Supplementary Information for "Techno-Socio-Economic Analysis of Geological Carbon Sequestration Opportunities"

Rania Faruq Suleman Kali[a], Dian Fan[a,b], Nick Hazel[a], Alberto Striolo[a,c]

[a]Department of Chemical Engineering, University College London, London, UK
[b]School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, 518055, PR China
[c]School of Chemical, Biological and Materials Engineering, University of Oklahoma, Norman, OK 73019, USA

Here we present a nomenclature for the parameters discussed in our analysis, detailed calculations for capital costs (CaPEX) in Table S1-S5, operational costs (OpPEX) in Table S6, Capture costs in Table S7.

Nomenclature

Symbol	Definition	Unit
A	Reservoir area	(m^2)
Th	Producing interval thickness	(m)
φ	Average reservoir porosity	(%)
ρ_{CO2}	Density of CO_2	(kg/m^3)
$(1-S_w)$	Oil saturation	(%)
S_w	Initial reservoir water saturation	(%)
B	Gas formation volume factor	(Rm^3/Sm^3)
G	Volumetric capacity	(m^3)
Q	Mass capacity	(tonne)
P_{sc}	Pressure at the standard condition	(kPa)
T_{sc}	Temperature at the standard condition	(K)
z	Compressibility factor	(m^3/m^3)
P	Reservoir pressure	(bar)
T	Reservoir temperature	(°C)
E	Rate of injectivity	(tonne/yr)
R_t	Annual Revenue	($/yr)
In	Annual income	($/yr)
N	Number of wells	
NPV	Net Present Value	($)
i	Discount factor	
I_t	Annual investment	($/yr)
t_{max}	Time to reach CO_2 capacity	(yr)

Capital Costs (CaPEX)

Table S1: Capital costs related to geological sites surveys and preparation. Historical data shows that the average capacity of one oil well is 1.26 Bcf = 35700000 m3. Using this information, the number of wells theoretically required for each site was calculated.

Activity	Cantarell	Frigg	Rio Vista
Seismic History			
Obtain historical seismic data in order to prevent any further risks. ***Assuming:*** Collation of seismic data is carried out by geologists which would take 60 hours, paid at the average hourly rate of each country in 2020.	60 hours × $120 per hour [117] = $7,200	60 hours × $143.50 per hour [118] = $8,610	60 hours × $144.51 per hour [119] = $8,670
Geochemical Analysis			
Analyse the chemical interaction between the water-rock-CO_2 complexes. In some rocks, injection of CO_2 can lead to the production of carbonic acid and heavy metals which is undesirable. ***Assuming:*** Testing takes an average of 10 days (240 hours) carried out by geologists payed at the average hourly salary rate of each country.	240 hours × $120 per hour [117] = $28,800	240 hours × $143.50 per hour [118] = $34,440	240 hours × $144.51 per hour [119] = $34,682
Obtaining existing data			
Assuming: The field having been used before has been thoroughly analysed, therefore formation data including porosity, thickness and permeability is readily available, initial land surveys and maps and maximum pressures for injection.	No cost	No cost	No cost
Prior Modelling			
Predictions for CO_2 flow and migration will be required. Therefore, a simulation based on subsurface flow of CO_2 within the reservoir must be carried out for the next 100 years. ***Assuming:*** The modelling takes about a week to complete, by a group of engineers currently paid at the hourly rate estimated for each country.	168 hours × $143.50 per hour [120] = $7,308	168 hours × $153.50 per hour [121] = $8,988	168 hours × $155.50 per hour [122] = $9,324
Survey for old wells			

In case some old wells have not been accounted for in databases, aeromagnetic survey of well casing is carried out. If new wells are identified an addition ground inspection is carried out. ***Assuming:*** Costs are dependent on the size of the land to be surveyed, literature provides typical costs for magnetic surveys are \$1132.25 per km^2 for collection of data, processing, mapping and analysis [123].	\$1132.25 per km^2 × 162 km^2 = \$183,384	\$1132.25 per km^2 × 115 km^2 = \$130,180	\$1132.25 per km^2 × 120 km^2 = \$135,840
Evaluate integrity of old wells			
It is possible for old wells to degrade; therefore, it is necessary to evaluate for integrity via cement bond logs, casing mechanical tests to ensure the wellbore can withstand required pressures, if pressure fall outs occurred this identifies potential leakage that must be identified. ***Assuming:*** Estimates for cement bond logs and mechanical well testing is based on the depth of the well. Literature values for median estimates provide on average \$4.10 per metre [124][125].	\$4.10per metre ×2300m = \$9,432.41 per well \$9,432.41 per well × 30 wells = \$282,972.44	\$4.10per metre ×1900m= \$7,791.99 per well \$7,791.99 per well × 24 wells =\$187,007.76	\$4.10per metre ×1676m= \$6,873.36 per well \$6,873.36 per well × 20 wells = \$137,467.19
Total	\$509,664.30	\$369,225.76	\$394,716.80

Table S2: Capital costs for new wells construction.

Field	Cantarell	Frigg	Rio Vista
Total field volume capacity (m^3)	1.28×10^9	1.13×10^9	1.44×10^9
Total number of wells required*	45	39	50
Number of old wells from literature	30	24	30
Number of new wells required	15	15	20

<table>
<tr><th>Activity</th><th></th><th>Cantarell</th><th>Frigg</th><th>Rio Vista</th></tr>
<tr><td colspan="5">Drilling Cost</td></tr>
<tr><td rowspan="7">Drilling contributes to a large proportion of the total costs, it depends on many factors such as the depth of the well required, rock type, location of drilling and equipment implemented. Parameters including depth, design, bit type and requirements of the well are taken into consideration by implementation of the following equation
$C_d = C_b + C_r \times (t_t + t_r)$
where:
C_d=drilling cost per well ($)
C_b=bit cost ($)
C_r=rental costs per hour ($day^{-1})
t_t= trip time (day)
t_r=time spent at drilling operation (day)
D=depth of well (m)
C_t=total drilling cost for all new wells in the field

Assuming:
C_b PDC (polycrystalline diamond compact) drill bit is implemented as past projects have chosen an increase in rate of penetration and reduced drilling time [126].
Cantarell, Frigg and Rio Vista existing wells initially implemented 14 in [123], 16 in [123] and 8 in [123] drill bits corresponding bit price is found from literature data.
C_r= the daily cost for rigs offshore is much costlier than land.
t_t= the time to pull and run the drill which is dependent on well depth, rig capacity and crew efficiency. Will be estimated by literature data for optimum rotary speeds and well depth [128].
t_r= drilling time to reach the required well depth is</td><td>C_b</td><td>$31,000 [126]</td><td>$45,000 [126]</td><td>$15,250 [126]</td></tr>
<tr><td>C_r</td><td>$35,000 [127]</td><td>$35,000 [127]</td><td>$15,000 [127]</td></tr>
<tr><td>t_t</td><td>16 [128]</td><td>11.5[128]</td><td>14[128]</td></tr>
<tr><td>t_r</td><td>144[128]</td><td>92.5[128]</td><td>60.5 [128]</td></tr>
<tr><td>D</td><td>2300 [123]</td><td>1900 [129]</td><td>1676 [130]</td></tr>
<tr><td>C_d</td><td>$4,581,000</td><td>$3,685,000</td><td>$1,132,750</td></tr>
<tr><td>C_t</td><td>$27,486,000</td><td>$29,480,000</td><td>$11,327,500</td></tr>
</table>

found using literature data for PDC drills implementing optimum rotary speeds and well depth to achieved the most efficient drilling possible [128]. Drilling of vertical wells are 2.5 times [131] less costly than horizontal wells, for estimation in this study it is assumed all wells to be drilled are vertical.				
Corrosion resistant casing and tubing				
The injection of water and CO_2 gas into the wells can induce the formation of carbonic acid, this is highly corrosive. Therefore, elastomeric material which is resistant to the solvent effects of supercritical CO_2 must be implemented to increase the lifespan of wells [72]. ***Assuming:*** Properties and condition of the wells is the same for all three fields. The cost per metre for corrosion resistant tubing and casing based on the Society of Petroleum Engineers study is $9.35 per metre [132].		$9.35 per m ×2300m = $21,505 per well $21,505 per well × 6 = $129,030	$9.35 per m ×1900m = $17,765 $17,765 × 8 wells = $142,120	$9.35 per m ×1676m = $15,670 $15,670 × 10 wells = $156,700
Cementing of well length				
Portland cement is insufficient in assuring the integrity of the wells. The degradation of cement by supercritical carbon dioxide is thermodynamically favoured, the cementing must be amended to impede this. Therefore, the injection wells will be cemented with corrosion resistant cement reinforced with composites such as latex. ***Assuming:*** The cost for cementing a well is outlined by Petroleum Service Association of Canada as $6.78 per metre [133] To account for resistant cement an estimated addition of 25% will be added to the costs. Therefore $8.47 per metre.		$8.47 ×2300 m = $19,481 $19,481× 6 = $116,886	$8.47×1900m = $16,093 $16,093 × 8 wells = $128,744	$8.47×1676m = $14,195 $14,195× 10 wells = $141,957
Total for field		$27,731,916	$29,750,864	$11,626,150

Table S3: Capital costs related to the remediation of existing wells.

Activity	**Cantarell**	**Frigg**	**Rio Vista**
Re-cementing of well			
As outlined above, degradation of wells exposed to CO_2 has occurred at the SACROC oil field. Mitigation includes implementing a portion on non-affected filler such as silica in place of Portland cement, decreasing the cement water ratio to decrease its permeability and further decreasing permeability by addition of materials like latex. ***Assuming:*** The cost for cementing a well is outlined by Petroleum Service Association of Canada as $3.78 per metre [133] To account for resistant cement an estimated addition of 25% will be added to the costs. Therefore $4.73 per metre.	$4.73 × 2300 m = $10,879 $10,879 per well × 30 wells = $326,370	$4.73 × 1900 m = $8,987 $8,987 × per well as 24 wells = $215,688	$4.73 × 1676 m = $7,927 $7,927× 30 wells = $237,810
Plugging old wells			
Old wells which are identified in surveys as a risk to cause a leakage of CO_2 from the reservoir must be plugged. This involves removing any obstructing materials, disinfecting wells and filling wells with plugging material. ***Assuming:*** Based on the Petroleum Service associated of Canada the average cost for plugging is $13,000, follow up logging is $11,000 and cleaning out is $30,000[133]. Estimating 10% of the old wells will be malfunctioning.	$54,000 × 3 = $162,000	$54,000 × 2.4 = $129,600	$54,000 × 3 = $162,000
Total for field	$1,946,370	$1,511,688	$1,857,810

Table S4: Capital costs related to the purchase of injection equipment.

Activity	**Cantarell**	**Frigg**	**Rio Vista**
Pumps			
Pumps are required to move the CO_2 from the pipeline to the injector. Costs depend on horsepower and installing electrical provision. ***Assuming:*** Flowrate requirements for all three sites are of the same order of magnitude and the pressure and temperatures are within a similar range. Therefore, pumping cost will be estimated using fixed data from literature values from previous projects. [134]	\$3,500,000	\$3,500,000	\$3,500,000
Injection wellhead			
Injection equipment is a dependant on its capacity, it consists of a lubricator and a series of valves. ***Assuming:*** Based on Petroleum Service Associated of Canada [131] [135] well cost study the cost of a wellhead is given as fixed estimate per well as \$500.	\$500 × 45 = \$18,000	\$500 × 39 = \$16,000	\$500 × 50 = \$20,000
Pipeline equipment			
Pipeline transport is required between the point source and the site of storage as well as the internal pipeline requirements within the field. ***Assuming:*** Pipeline cost estimates from oil and gas journal state the cost per \$35,000/km. It will be assumed around 50 km of pipeline required immediately on site.	\$35,000 × (171.9 km + 50 km) = \$7,766,500	\$35,000 × (303 km +50 km) = \$12,355,000	\$35,000 × 93 km = \$3,255,000
	\$11,289,000	\$15,874,500	\$6780,000

Table S5: Post-injection capital costs.

Activity	**Cantarell**	**Frigg**	**Rio Vista**
Plugging Wells			
Assuming: Plugging wells, cost estimates are provided from Petroleum Service Associated of Canada plugging is $13,000, logging is $11,000 and cleaning out with chemical buffers is $30,000 [133].	$32,400 × 36 wells = $1,944,000	$54,000 × 32 wells = $1,728,000	$54,000 × 40 wells = $2,160,000
Assuming: Removing surface equipment including injection equipment and pumps. Data taken as an average for all decommissioning fields provided by Resilience [135].	$600	$15,000	$15,000
Post injection monitoring			
Assuming: Monitoring of wells, seismic surveys and oil and soil surveys in case of potential leakages. The US Energy Administration have averages monitoring of abandoned oil wells at $10,000 a year. Estimate costing for monitoring for 5 years [136]. Taking 5 years for post injection operations to complete.	$6,000 per year × 5 years = $50,000	$10,000 per year × 5 years = $50,000	$10,000 per year × 5 years = $50,000
	$2,981,200	$4,426,000	$5,530,000

Operational Costs (OpEX)

Table S6: Operation and maintenance costs per year

Activity	**Cantarell**	**Frigg**	**Rio Vista**
Engineering labour			
Costs for the labour required to operate the system and maintenance of the equipment. ***Assuming;*** The labour cost is estimated to be the same by the US Environmental Protection Agency as $125,000 per well each year [134]. Labour costs in Mexico are estimated to be 60% less comparative to the US [137].	$125,000 × 0.4 × 36 wells = $2,700,000	$125,000 × 32 wells = $4,000,000	$125,000 × 40 wells = $5,000,000
Injection monitoring (flowrate, pressure.)			
Pressure and temperature monitor of CO_2 into the well in the casing and tubing. Chemical tracers are implemented in the CO_2 stream for monitoring. ***Assuming:*** This is approximated to be $2,500 per well each year by the US Environmental Protection Agency [125].	$12,500 × 0.4 × 36 wells = $180,000	$12,500 × 32 wells = $400,000	$12,500 × 40 wells = $500,000
Corrosion detection and prevention			
Due to the readiness of CO_2 to form an acid a programme must be set in place to monitor for corrosion. ***Assuming:*** Work can be completed by engineers in 24 hours at the average rate for each country.	24 hours × $143.50 per hour [120]= $3,344	24 hours × $153.50 per hour [121]= $3,684	24 hours × $155.50 per hour [122]= $3,732
Maintenance and monitoring of wells			
This includes integrity pressure testing, periodic testing by inducing high pressure to the annulus between the casing and tubing, wells which fail the test must be reworked or plugged, ***Assuming:*** Testing is estimated at $4,000 per well per year by the US Environmental Protection Agency [125].	$20,000 × 36 wells = $720,000	$20,000× 32wells = $640,000	$20,000 × 40 wells = $800,000
Leakage testing with radioactive material injected into the well, gamma ray detection will indicate if there is any leakage through the well material. ***Assuming:*** The average cost per test has been approximated by the US Environmental Protection Agency $5,000 per year [125].	$25,000 × 36 wells = $900,000	$25,000 × 32 wells = $800,000	$25,000 × 40 wells = $1,000,000
Consistent cement bond logs must be taken for all wells to detect deterioration in the wall, ***Assuming:*** Which is estimated in literature per year at $2.78m^{-1}$ [124]	$2.78m^{-1}$ × 2300m = $6,394 per well $6,394 × 36 wells = $230,184	$2.78m^{-1}$ ×1900m = $5,282 per well $5,282 × 32 = $169,024	$2.78m^{-1}$ ×1676m = $4,659 per well $4,659 × 40 = $186,360
Pressure falloff tests where the well shut in and the decline in pressure measured. This provides pressure data of the	$10,000 × 0.4 × 36 wells =	$10,000× 32 wells =	$10,000 × 40 wells =

reservoir and of the final condition of the well. This is estimated at $2000 per pressure test per well by the US Environmental Protection Agency per year [125]. ***Assuming:*** Labour costs in Mexico are estimated to be 60% less comparative to the US [137].	$216,000	$320,000	$400,000
Seismic Survey			
Injection could cause faults and fractures in the geological structure. Commonly 4D seismic monitoring is implemented, surveys are carried out periodically in time. From literature the cost is dependent on the area of land that is to be surveyed. ***Assuming:*** On average the cost of a surveying 1km^2 area (data from the current year 2020) is $30,000[138].	$30,000 × 162km^2= $4,860,000	$30,000 × 115km^2= $3,450,000	$30,000 × 120km^2= $3,600,000
	$10,285,713	$13,120,368	$15,653,460

Capture costs

Table S7: Carbon capture from site and transportation to sequestration site costs

Activity	**Cantarell**	**Frigg**	**Rio Vista**
Capture and transportation costs			
Assuming; Capture and transportation costs are the main contribution to the CCS project. It is evaluated as 80% of the total CCS costs [94].	$34,943,954.52	$31,731,275.90	$15,848,461.12