Recovering liquefaction cost of captured carbon dioxide

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Our team involved in this research

Research team

- Dr. Kumar Patchigolla (Reader in low carbon energy systems)
- Dr. Kranthi Jonnalagadda

MSc students

- Sandeep Velmurugan
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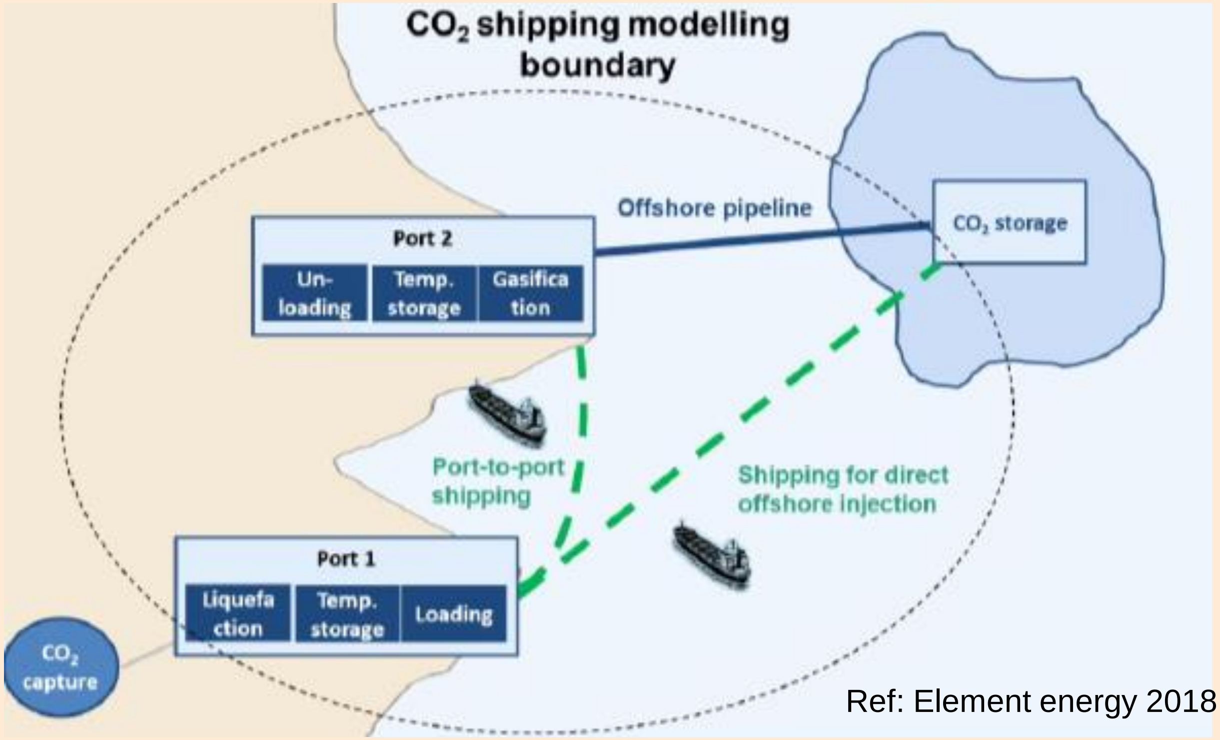
Outline

- Introduction
- Power generation using liquid CO2
- Direct cold utilization using liquid CO2

CO2 shipping chain



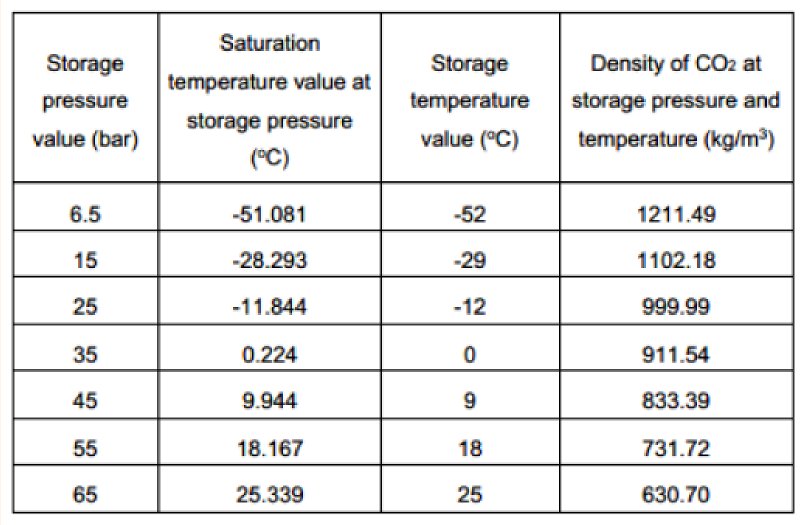
Ref: Element energy 2018

- Aim of CO2 transport research
  - Estimate costs of shipping
  - Identify the opportunities and barriers to CO_2 shipping

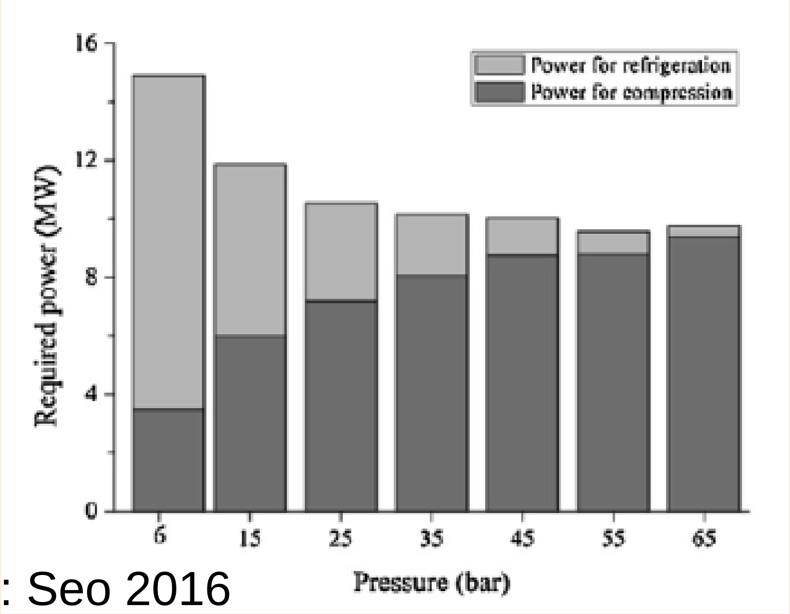
Optimal liquid CO_2 transport conditions from literature

- Costs to be considered in shipping chain
  - Liquefaction cost
  - Ship cost
  - Storage cost

- Seo 2016 concluded that 15 bar, -28.5 C transport condition is the optimal.

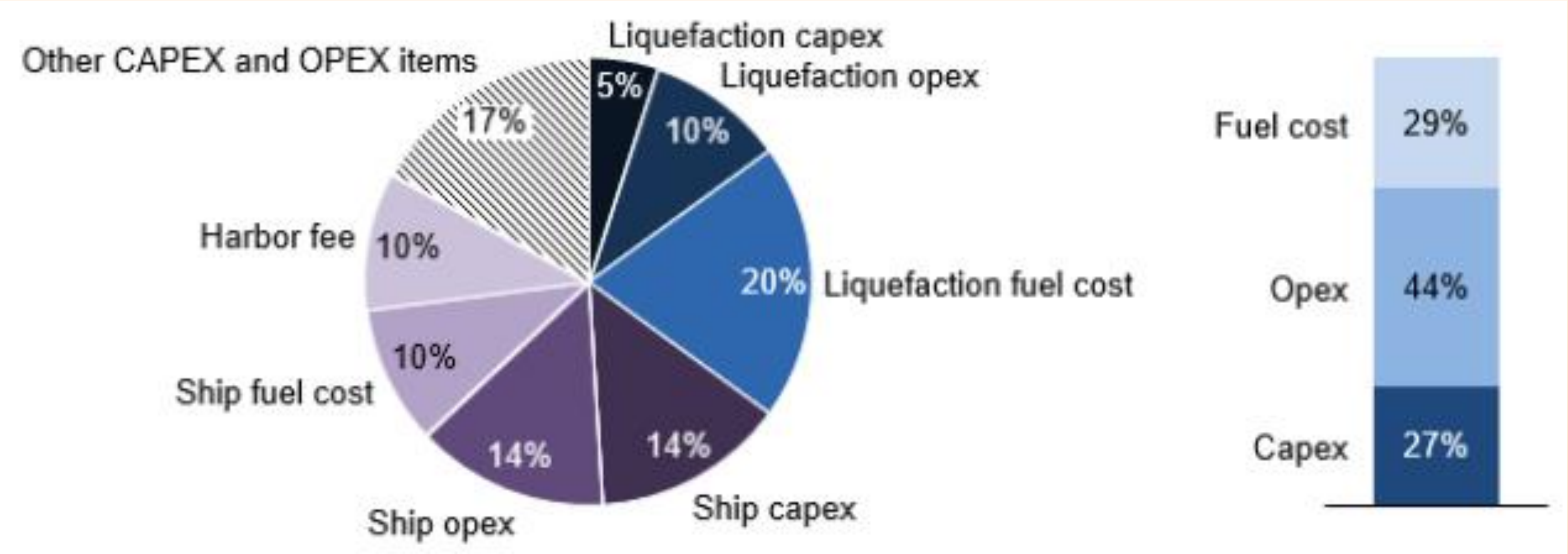


Storage pressure value (bar)	Saturation temperature value at storage pressure (ºC)	Storage temperature value (ºC)	Density of CO_2 at storage pressure and temperature (kg/m³)
6.5	-51.081	-52	1211.49
15	-28.293	-29	1102.18
25	-11.844	-12	999.99
35	0.224	0	911.54
45	9.944	9	833.39
55	18.167	18	731.72
65	25.339	25	630.70



Ref: Seo 2016

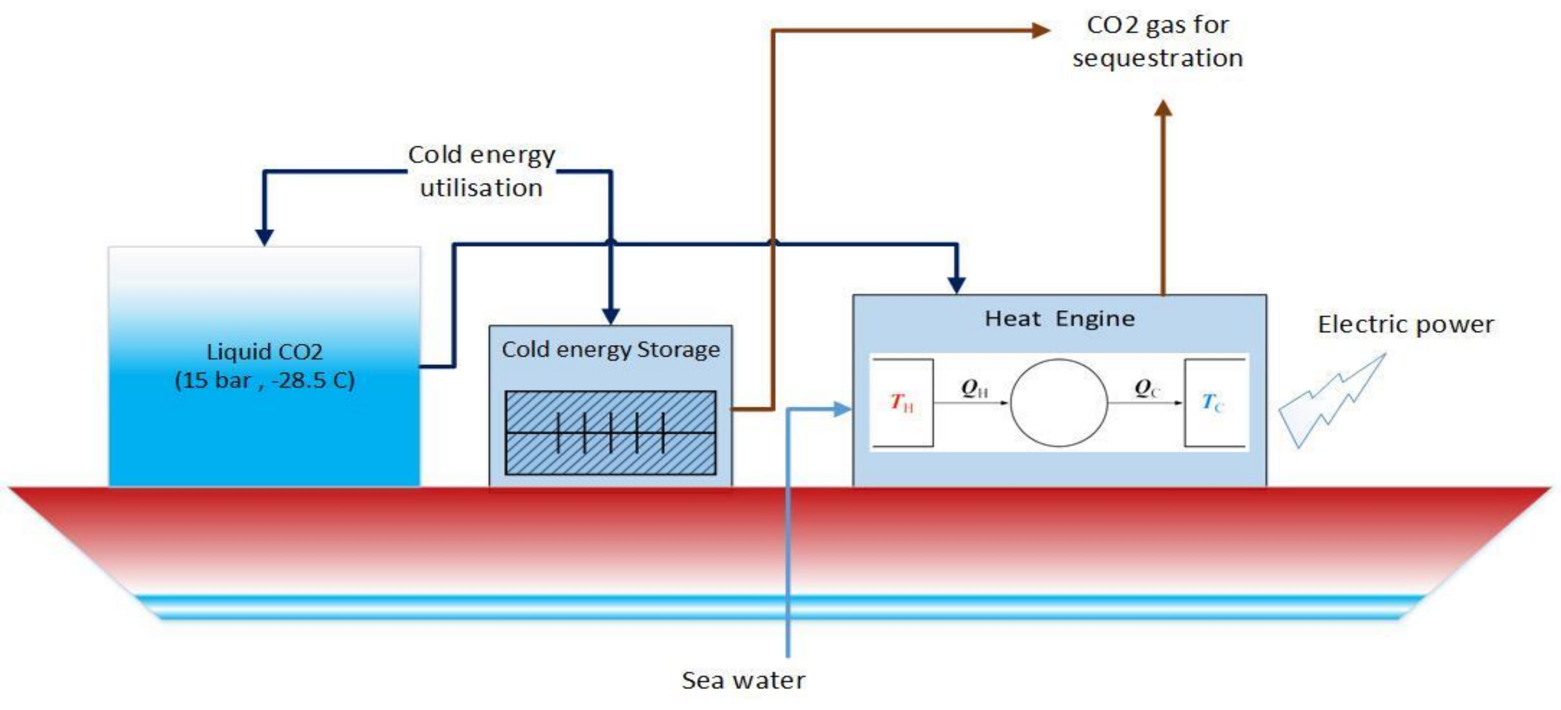
Cost components of CO2 shipping



Element energy 2018

- Liquefaction cost accounts for 35% of total cost : most significant component of CO2 shipping
- Opex and fuel costs are more than Capex costs unlike the pipelines
- Can we do something to recover this cost?

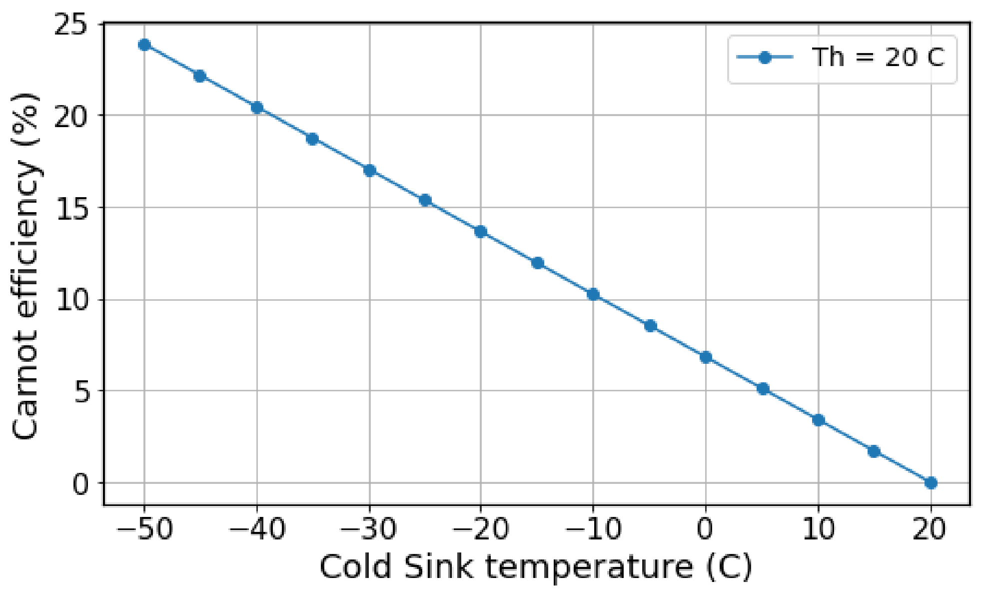
Liquid CO2 cold energy utilization



Goals of research

1. Design Heat engine
2. Design cold thermal energy system
3. Perform techno-economic analysis

Thermodynamic limitation on heat engine

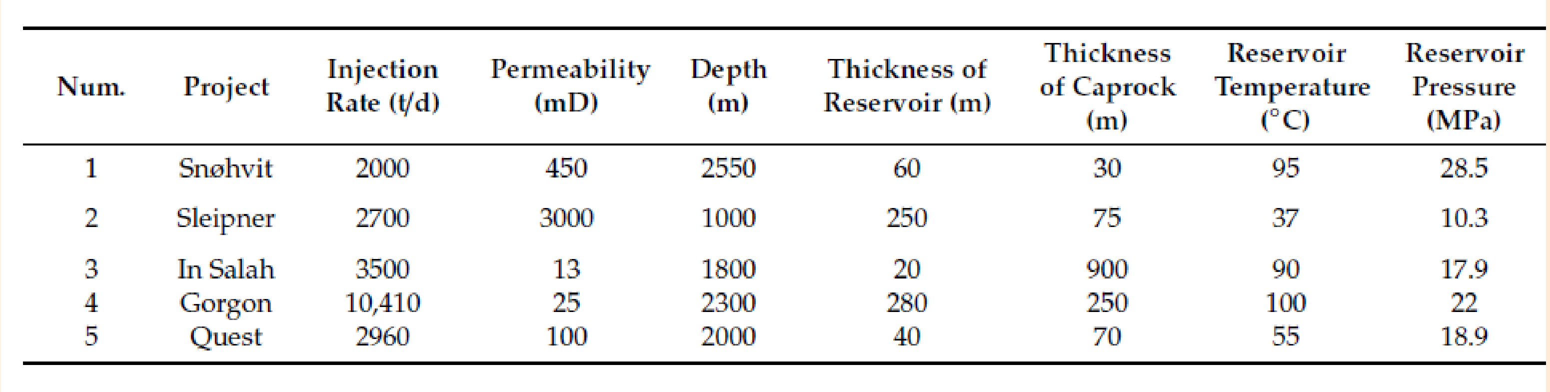


- Heat source temperature 20C when using sea water as heating medium

- As the heat sink temperature increases (LCO2) the Carnot efficiency decreases

- At 0 C the efficiency is 6.8%

Storage conditions



Num.	Project	Injection Rate (t/d)	Permeability (mD)	Depth (m)	Thickness of Reservoir (m)	Thickness of Caprock (m)	Reservoir Temperature (°C)	Reservoir Pressure (MPa)
1	Snøhvit	2000	450	2550	60	30	95	28.5
2	Sleipner	2700	3000	1000	250	75	37	10.3
3	In Salah	3500	13	1800	20	900	90	17.9
4	Gorgon	10,410	25	2300	280	250	100	22
5	Quest	2960	100	2000	40	70	55	18.9

- Storage options: saline aquifer, depleted oil reserves, coal beds, deep ocean

- Average pressure of saline aquifer in demonstration projects is 200 bar
  - Depleted oil reserves 20 bar

- Temperature at the reservoir inlet to be higher than 15 C to prevent hydrate formation

Problem statement

Hot reservoir : Sea water at 20 C

Initial state of CO2:

- Low pressure: 8 bar -53 C
- Medium pressure: -28.5 C and 15 bar

Final state:

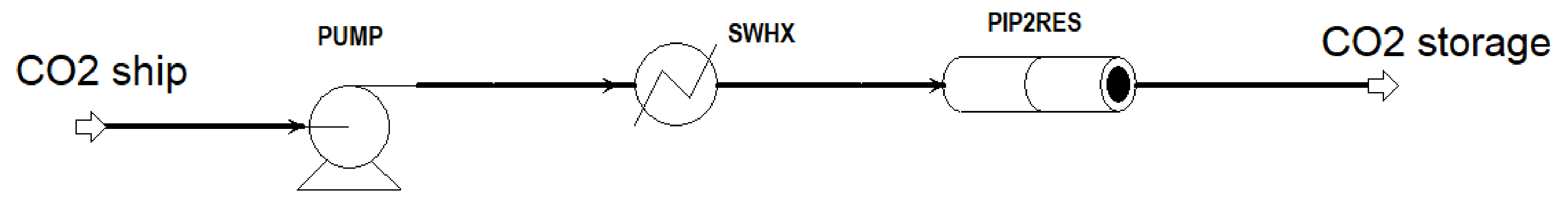
- 15 C and 200 bar or 20 bar

Average depth of reservoir 2000 m

Injection flow rate is 25 Kg/s

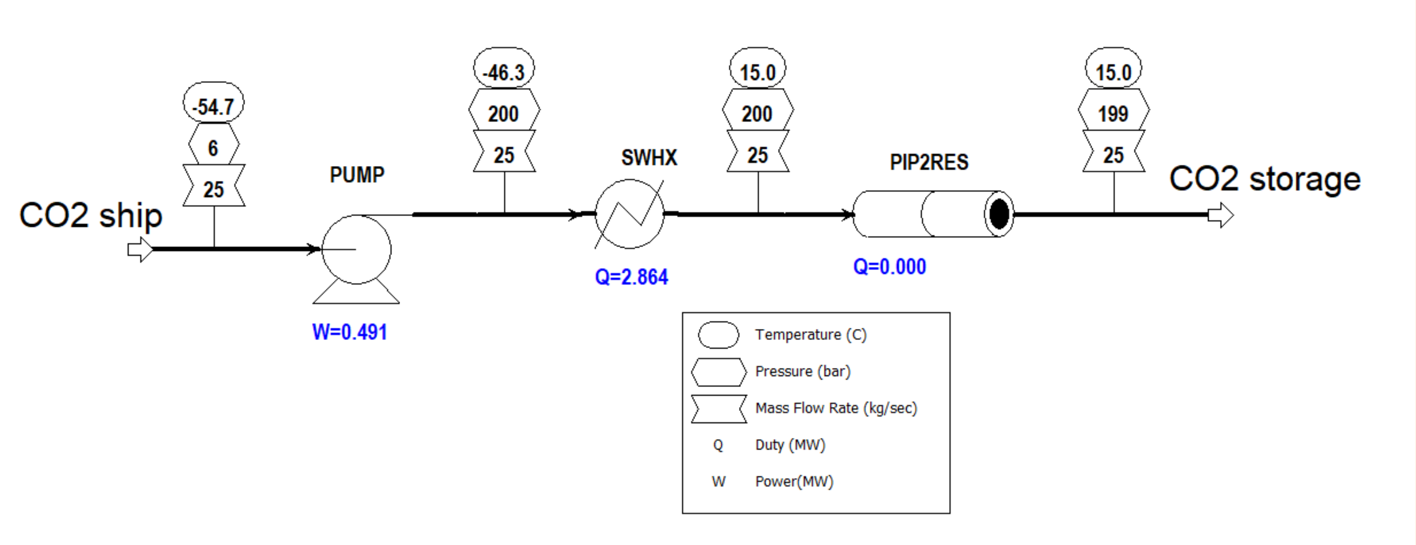
Ship payload is 11500 m3 to be offloaded in 24 hours

Storage process flow



- Pump: Increases CO2 pressure to storage conditions
- SWHX: liquid CO2 temperature is increased using sea water
- Pip2res: Pipeline carrying CO2 to the reservoir
  - Temperature at the downstream end of the pipe should be greater than 15 C to prevent hydrate formation

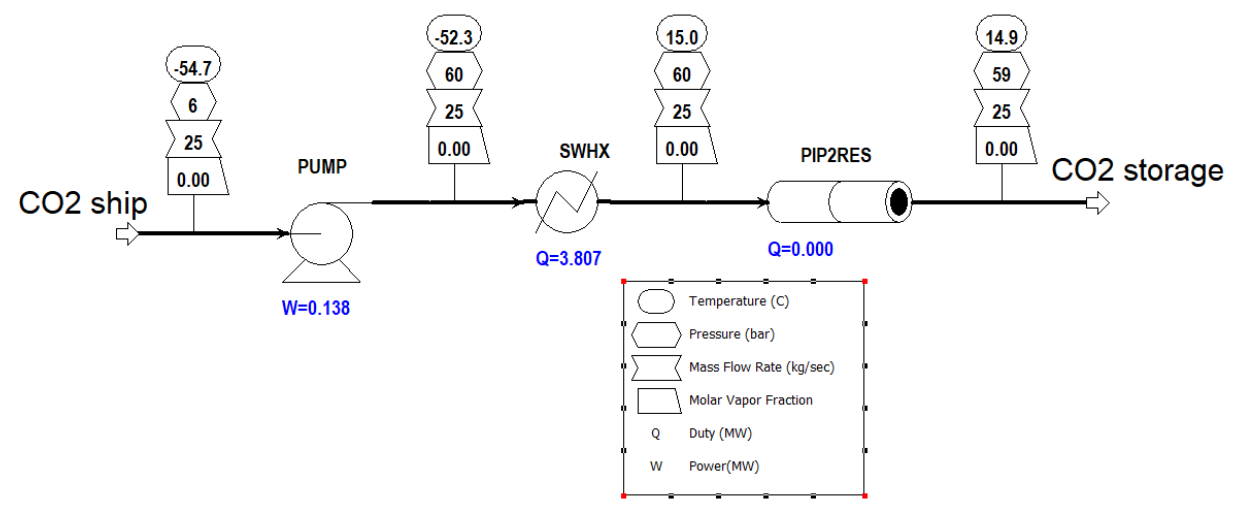
Results : Saline aquifers



- Note rise in temperature of liquid CO2 as it is pumped to storage conditions

				Aquifer P = 200 bar			
	Pressure	Temperature	Injection rate	Pump work	HX duty	Pump work	Heat Duty
	bar	C	kg/s	kW	kW	kWh/tonne	kWh/tonne
Medium pressure	20	-19	25	517	1071	5.74	11.90
	15	-28	25	512	1557	5.69	17.30
Low pressure	10	-39.6	25	503	2146	5.59	23.84
	5.5	-54.7	25	491	2864	5.46	31.82

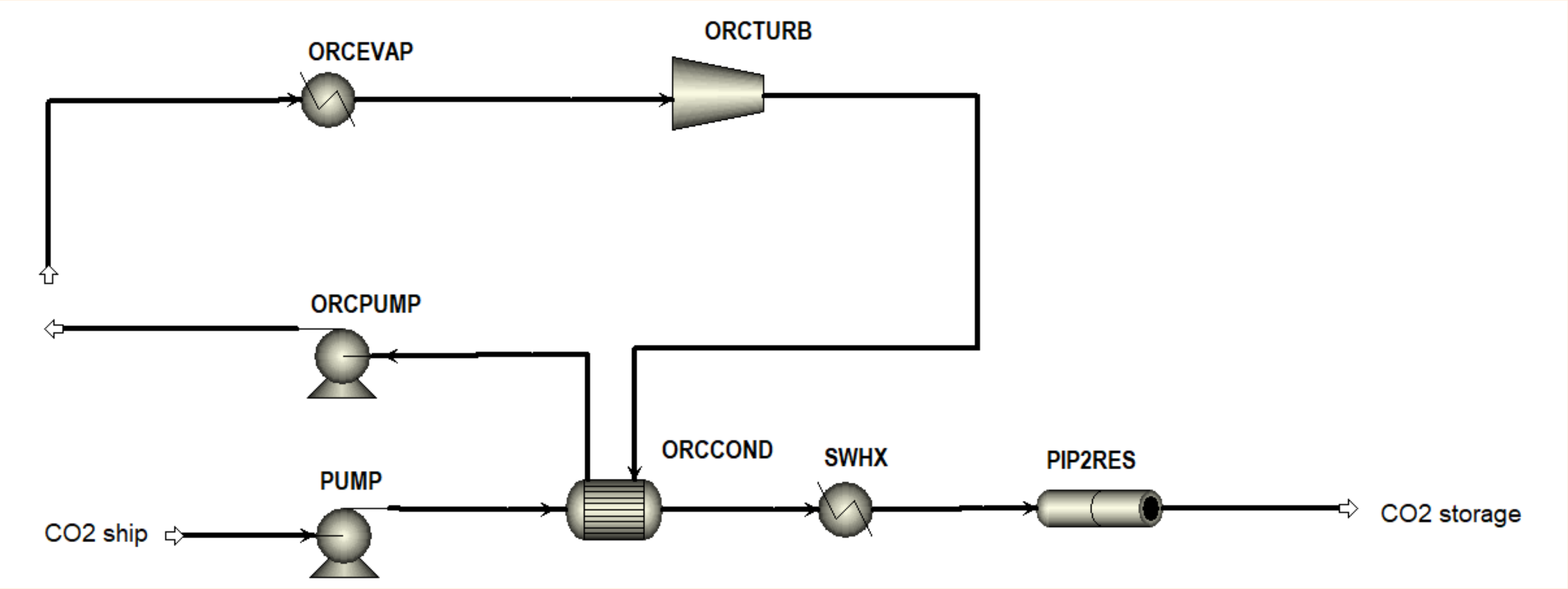
Results: Depleted wells



- A pressure rise of up to 60 bar is required to keep the CO2 in liquid state in SWHX

				Depleted well P = 20 bar (compression to 60 bar required)			
	Pressure	Temperature	Injection rate	Pump work	HX duty	Pump work	Heat Duty
	bar	C	kg/s	kW	kW	kWh/tonne	kWh/tonne
Medium pressure	20	-19	25	115	2063	1.28	22.92
	15	-28	25	124	2534	1.38	28.16
Low pressure	10	-39.6	25	132	3107	1.47	34.52
	5.5	-54.7	25	138	3807	1.53	42.30

Injection process with ORC integration



- ORCXXX : components of Organic Rankine Cycle

- ORCCOND: integrates the ORC cycle with the injection process. The condenser thermal average temperature is 0 C

- R114 is chosen as refrigerant for its thermodynamic properties and suitability to ship board conditions

Integrated ORC and injection results: Saline aquifer

				Aquifer P = 200 bar					
	Pressure	Temperature	Injection rate	Pump work	ORC work	Pump work	ORC work	Percentage pump work	Ship equivalent
	bar	C	kg/s	kW	kW	kWh/tonne	kWh/tonne	%	kW
Medium pressure	20	-19	25	517	13.30	5.74	0.15	2.57	70.8
	15	-28	25	512	36.80	5.69	0.41	7.19	195.9
Low pressure	10	-39.6	25	503	67.00	5.59	0.74	13.32	356.7
	5.5	-54.7	25	491	100.00	5.46	1.11	20.37	532.4

- The ORC system can provide 20% of the pump work at low pressure condition of 5.5 bar

- At 20 bar medium pressure condition, ORC can generate only 3% of the compression work

- Ship equivalent is calculated for 11500 tonne ship offloading in 24 hours

Integrated ORC and injection results : depleted well

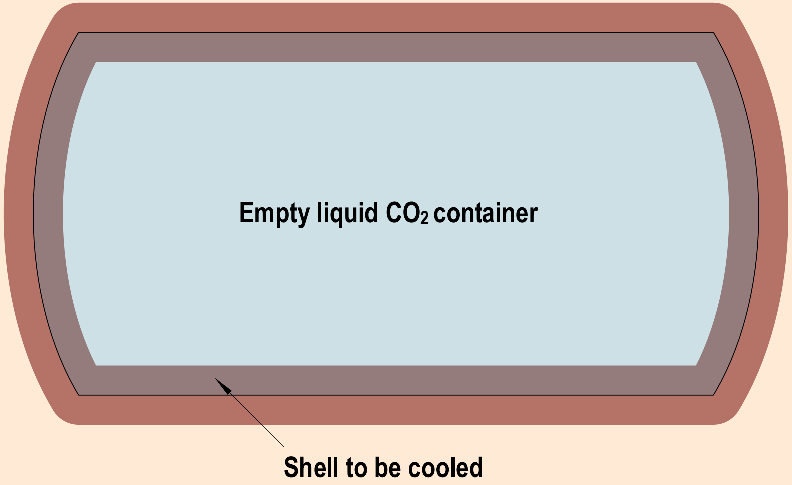
				Depleted well P = 20 bar (compression to 60 bar required)					
	Pressure	Temperature	Injection rate	Pump work	ORC work	Pump work	ORC work	Percentage pump work	Ship equivalent
	bar	C	kg/s	kW	kW	kWh/tonne	kWh/tonne	%	kW
Medium pressure	20	-19	25	115	46.80	1.28	0.52	40.70	249.2
	15	-28	25	124	66.90	1.38	0.74	53.95	356.2
Low pressure	10	-39.6	25	132	93.70	1.47	1.04	70.98	498.9
	5.5	-54.7	25	138	127.00	1.53	1.41	92.03	676.2

- At low pressure condition of 5.5 bar, 92% of the compression work can be obtained using the ORC

Direct utilization of liquid CO2 cold thermal energy

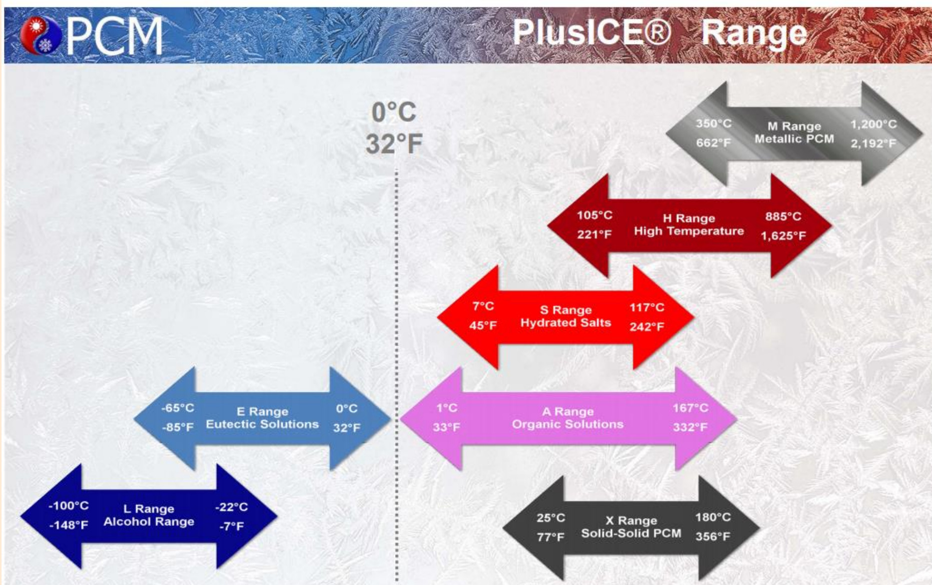
CTES sizing

- Each ship to carry 11500 m3 of liquid CO_2
- Considered a typical tank of volume - 1850 m^3 : seven tanks are required
- Assumed thickness of shell - 2 mm
- Shell to be cooled from ambient (25 C) to liquid CO_2 temperature (0 C)
- Cold energy required is 23 kWh for each tank
- Total 161 kWh of cold energy required for all the 7 tanks



CTES sizing

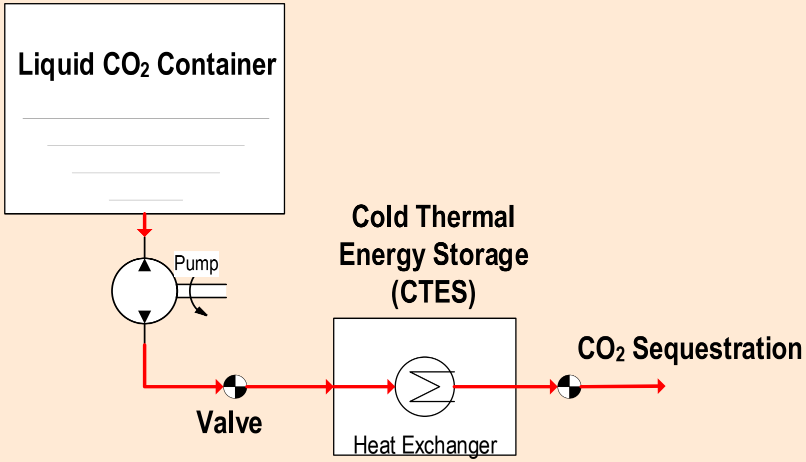
- Target storage temperature 0 C using liquid water/ice phase change
- Estimated mass of the material required is 248 kg per tank.
- Total CTES material is 1736 kg



CTES process flow

- Charging

- Liquid CO_2 can be pumped into CTEX HX



Liquid CO_2 Container

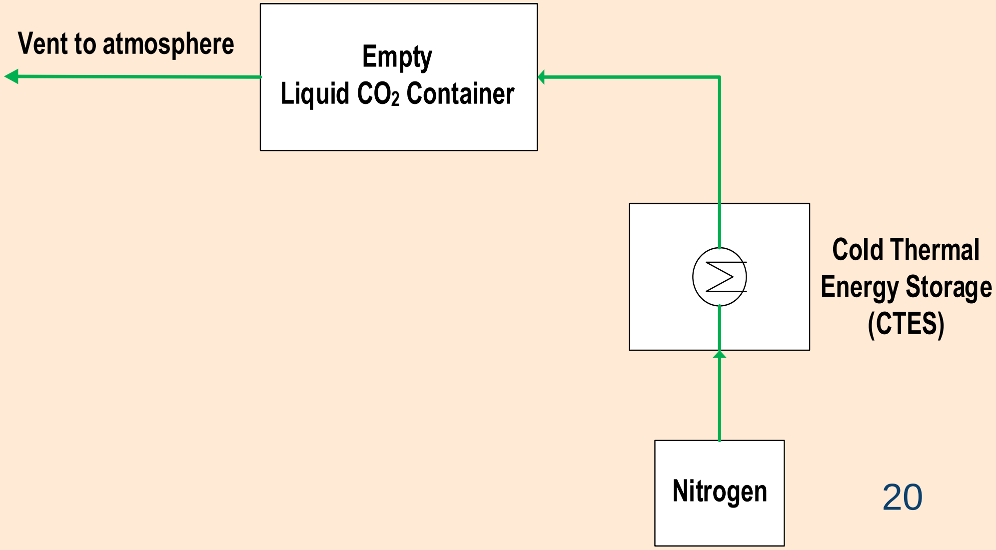
Pump

Valve

Cold Thermal Energy Storage (CTES)

Heat Exchanger

CO_2 Sequestration



Vent to atmosphere

Empty Liquid CO_2 Container

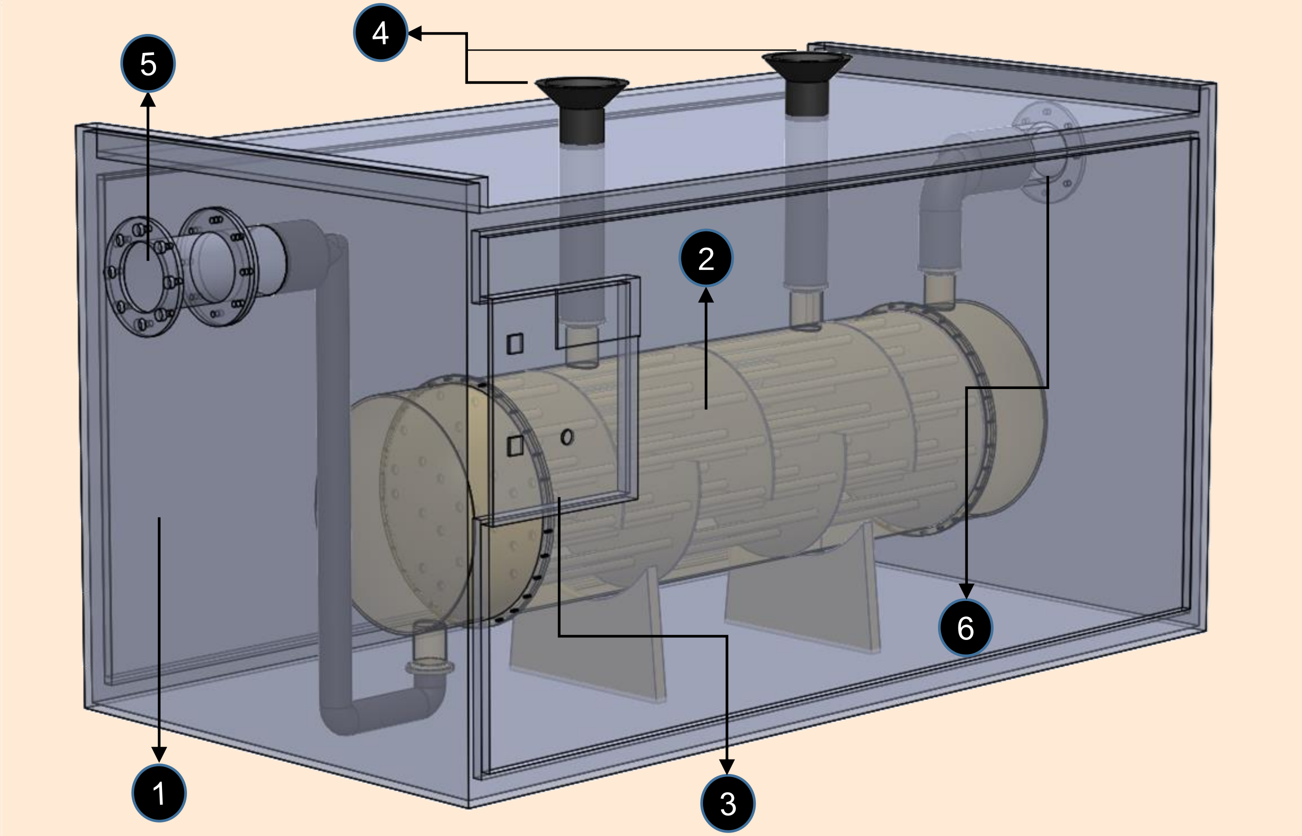
Cold Thermal Energy Storage (CTES)

Nitrogen

- Discharging

- Nitrogen gas can be used

CTES design



1 – CTES unit
2 – Heat Exchanger
3 – Control centre
4 – Shell side Inlet & Outlet

5 – Tube Inlet
6 – Tube Outlet

Conclusions

- The potential for energy recovery from liquid CO_2 depends on the storage conditions

- Recovery potential maximum at low pressure transport conditions of 5.5 bar

- Power generation using ORC: maximum at 5.5 bar
  - Saline aquifer - 20% of the compression work can be generated with ORC
  - Depleted well - 92%

- Direct utilization of cold energy at 0 C may be a practical approach

Impact

- Flexible funding : opportunity to work on cold thermal energy storage

- Inspiration for a cold thermal energy storage material testing facility
  - Innovate UK funding

Thanks for your attention.
Questions please!

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