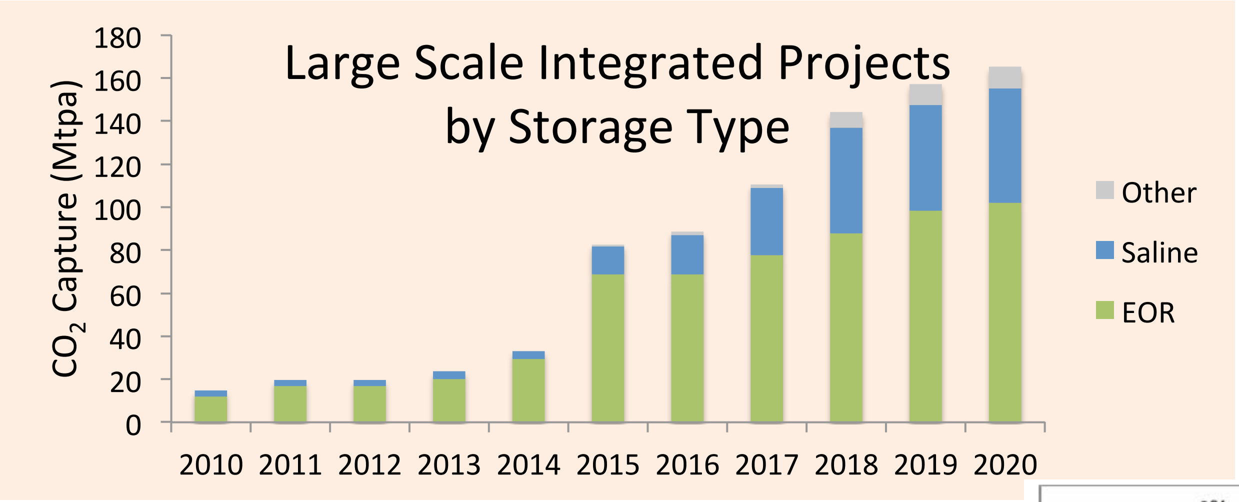
Early EOR may catalyze infrastructure for later saline storage when demand is much higher

ARI estimate of 20 to 45 Gt EOR storage (EPSA, 2011) equates to N American demand growth of 10-15% every year until 2050

At 30% per annum projected growth (2014-2020, next slide) ARI (2013) global EOR capacity would be reached in 2042

Estimated UK EOR capacity of 1 Gt (Gluyas, 2010) is sufficient for 10-15 yrs of current emissions, whilst current capture is 0.04 Mtpa

Outlook for CCS with EOR

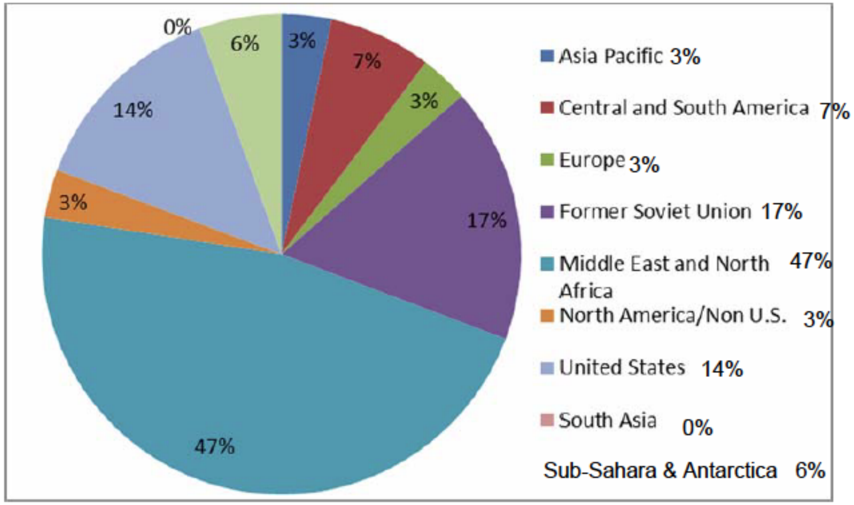


data modified from GCCSI, 2012

Planned projects show 30% annual capture growth 2014-20

Projects in this decade are dominated by EOR storage

from ARI, 2013



Large EOR *potential* in ME and FSU, but policy is driving USA and China projects

Growing gas demand may spur capture in CO_2-rich basins (e.g., SE Asia)

Moving offshore (US, Brazil, possibly Europe) depends on capture incentives and oil price

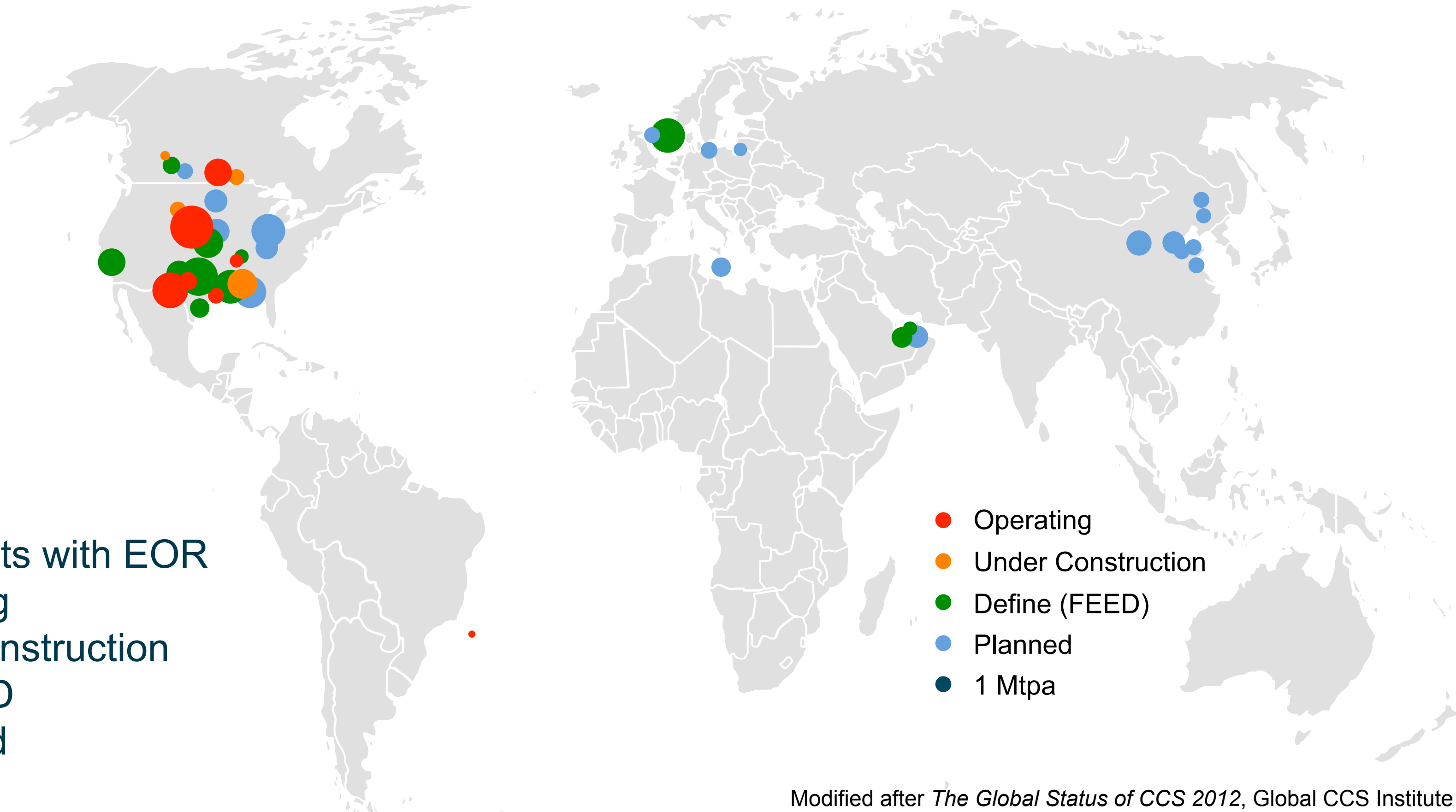
Summary

- Most CO_2 captured today is stored in EOR projects
- CO_2 EOR offers lower net cost than other storage, on a risked basis
- EOR application is limited by CO_2 supply in many areas
- Miscible CO_2 floods are economically attractive in many reservoirs
- EOR can be designed for increase CO_2 storage, at additional cost
- CO_2 supply and demand must be managed with capture plant(s)
- EOR storage capacity greatly exceeds near-term demand from CCS
- In the near term, CO_2 EOR and storage is likely to be concentrated in North America, followed by China

CO_2 EOR has an important role in overcoming hurdles to CCS deployment, particularly cost

Additional Slides

CO_2 EOR and storage projects



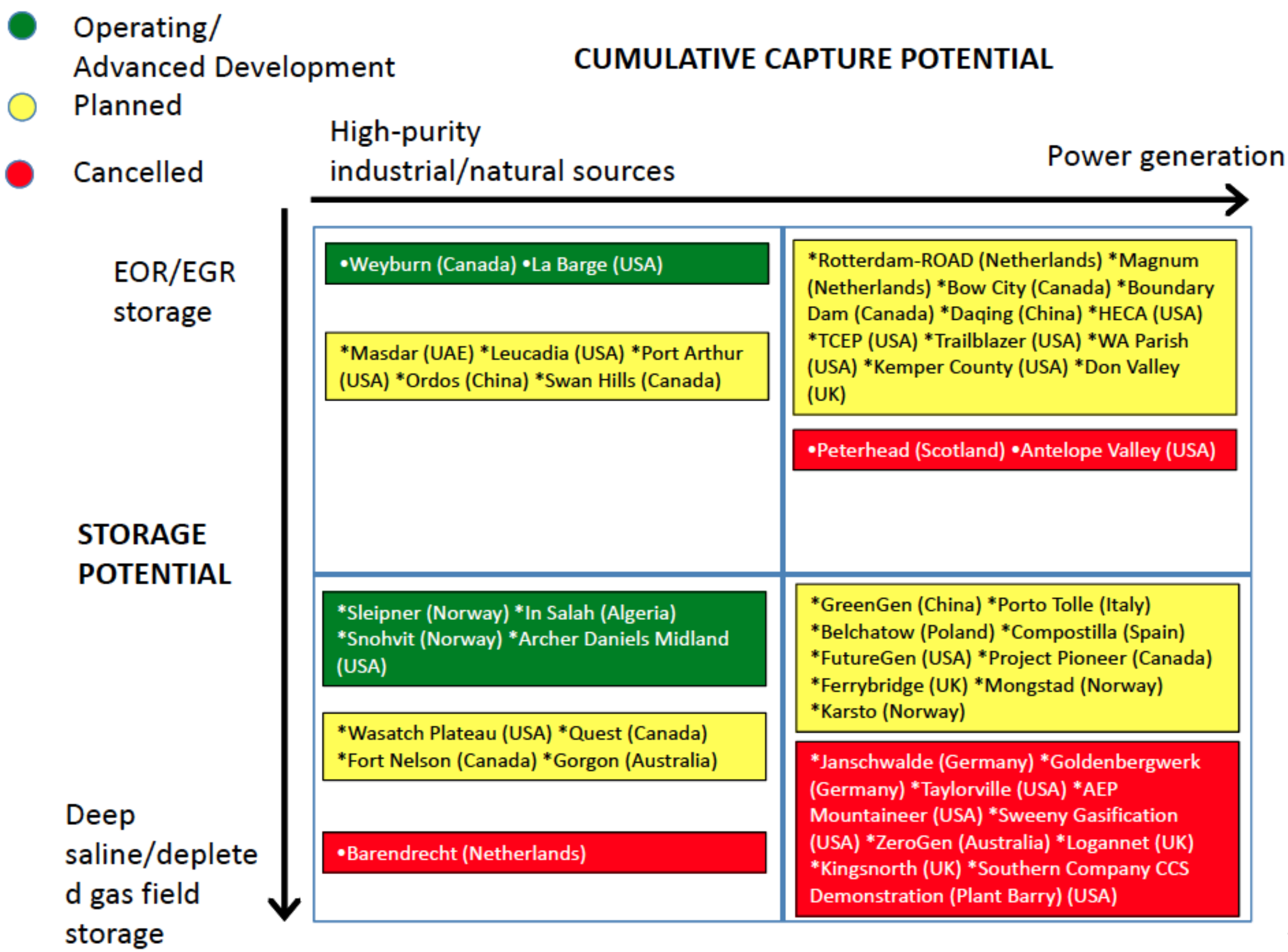
Modified after *The Global Status of CCS 2012*, Global CCS Institute

GCCSI projects with EOR

- 6 operating
- 4 under construction
- 12 in FEED
- 17 planned

Dominantly in North America, with Europe, Middle East and China longer term

Project success for capture and storage types (so far)



Operating capture is from high-purity sources, mostly with non-EOR storage

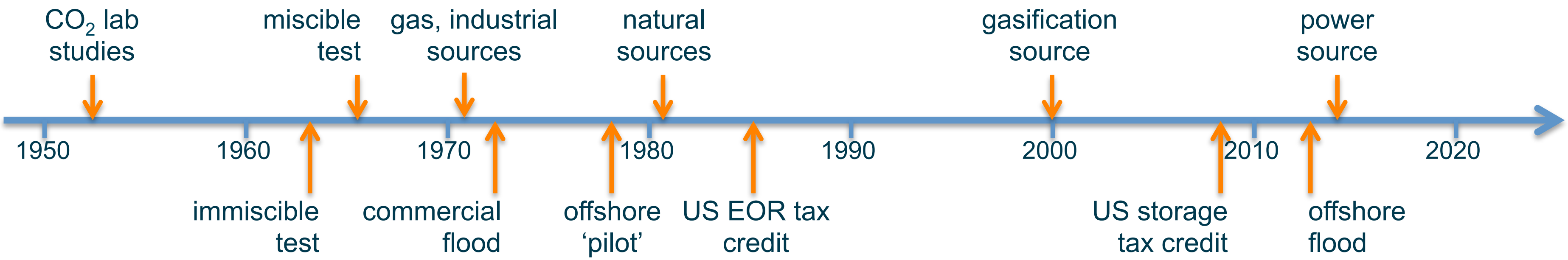
High cancellation rate for power projects with non-EOR storage

No EGR projects

from Herzog, 2012

CO_2 EOR history

CO_2 EOR is a mature technology that originated in the US in the 1950's



- CO_2 originally sourced from gas and fertiliser plants
- Once demonstrated, demand drove long-distance pipelines from natural sources
- Offshore applications limited by costs
- US expansion augmented by favourable tax, but limited by CO_2 supply
- CCS promises major new CO_2 supplies and is leading to offshore developments

CO_2 – oil miscibility

At microscopic scale, fully miscible CO_2 displaces nearly all oil in the rock

Oil remaining after water flooding typically occupies 20-35% of the pore volume

Miscible CO_2 releases nearly all of the remaining oil, typically leaving <10% pv

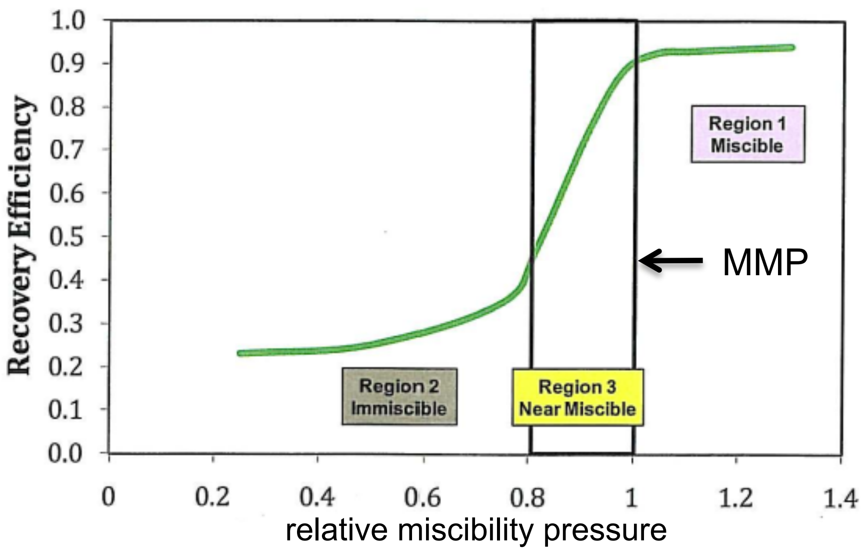
CO_2 displaces oil over a range of conditions, but above a certain threshold, recovery is nearly 100% of oil in the rock

This is the ***minimum miscibility pressure*** (MMP) for a given temperature and oil composition

Reservoir pressure may be increased to approach MMP and improve recovery

Near MMP, CO_2 is still very effective

Below MMP, immiscible displacement recovers much less oil



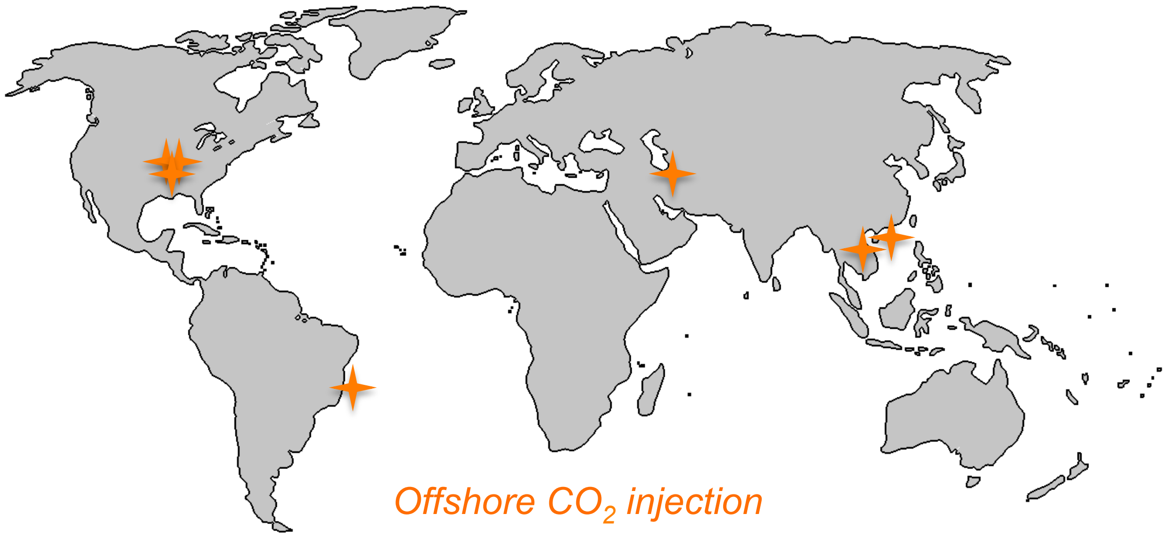
From ESPA and others, 2011

Nearly all CO_2 EOR is miscible

Moving CO_2 EOR offshore

CO_2 injection has been successfully conducted offshore in 12 projects, including:

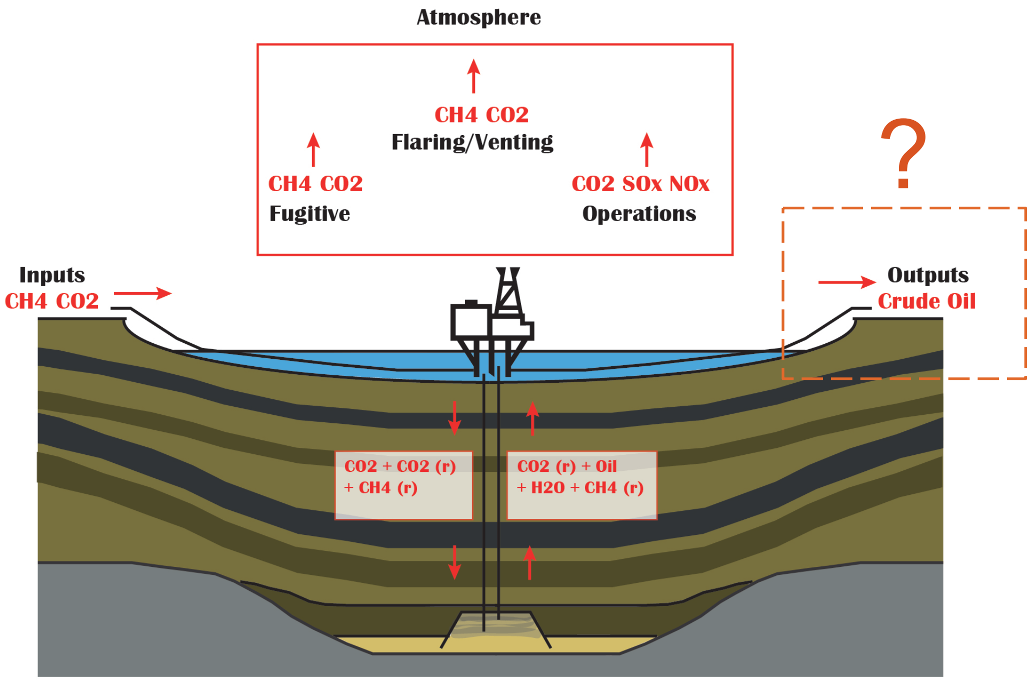
- Deep water, far offshore
- Large-scale injection
- Produced gas recycling
- Extended operation
- All limited by CO_2 supply



Lula Field, Brazil – 4-well pilot from 2011, injecting 520 tpd CO_2 separated from produced gas on FPSO; planned full-scale EOR with field development (Pizzaro & Branco, 2012)

CO_2 EOR carbon balance

Should emissions from oil produced in CO_2 EOR and storage projects be deducted from the CO_2 mass deemed to be stored?



after Stewart, 2013

Emissions are accounted at point of combustion for all other fossil fuel production

"Additionality" assumes that oil is consumed because it is produced

- Production is driven by demand, which declines slowly with increased price
- Global CO_2 EOR is insufficient to materially affect oil price

Oil revenues reduce overall CCS cost, accelerating deployment and large-scale emissions abatement

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