Electronic Supplementary Material (ESI) for Energy & Environmental Science.

Supplementary Information

Can CO_2 enhanced oil recovery catalyze gigatonne carbon capture and storage deployment?

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S1 MIICE MATLAB code

MIICE MATLAB script is attached.

S2 Model scoping and assumptions

S1 Model envelope

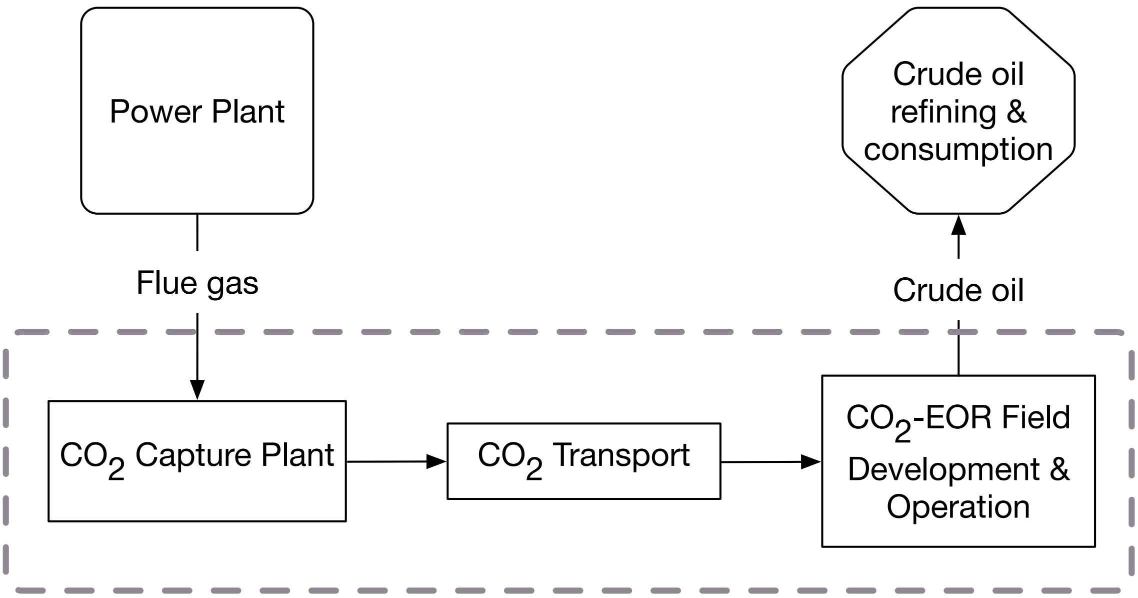

Figure S1: Conceptual representation of the CCS + CO_2-EOR model envelope (dotted line box) without considering physical flow streams

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S2 CCS and CO_2 enhanced oil recovery field development and cost modeling

S2.1 CO_2 capture cost in literature and model-based assumptions

Table S1: Real-time and literature-based capital cost values of amine-based CO_2 post-combustion capture plants coupled with supercritical pulverized coal fired plants adjusted to 1 $MtCO_2$ captured per year

Reference Source	Capital Cost Value (2016 US$/$MtCO_2$ captured)	Information & Assumptions
Boundary Dam CCS [S1]	$1.5 billion	Successfully deployed project, over-budget
Petra Nova Parish CCS [S2–S5]	$714 million	Successfully deployed project, on-budget
Rubin et al. Study [S6]	$326 million	Literature based study for new build power plants with CCS
Adjusted SRCCS study [S6]	$270 million	Literature based study conducted in 2005 [S7] for a new build power plant + CCS
Worley Parsons Report [S8]	$209 million	Literature based study for a new build power plant + CCS

Table S2: Operating costs for CO_2 capture as reported by Worley Parsons and adjusted to a $MtCO_2$ basis - all cost values adjusted to 2016 US$.

Parameter	Worley Parsons Report	Adjusted Calculations for this Study
Type of power plant considered	Pulverized coal firing	idem
Type of capture technology	Post-combustion amine scrubbing	idem
Net Power Output	546 MW	approx. 110 MW
Capture rate	90%	90%
CO_2 Captured	4.98 Mt/year	1 Mt/year
Power associated with capture plant	87 MW	17.5 MW
Cost of electricity consumed	$30.25 million/year	$6.07 million/year
Variable O&M	$4.53 million/MWh	$0.69 million/year
Fixed O&M	$11.41 million	$2.29 million

S2.2 CO_2 transport costs

Table S3: Capital and operating costs for transport pipelines from source to sink required for projects of 1- 4MtCO_2/year capture rates (M$ = $ million)

Cost type	Function of	1MtCO_2/year	2 - 3MtCO_2/year	>3MtCO_2/year
		Pipeline Capital Costs		
Materials	Diameter (D) & Length (L)	7.223 M$	11.115 M$	15.377 M$
Labor	D & L	28.209 M$	32.976 M$	36.672 M$
Miscellaneous	D& L	7.825 M$	11.287 M$	13.815 M$
Right of Way	D& L	2.976 M$	3.172 M$	3.1547 M$
CO_2 surge tank	Fixed	1.332 M$	idem	idem
Pipeline control system	Fixed	0.120 M$	idem	idem
Total Capital Costs		47.686 M$	60.003 M$	75.567 M$
		Pipeline Operating Costs		
Operating & Maintenance	L	0.561 M$	idem	idem
Total Operating Costs		0.561 M$/year	idem	idem

S2.3 EOR field model development and assumptions

Equation S1 is used to calculate the minimum miscibility pressure (MMP) required for CO_2 to be miscible with oil at injection. This is based on characteristic assumptions presented in Table S4.

$$MMP = 15.988 \times T(0.744206 + 0.0011038 \times MWC5) \tag{S1}$$

with
MMP: minimum miscibility pressure (psi)
T: reservoir temperature (Farenheit)
$MWC5$: molecular weight of pentanes & heavier fractions of oil

Table S4: Reservoir characteristics assumed and calculated in order to obtain fluid properties

Parameter	Value	Unit	Reference
Median reservoir depth	2026	m	[S9]
Pressure gradient	10.52	kPa/m	[S10]
Temperature gradient	30	°C/km	[S11]
Surface temperature	15	°C	Assumption of study
Reservoir pressure (P)	21.3	MPa	Calculated
Reservoir temperature (T)	75.8	°C	Calculated
CO_2 density at reservoir P & T	614.08	kg/m^3	[S12]
CO_2 viscosity at reservoir P& T	47.8	microPa.s	[S12]
CO_2 fluid phase	Supercritical		[S12]
Average reservoir oil gravity	37	API	[S9]
MWC5+	183.67	g/mol	[S13]
Average MMP	17.6	MPa	Calculated
Formation volume factor	1.3	m^3/m^3	Assumption of study

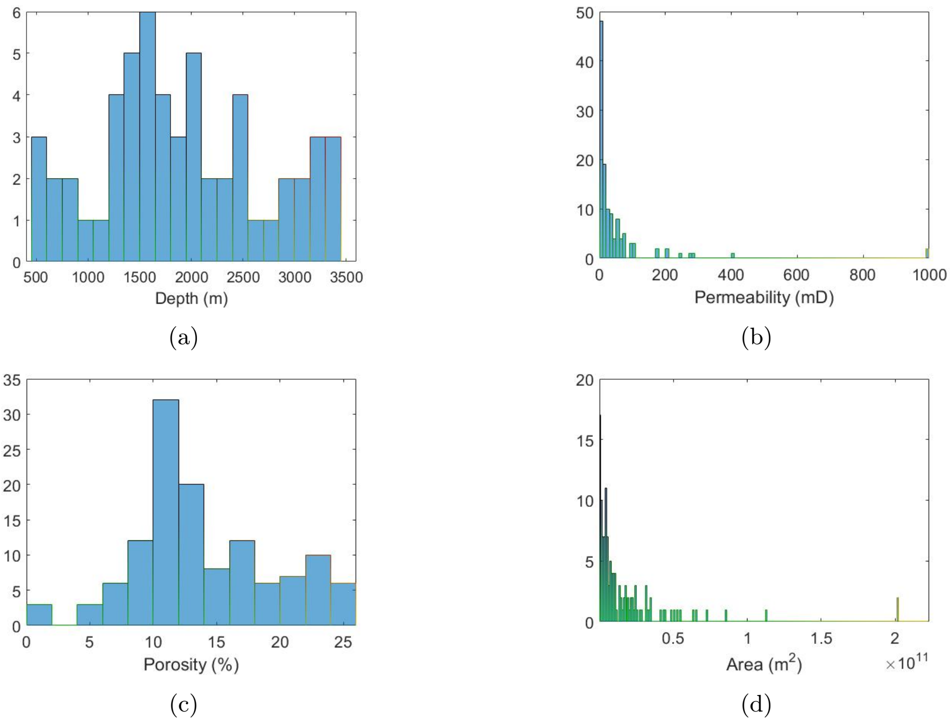


Figure S2: Distributions of reservoir characteristics including depth (m), porosity (%), permeability (mD) and field area (m^2) for oil fields with CO_2-EOR activity in the U.S. as well as Prudhoe Bay hydrocarbon miscible injection field based on Oil & Gas Journal 2014 Survey data.

S2.4 CO_2-EOR pattern deployment strategy description

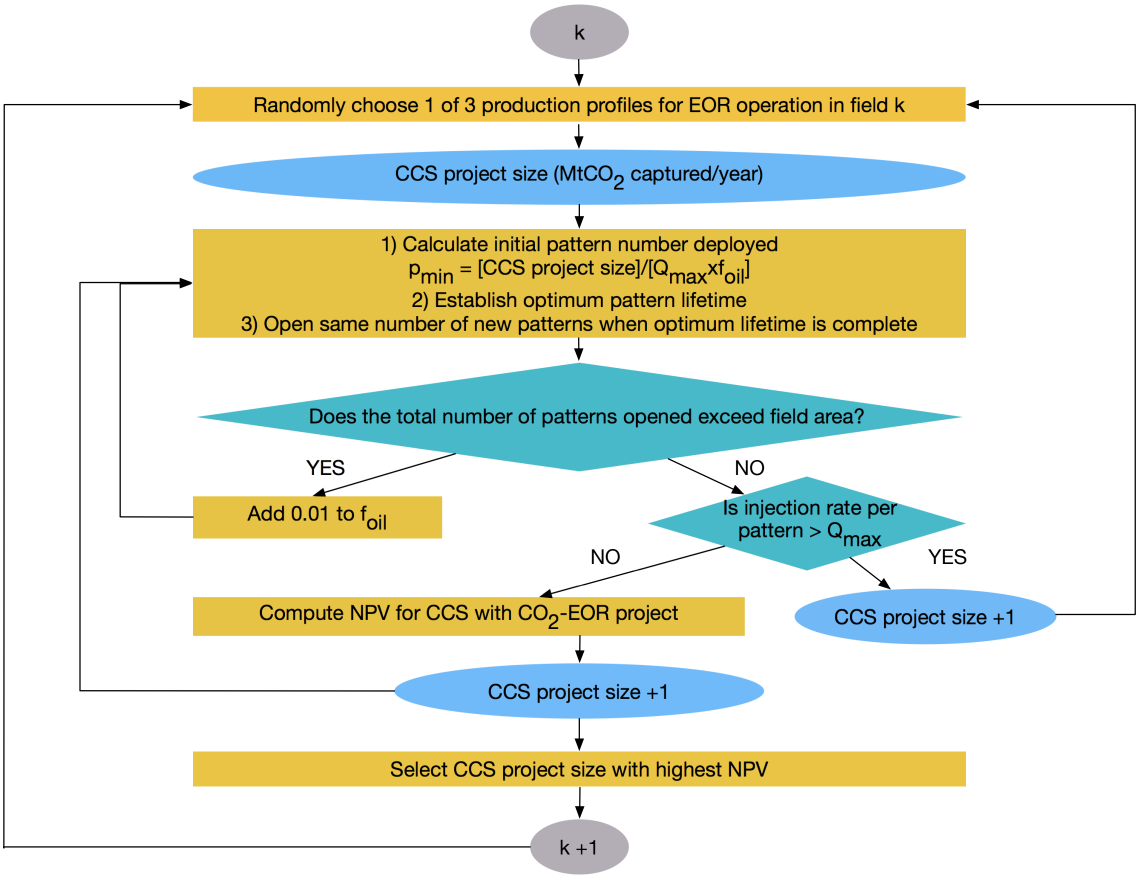


Figure S3: Flow diagram describing the decision strategy process for CO_2-EOR pattern deployment within a field k.

S2.5 EOR production profile fit parameters

Table S5: Parameters of logistic and exponential equations of curve fits for production profiles of oil and CO_2 as a percentage of OOIP and HCPV respectively

Oil production fit	d	a	b	c	RMSE/R-Square
Low	0.0	0.105	9.813	0.4213	0.001414/0.9977
Medium	0.01	0.1774	4.86	0.447	0.002853/0.9954
High	0.09	0.3818	3.449	0.3415	
CO_2 production fit	d'	a'	b'	c'	RMSE/R-Square
Low	0.33	0.3155	0.8515	0.1492	0.01481/0.9751
Medium	0.4	0.6357	0.9292	0.5785	0.009409/0.997
High	0.4792	1.276	0.9086	1.078	

S3 Cost inflation factors

Table S6: Inflation factors used to convert US$ costs from literature to constant 2016 US$ based on the Bureau of Labor Statistics Consumer Price Index inflation calculator[S14].

Year of cost reported	Inflation factor to 2016 US$
2004	1.270
2010	1.100
2013	1.030
2014	1.017

S4 Compound annual growth rates

A compound annual growth rate (CAGR) is used to compare results of cumulative CCS capacity deployed by 2050 and cumulative oil production rates to both industries' growth rate predictions. The CAGR describes a rate at which an industry would need to grow by every year, if this were at a steady rate, to achieve a final industry objective size. These rates are calculated against values of oil production from CO_2-EOR in the US, which was at 156.95 MMbbl/year in 2015 [S15] and the global value for CO_2 captured in 2016 of 27 $MtCO_2$/year [S16].

S5 Slow and fast industry growth scenarios

In a slow deployment scenario, we assume that the 5-year demonstration period is followed by a growth to materiality of 20% per year (lower than the exponential growth assumed), followed by a stagnated growth of 3% per year based on a low carbon technology study by Napp et al. [S17]. Meanwhile, a much faster industry growth scenario considers that the first 5 years of project initiation has an upper bound of 2^{year} project investments. In the 10 years that follow, the number of projects that can be built is limited by a 40% growth rate year on year. The 10 years that follow see a slower allowable growth rate as momentum is reduced to a 20% growth rate and the 10 years that follow are limited by a 10% yearly growth rate.

S3 Results

S1 Five world scenarios

S1.1 Cumulative CO_2 stored and oil produced

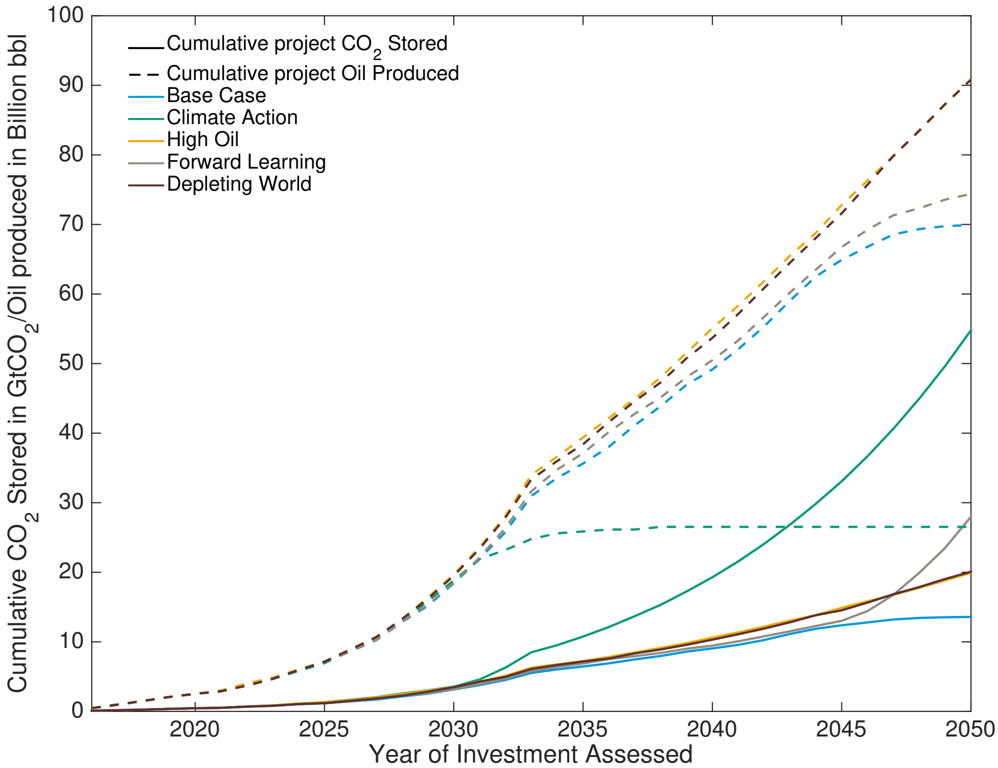


Figure S4: Graph showing cumulative CO_2 stored and oil produced as a result of successful projects obtained in each of the Five World Scenarios

S1.2 Average field characteristics of successful projects

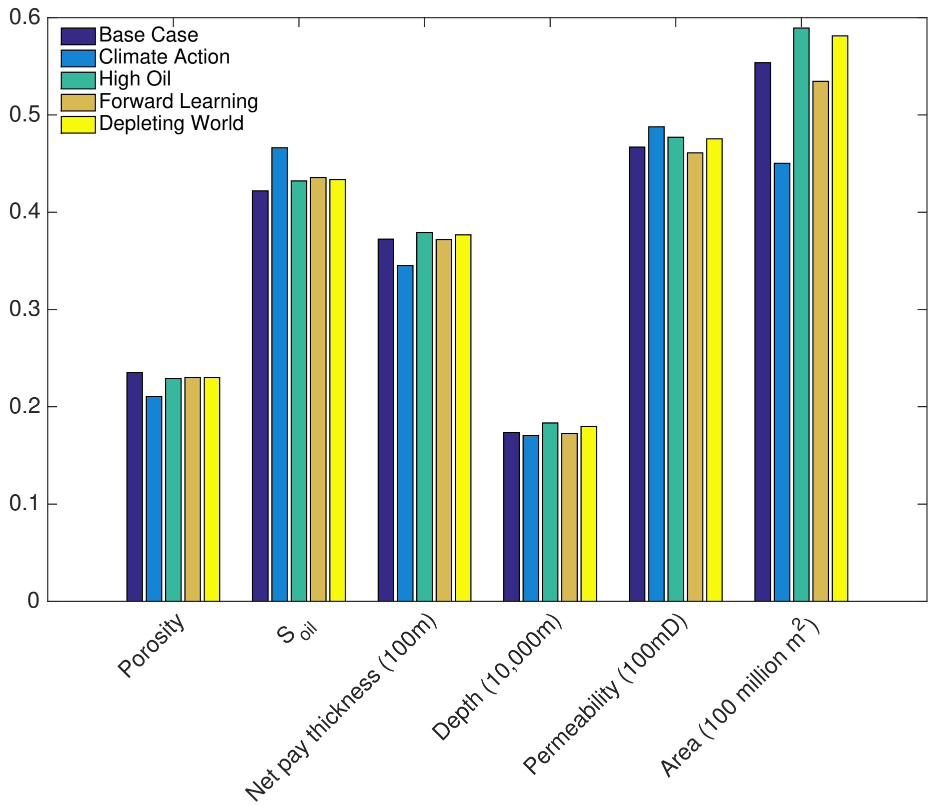
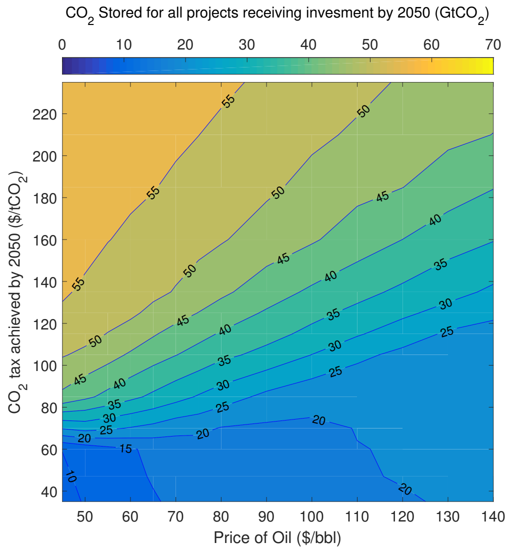
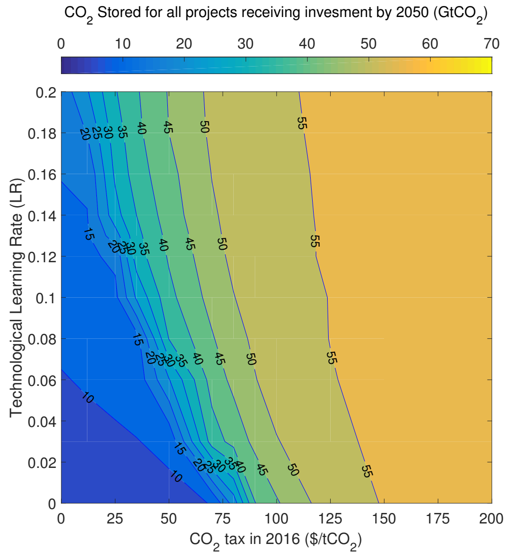


Figure S5: Bar chart showing the total average field characteristics for all successful projects resulting from each of the five world scenarios from the pool of 1000 fields

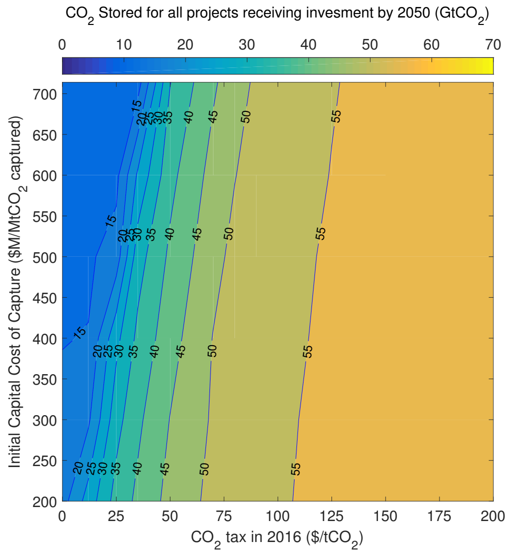
S2 Heat maps showing sensitivity of CO_2 storage and oil production to 2-D variation in CO_2 tax, oil price, technological learning and initial capital cost of capture



(a)



(b)



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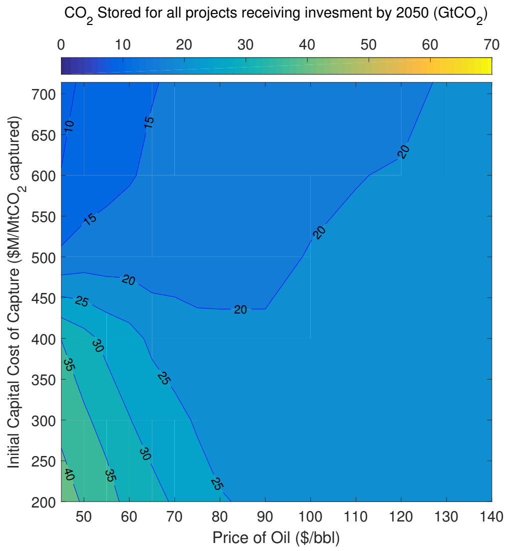

(d)

Figure S6: Heat maps showing contours of CO_2 storage achieved for all invested CCS with CO_2-EOR projects by 2050 as a function of (a) the CO_2 tax achieved by 2050 and the price of oil, (b) the CO_2 tax in 2016 and the amount of technological learning assumed, (c) the price of oil and the initial capital cost of capture assumed per $MtCO_2$ capture capacity in 2016, and (d) the price of oil and the initial capital cost of capture assumed per $MtCO_2$ capture capacity in 2016.

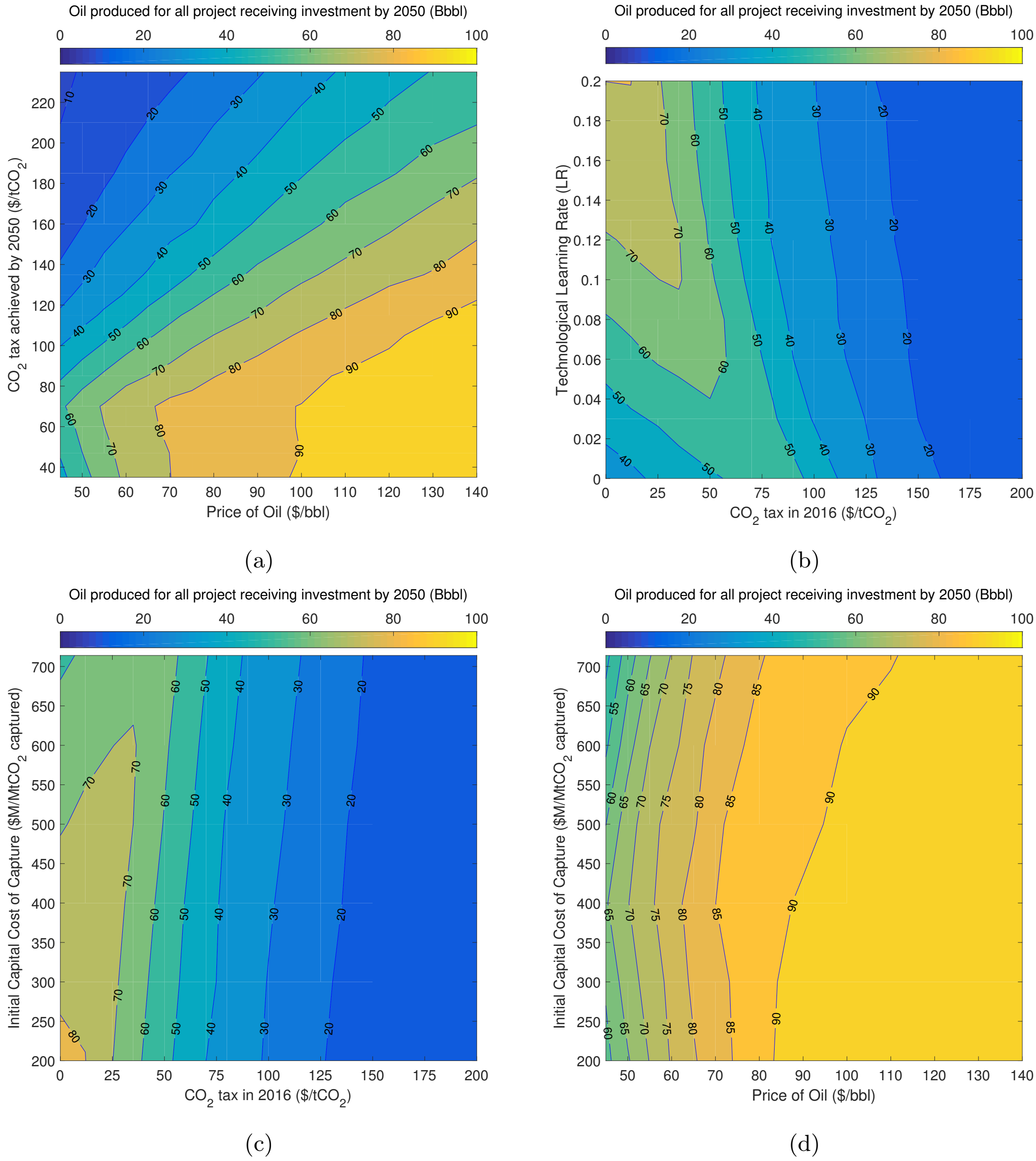

Figure S7: Heat maps showing contours of oil production for all invested CCS with CO_2-EOR projects by 2050 as a function of (a) the CO_2 tax achieved by 2050 and the price of oil, (b) the CO_2 tax in 2016 and the amount of technological learning assumed, (c) the price of oil and the initial capital cost of capture assumed per $MtCO_2$ capture capacity in 2016, and (d) the price of oil and the initial capital cost of capture assumed per $MtCO_2$ capture capacity in 2016.

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