Techno-Economic Modeling of Dual-Purpose LNG LCO_2 Shipping

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Outline

- Motivation
- Proposed Model to exploit CO_2 as a commodity feedstock & optimize shipping
- Techno-Economic Analysis
- Results & Opportunities
- Conclusions

Motivation

- ~ 37 Gt CO_2 emitted globally per year
- Decarbonization is a necessity; however CO_2 is viewed as a waste product and not a commodity
- In the absence of utilization, CO_2 removal will be a cost center
- Transportation is a significant part of the current cost structure; source-use matching is not optimized

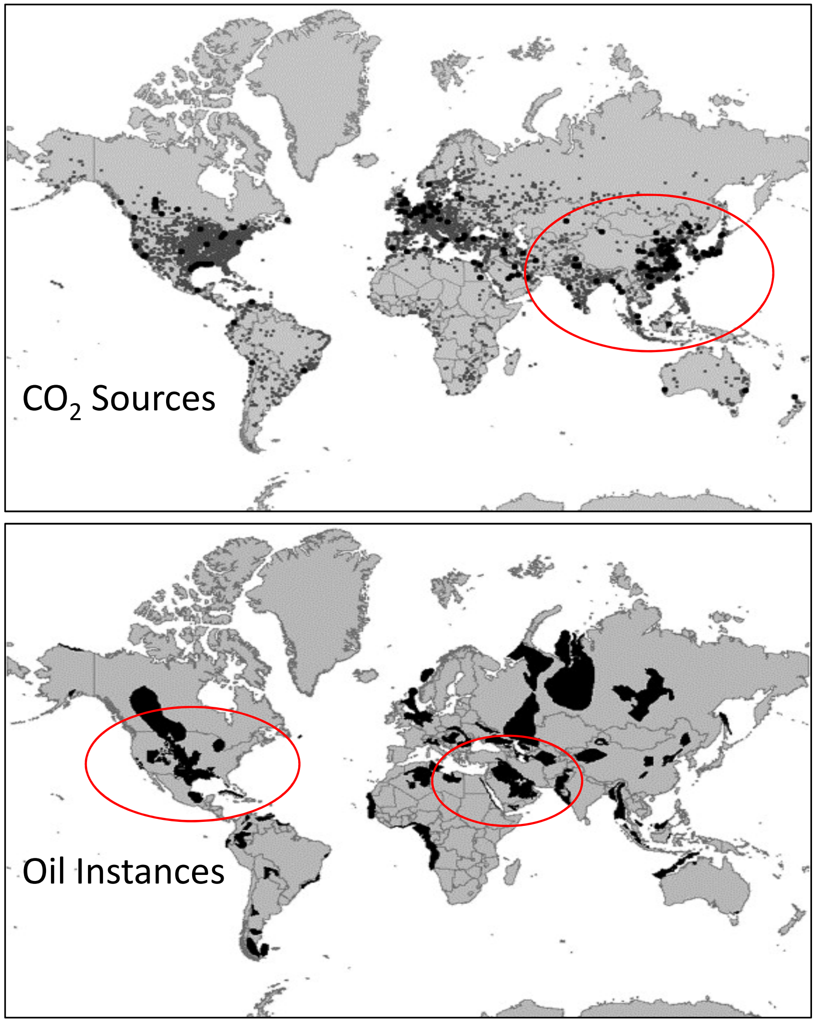


Figure from ref. 1

Ref.
1. Damen, K., et al. (2005). "Identification of early opportunities for CO2 sequestration—worldwide screening for CO2-EOR and CO2-ECBM projects." Energy **30**(10): 1931-1952.

Global LNG Trade

- 317 MM t of LNG traded globally in 2018
- 525 LNG carriers; ~ 5,100 voyages in 2018
- Substantial and continued growth

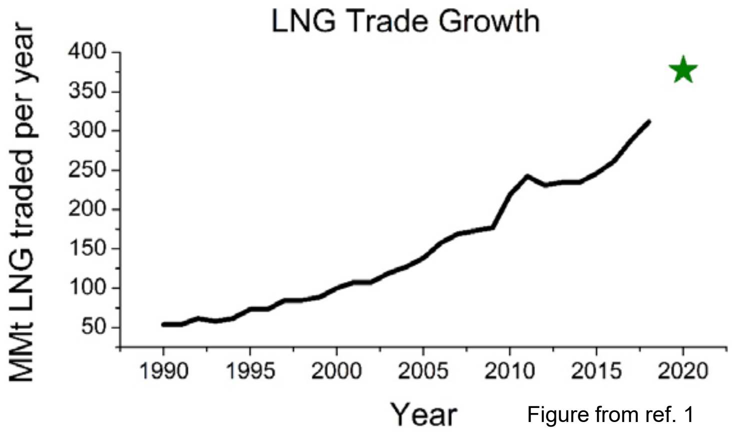
  ~10% in LNG trade & carriers
- Matching with EOR:

  -North Sea and US have suitable oil fields

  -Japan and South Korea have carbon credits
- US 45Q is incentive for use or storage of CO_2

Exporters of LNG	Amount (MM t)
Qatar	79
Australia	69
Malaysia	25
US	22

Importers of LNG	Amount (MM t)
Japan	83
China	55
South Korea	45
India	23



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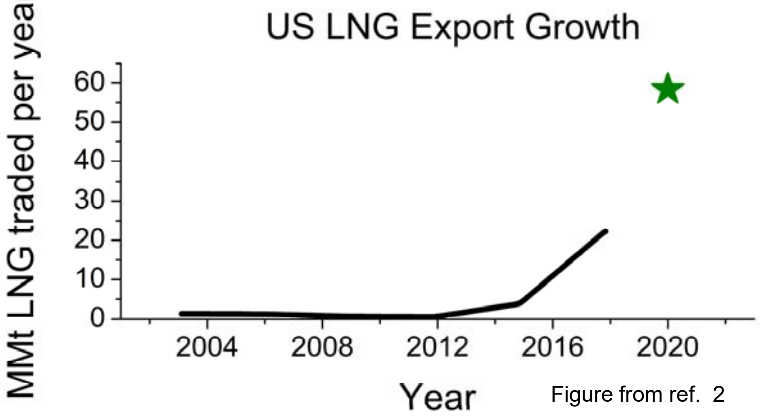


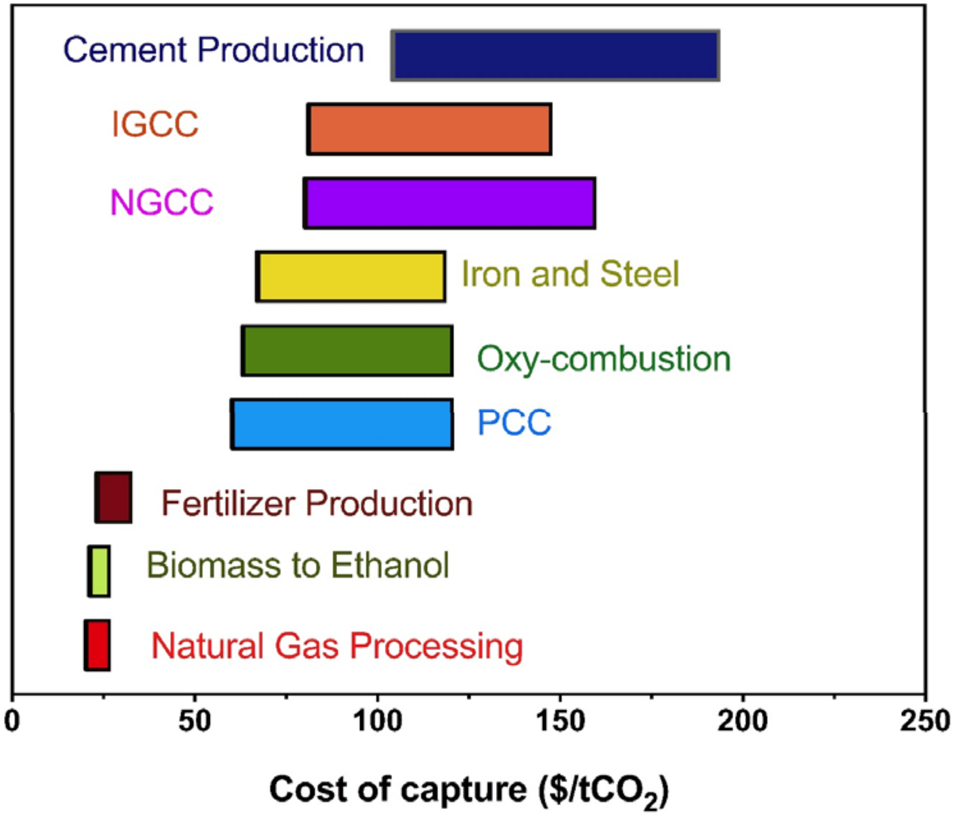
Figure from ref. 2

Ref
1. 2019 World LNG Report, IGU
2. Energy Information Administration (2019)

CO_2 Value Addition

- CO_2 capture costs range from \$20-200 /tCO_2
- Additional cost for transport, conversion & sequestration
- Potential Value Addition: CO_2 for EOR

  ~1 - 4 Barrels of oil per tCO_2
  ~\$65 - \$260/tCO_2
- CO_2 to Chemicals/Fuels
  - Economically feasible if energy is free or hydrogen is readily available



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Ref.

1. Gibbins, J. and H. Chalmers (2008). "Carbon capture and storage." Energy Policy 36(12): 4317-4322.
2. Datta, A., et al., *Advancing Carbon Management through the Global Commoditization of CO_2 – The case for Dual-use LNG-CO_2 Shipping,* under review

Transport Costs

- Pipelines are advantageous for short distances; not for long distance source to use matching
- Extrapolation of exclusive transport costs to 17,000km is ~\$62/tCO_2
- LNG ships returning empty present opportunity to cut CO_2 transport costs
- Combined with CO_2 based EOR, a potentially compelling economic argument can be made

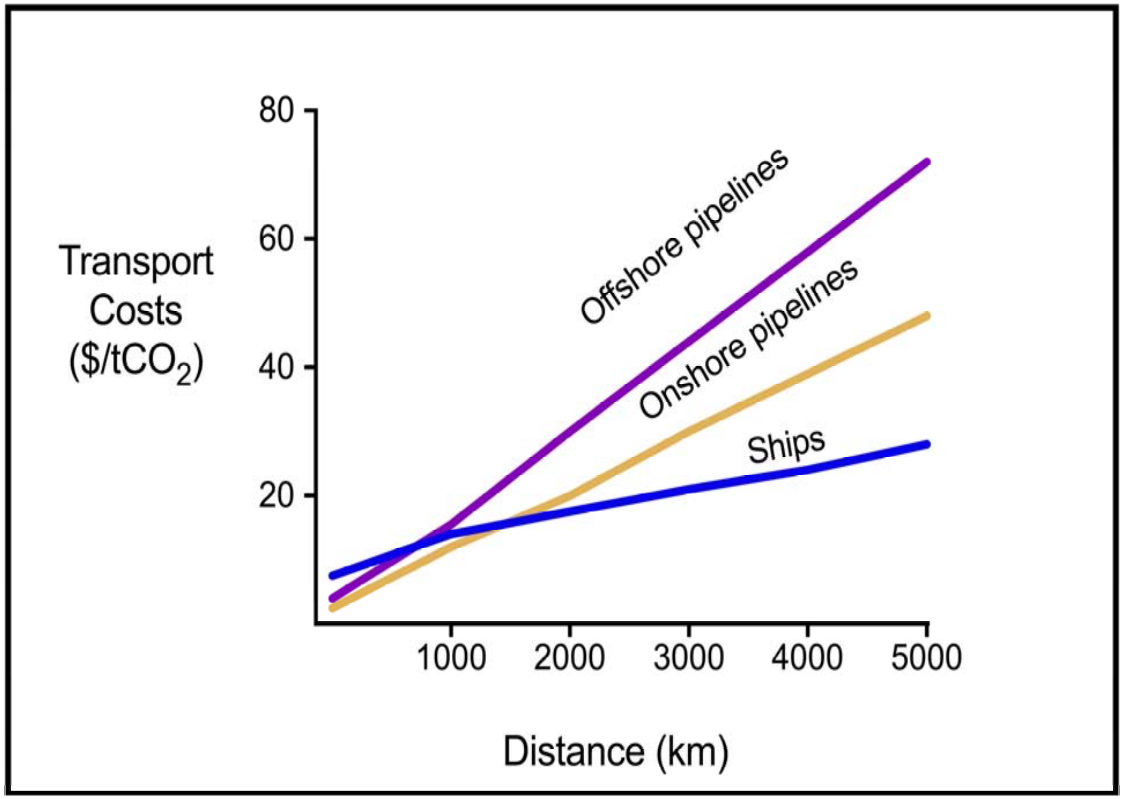


Figure from ref. 1

Ref.
1. Global CCS Institute

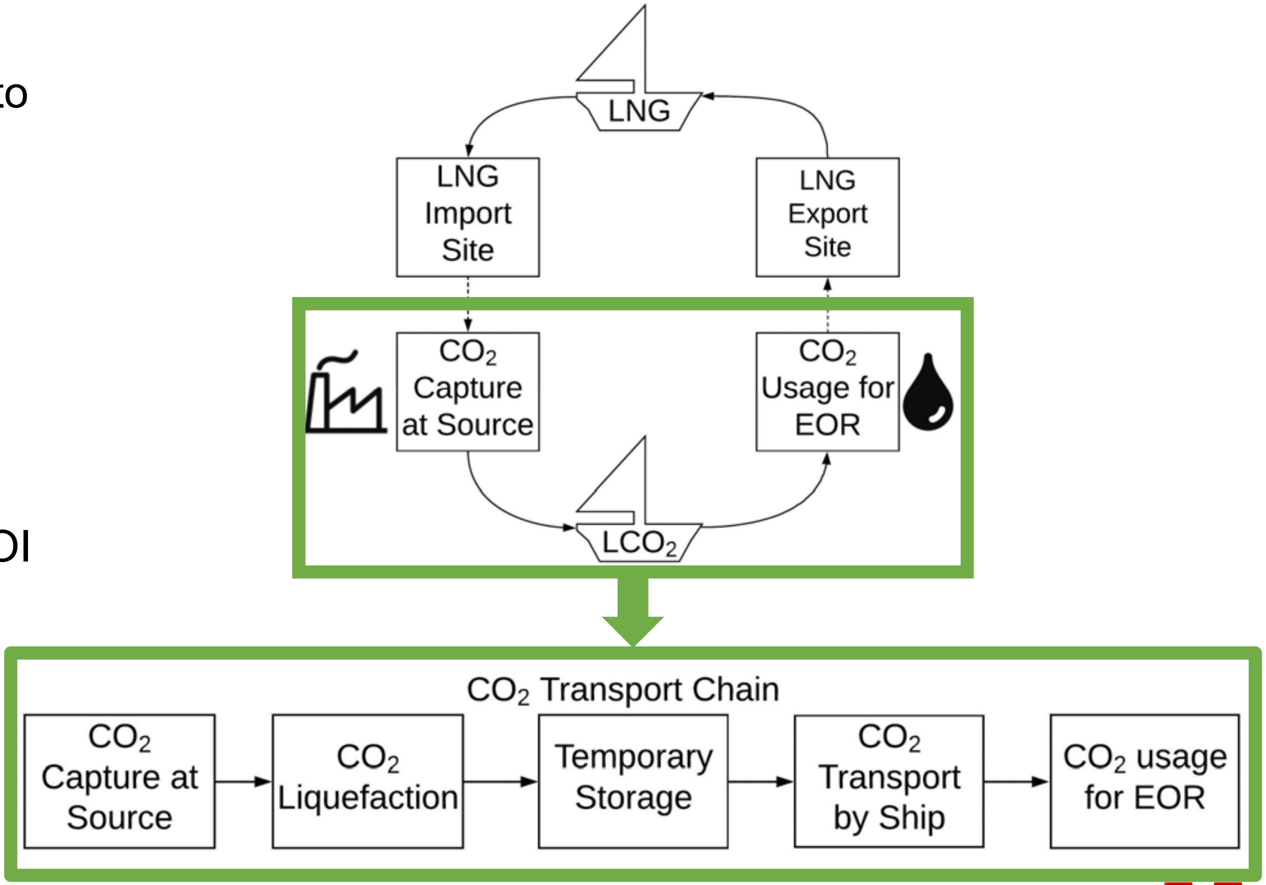
Proposed Process

- LNG ship w/o cargo on return journey
- Empty ship travels from South Korea to Gulf of Mexico (Texas)

- Capture of CO_2 in South Korea
- Transport to GoM
- Use CO_2 in GoM for EOR

- Utilize US and Korean incentives
- Technoeconomic model to quantify ROI

- Existing CO_2 tanker ships
  -Anthony Veder (Dutch): 1 Ship 1250m^3
  -IM Skaugen (Norwegian): six 10,000m^3
  -Normal cargo is LPG (-48^{o}C, 1 bar)



Material Comparison

- Refrigeration requirements
- Pressurization
- Density
- Flammability

- Contaminant Challenges:

CO_2 - Hydrate formation @ -50 °C and 7 bar with water<100 ppm

Corrosiveness of water contamination

	LNG	**CO_2**
Temperature (°C)	-163	-50
Pressure (bar)	1	7
Viscosity (cp)	0.2	0.19
Density (kg/m^3)	470	1152

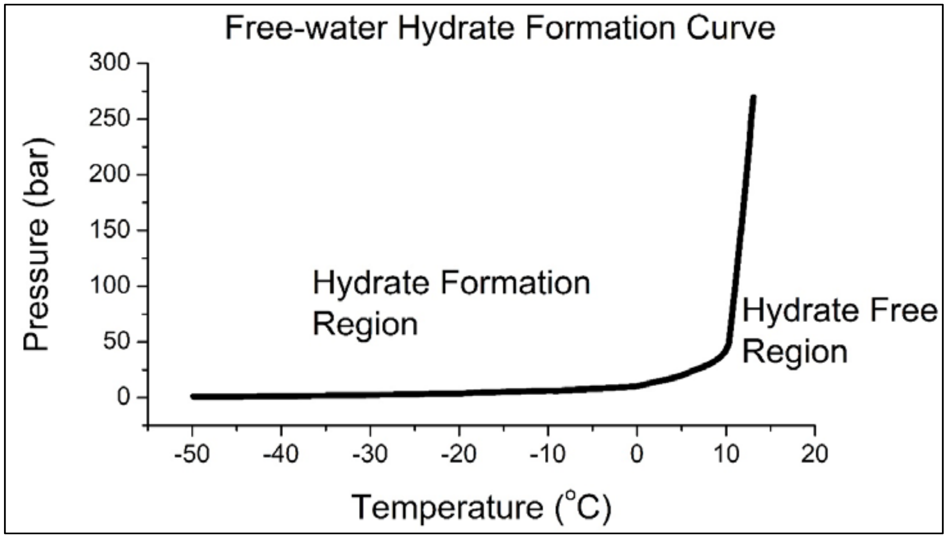


Figure from ref. 1

Ref.
1. Onyebuchi, V.E., et al., *A systematic review of key challenges of CO2 transport via pipelines*. 2017.

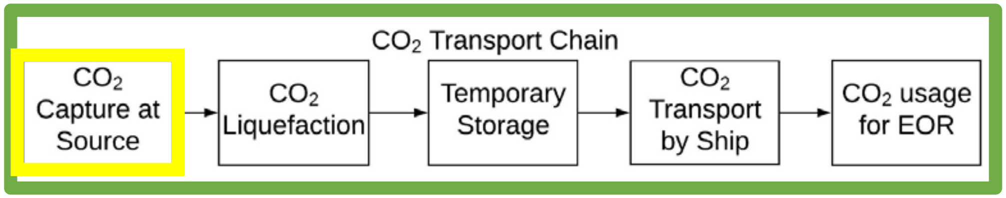
Techno Economic Modeling

- TEA of dual shipping scenario
- LCO_2:
  1. Capture,
  2. Liquefaction,
  3. Temporary storage,
  4. Shipping,
  5. Regasification + EOR
- Analysis of Additional CAPEX
- Modeling of OPEX

Carbon Capture

- Assuming 5,000 tCO_2 captured each day (~2 MM tCO_2 per year)
- ~500 MW Natural gas power plant
- Technological maturity
  - Solvents
  - Sorbents
  - Membranes
- Cost and flexibility of CC plant types
- Retrofit investment costs: Post vs Oxy, 870$/kWh vs 1530 $/kWh

Carbon capture costs are due to energy intensity of capture process; Costs are largely recovered through tax credits in Korea



CO_2 Transport Chain

CO_2 Capture at Source → CO_2 Liquefaction → Temporary Storage → CO_2 Transport by Ship → CO_2 usage for EOR

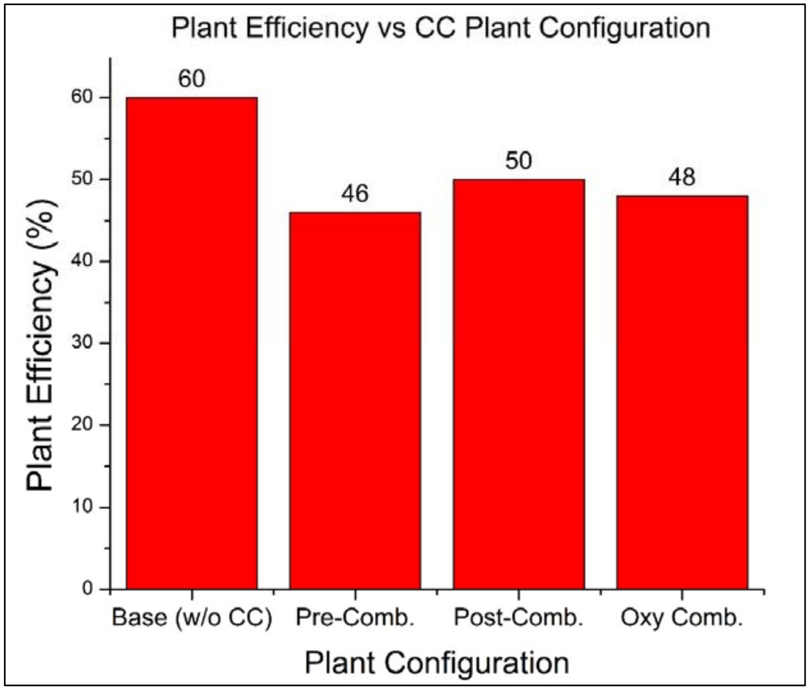


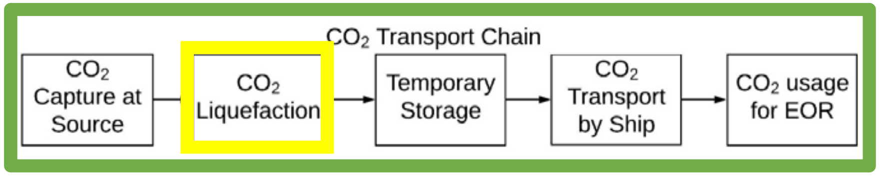
Figure from ref. 1.

Ref.
1. Kanniche, M., et al., *Pre-combustion, post-combustion and oxy-combustion in thermal power plant for CO2 capture.* Applied Thermal Engineering, 2010. **30**(1): p. 53-62.

Liquefaction

- Types of systems
  - -Open systems
  - -Closed systems
- Comparable costs

- Open compression cycle
- Four stage compressor, two process heat exchangers, and two multistream exchangers
- Removal of volatiles and water
- Direct costs and electricity account for ~70% of costs



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Liquefaction Process

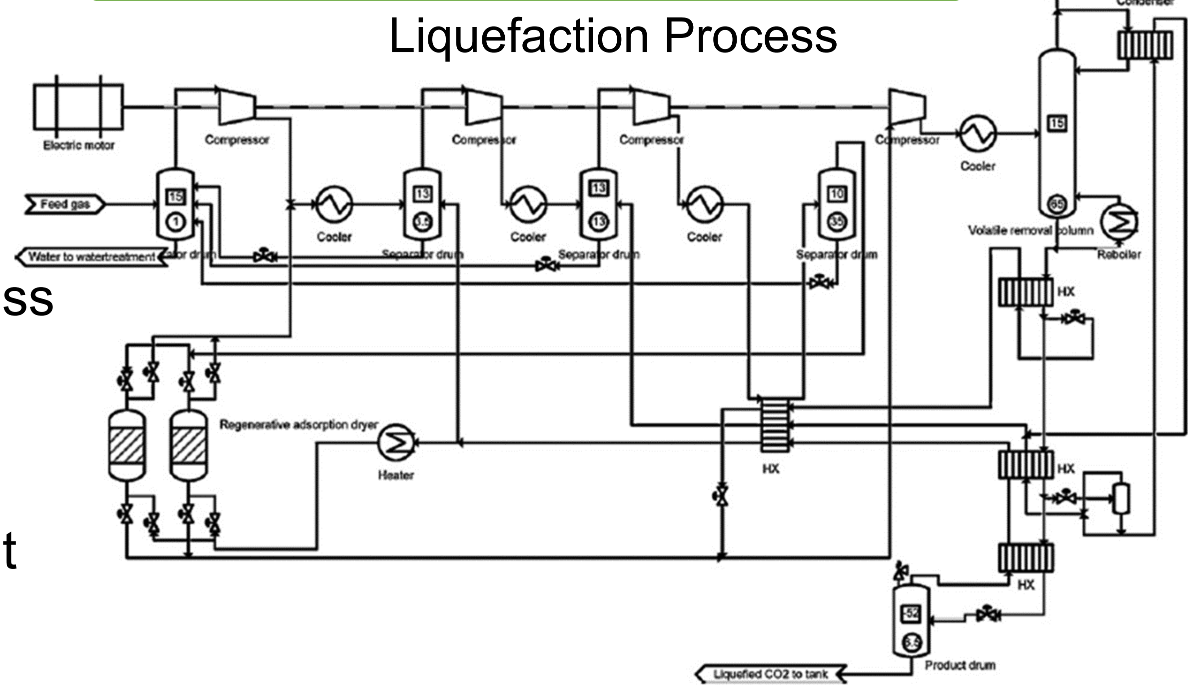
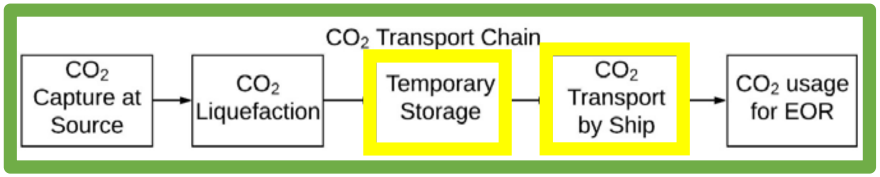


Figure from ref. 1

Ref.
1. Lee, U., et al., *Carbon Dioxide Liquefaction Process for Ship Transportation.* Industrial & Engineering Chemistry Research, 2012. **51**(46): p. 15122-15131.

Temporary Storage & Vessel

- Needed to store accumulating CO_2 at CC plant
- Should be 1.5 times the size of the vessel
- Material steel, thickness based on pressure[1]
- Cost capacity equation
- Complexity factor to account for carrying LNG and LCO_2
- Sprayers, reinforced tankers, and associated piping
- Conventional LNG vessel cost ~$330MM
- Dual-Purpose cost: $409MM



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Vessel Operation Characteristics	
Vessel Speed	14 knots
Voyage Distance	17,000 km
Trip time (includes 1 day each for unloading and loading)	30.4 days
Number of Vessels	4 vessels
DWT per vessel	80,000 tons per vessel

$$I_n = I_r \left[\frac{S_n}{S_r}\right]^{S_f} C_f$$

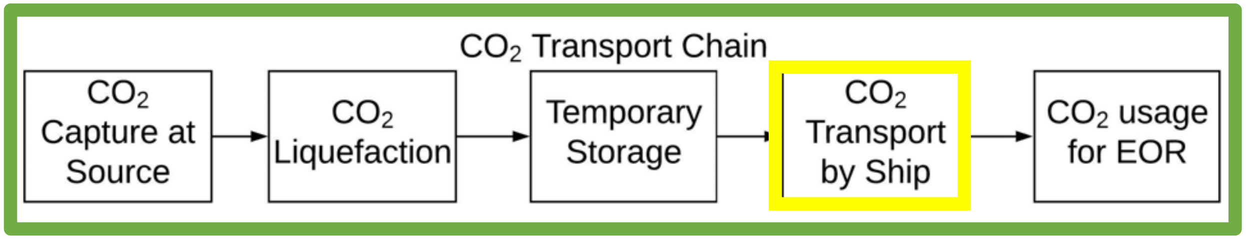
Ref. 2

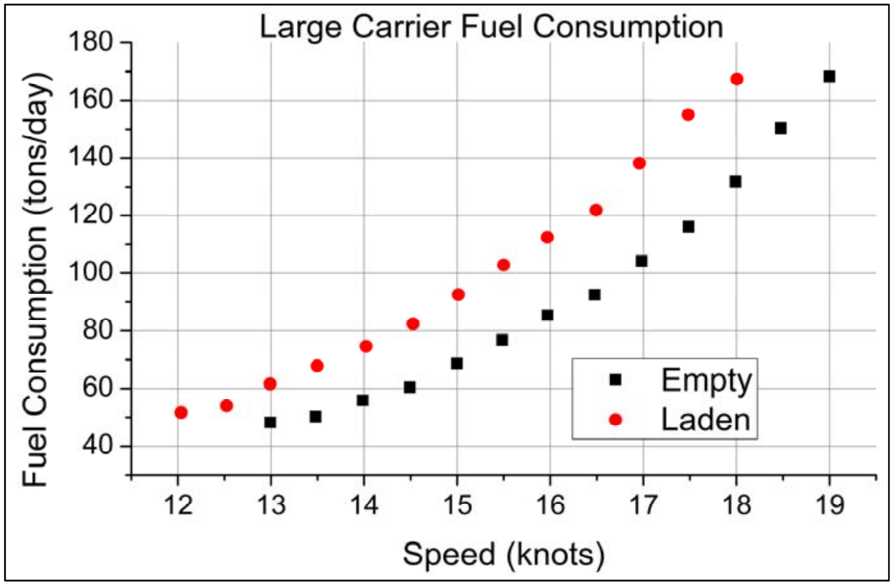
Ref.

1. Kang, K., et al., *Estimation of CO2 Transport Costs in South Korea Using a Techno-Economic Model*. Vol. 8. 2015. 2176-2196
2. Aspelund, A. and T. Gundersen, *A liquefied energy chain for transport and utilization of natural gas for power production with CO2 capture and storage – Part 1.* Applied Energy, 2009. **86**(6): p. 781-792.

Dual-Purpose Vessel: OPEX

- Increasing costs
  - -Fuel cost: laden vs empty
  - -Port costs
  - -Canal fees
- Fuel: $\$3/tCO_2$
- Port: $\$1/tCO_2$
- Canal: $\$0.59/tCO_2$
- Reduced transport costs:
  - $-\$62/tCO_2$ vs $\$26/tCO_2$
  - ~60% decrease





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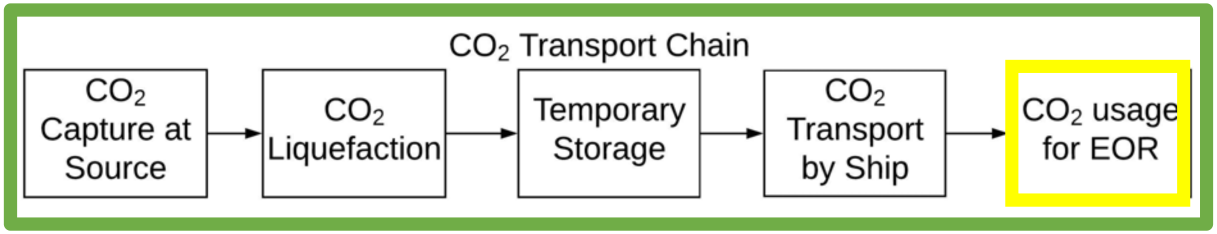
Ref.

1. Psaraftis, H.N. and C.A. Kontovas, *Ship speed optimization: Concepts, models and combined speed-routing scenarios.* Transportation Research Part C: Emerging Technologies, 2014. **44**: p. 52-69.

CO_2-EOR

- Based on miscibility of CO_2 with oil
- Function of temperature and pressure
- Screening criteria include: depth, permeability, and viscosity
- Southeast Texas well used for reference
- Major costs include: equipment for wells, CO_2 recycle plant CAPEX, and CO_2 recycle plant OPEX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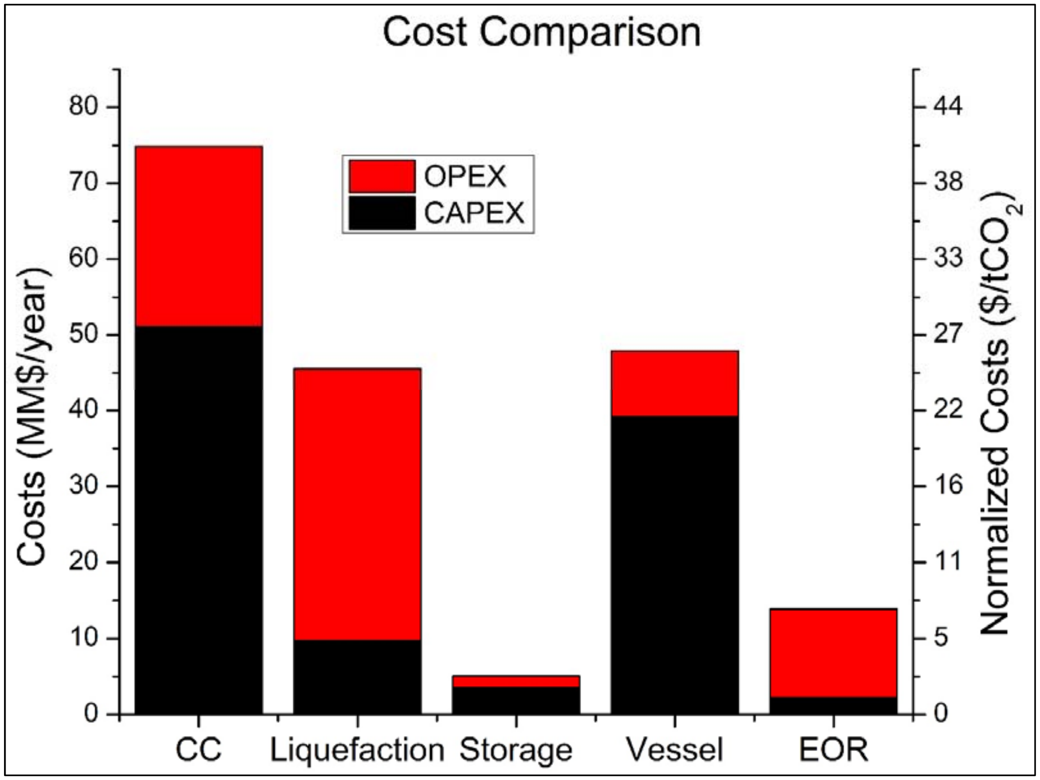
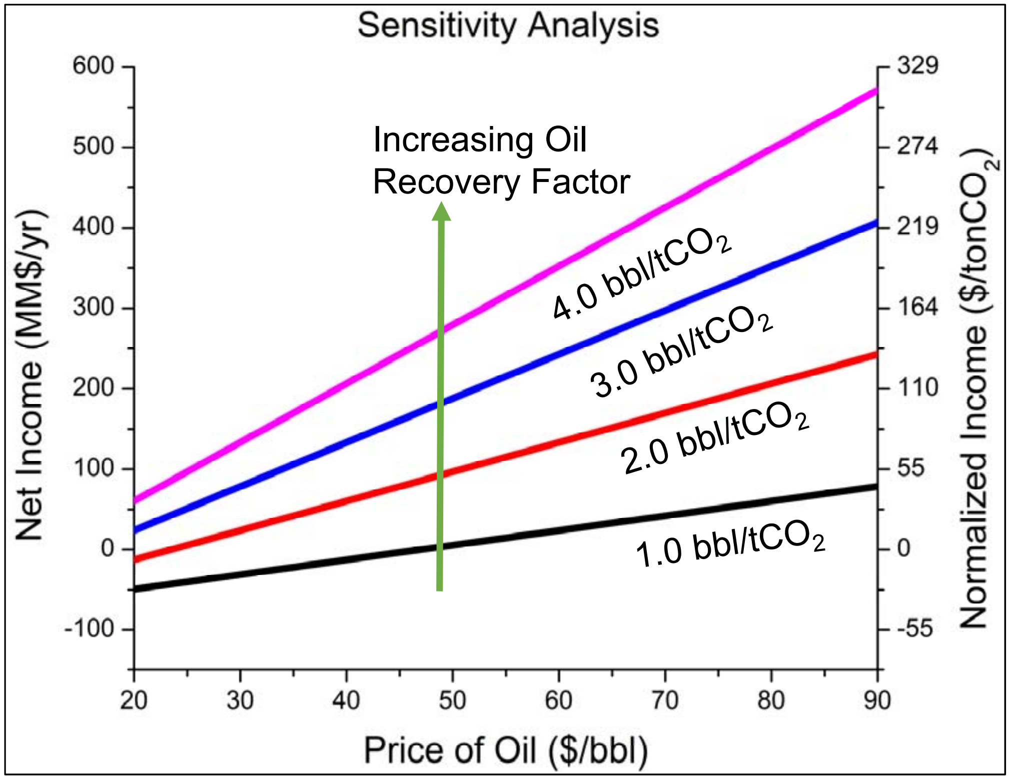
Well Characteristics	
Depth (ft)	6000
Total Oil Production (million barrels)	82
Produced Oil (bbls/ton of stored CO_2)	1.5

Results

	Total (MM US$/yr)	**US$ per ton CO_2**
Revenue		
South Korean Tax Credit	38	21
US 45Q for EOR	64	35
Sale of Crude Oil	172	97
Total Revenue	**274**	**153**
Costs		
CO_2 Capture	75	41
CO_2 Liquefaction	46	25
Temporary Storage	5	3
Vessel Costs	48	26
EOR Costs	14	8
Total Costs	**187**	**103**
Net Income	**87**	**50**

Results





Oil Recovery Factor = barrels of oil recovered/tCO_2 stored

Limitations and Future Scope

- TEA and the valorization of CO_2 are highly sensitive to policy incentives, which may not be stable over time
- Analysis is focused on US and South Korea; however, economic gains may be greater in other countries if
  - There is an incentive to capture and utilize CO_2
  - Fields are mature and amenable to CO_2-based tertiary recovery
- Regulatory framework for sharing profits and environmental credits between countries needs to be addressed

Conclusions

- Eliminated the cost of operating an empty LNG ship on its return journey and cut transport costs from \$62/tCO_2 to \$26/tCO_2
- Process provides a market for CO_2 mitigation with a net income of \$50/tCO_2
- Provides a compelling economic argument for dual-shipping of LNG and LCO_2 paired with CO_2 based EOR

Acknowledge funding from: RAPID Transforming Process Industries

Q&A

Thank you

Appendix: Carbon Capture Cost Tables

	Year: 2012
Capital Cost, $/kW	525
O&M, mills/kWh	2.4
Heat Rate (LHV), Btu/kWh	5677
Incremental Capital Cost,	829
$/(kg/h)	
Incremental O&M, mills/kg	4.68
Energy Requirements, kWh/kg	0.297
Yearly Operating Hours, hrs/yr	6570
Capital Charge Rate, %/yr	15
Fuel Cost (LHV), $/MMBtu	2.93
Capture Efficiency, %	90
Reference Plant	
CO_2 Emitted, kg/kWh	0.337
coe: CAPITAL, mills/kWh	12
coe: FUEL, mills/kWh	16.6
coe: O&M, mills/kWh	2.4
Cost of Electricity, ¢/kWh	3.1
Thermal Efficiency (LHV), %	60.1

Capture Plant	
Relative Power Output, %	90
Heat Rate (LHV), Btu/kWh	6308
Capital Cost, $/kW	894
CO_2 Emitted, kg/kWh	0.037
coe: CAPITAL, mills/kWh	20.4
coe: FUEL, mills/kWh	18.5
coe: O&M, mills/kWh	4.4
Cost of Electricity, ¢/kWh	4.33
Thermal Efficiency (LHV), %	54.1
Comparison	
Incremental coe, ¢/kWh	1.23
Energy Penalty, %	10
Mitigation Cost, Capture vs. Ref., $/t of CO_2 avoided	41

Appendix: Liquefaction CAPEX

	Cost (MM$)
Direct Costs	
Purchased Equipment	22
Purchased equipment installation	4
Instrumentation and control	1
Piping	4
Electrical	1
Building and building services	4
Yard improvements	1
Services facilities	5
Land	1
Total direct Costs	45
Indirect Costs	
Engineering	3
Construction expenses	3
Contractor’s fees	1
Contingency	3
Total Indirect Costs	11
Total Capital Investment (CAPEX)	66 R4 R12

Slide 21

R4	round up to MM \$ Ramanan, 7/15/2019
R12	done, thanks Rafael, 7/15/2019

Appendix: Liquefaction OPEX

	Cost (MM$/year)
Fixed charges	
Local taxes	0
Insurance	0
Direct production costs	
Cooling water	2
Electricity	23
Maintenance	1
Operating Labor	1
Supervision and support labor	0
Operating supplies	0
Laboratory charges	0
Overhead costs	1
General Expenses	
Administrative cost	0
Distribution and marketing	1
R&D costs	1
Total production cost (OPEX)	30

Appendix: Temporary Storage

Storage Size	103,693	m^3
	Cost (MM$)	**Normalized cost (\$/tCO$_2$)**
Annualized CAPEX of the tank	4	2
OPEX of the tank	1	1
Total cost of the tank	5	3

Appendix: Vessel Costs OPEX

	Cost (MM$)	**Normalized cost ($/tCO$_2$)**
Canal Fees	1	1
Port Cost	2	1
Fuel Cost	5	3
Total	8	5

Appendix: Vessel Costs CAPEX

$$I_n = I_r \left[\frac{S_n}{S_r}\right]^{S_f} C_f$$

Parameter	Value	Unit
I_r	45	MMUSD
S_n	161791	m^3
S_r	12000	m^3
S_f	0.85	unitless
C_f	1.35	unitless

	Additional CAPEX	
one ship	79	MM$/year
4 ships	315	MM$/year
Annualized Cost	39	MM$/year

Appendix: EOR Costs

	MM$/yr	**$/tCO$_2$**
Capital costs		
well cost	0	0
recycle plant	1	1
CO$_2$ distribution	1	1
compressor	0	0
Lease Equipment for Fluid Management	0	0
Lease Equipment Costs for New Injection Wells	0	0
Operating costs		
recycle plant	8	4
Compressor	1	1
Annual O&M Costs, Including Periodic Well Workovers	0	0
Fluid lifting costs	1	0
Regas cost	2	1
Injection Energy Costs	0	0
Total	14	8