CO2 Compression for Advanced Oxy-Fuel Cycles

Workshop on Future Large CO2 Compression Systems

Presentation by

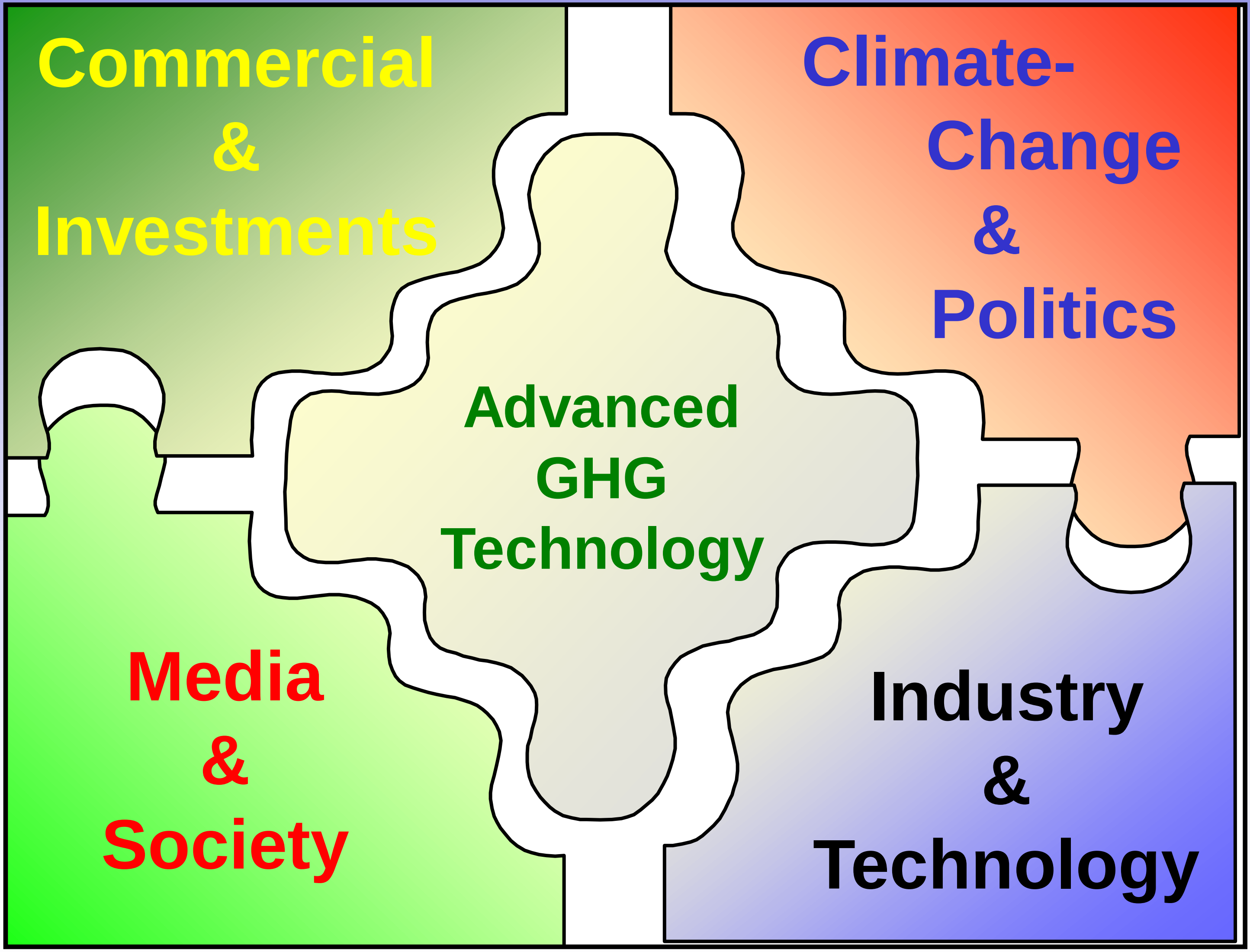
Carl-W. Hustad, CEO, CO2-Global

At Workshop on Future Large CO2 Compression Systems

DOE Office of Clean Energy Systems, EPRI, and NIST

March 30th and 31st, 2009 Gaithersfield, MD

Complex Interaction of Arenas!



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Capturing, Managing and Gathering CO2 for EOR Onshore and Offshore: Challenges and Opportunities

Presented by

Carl-W. Hustad, President & CEO

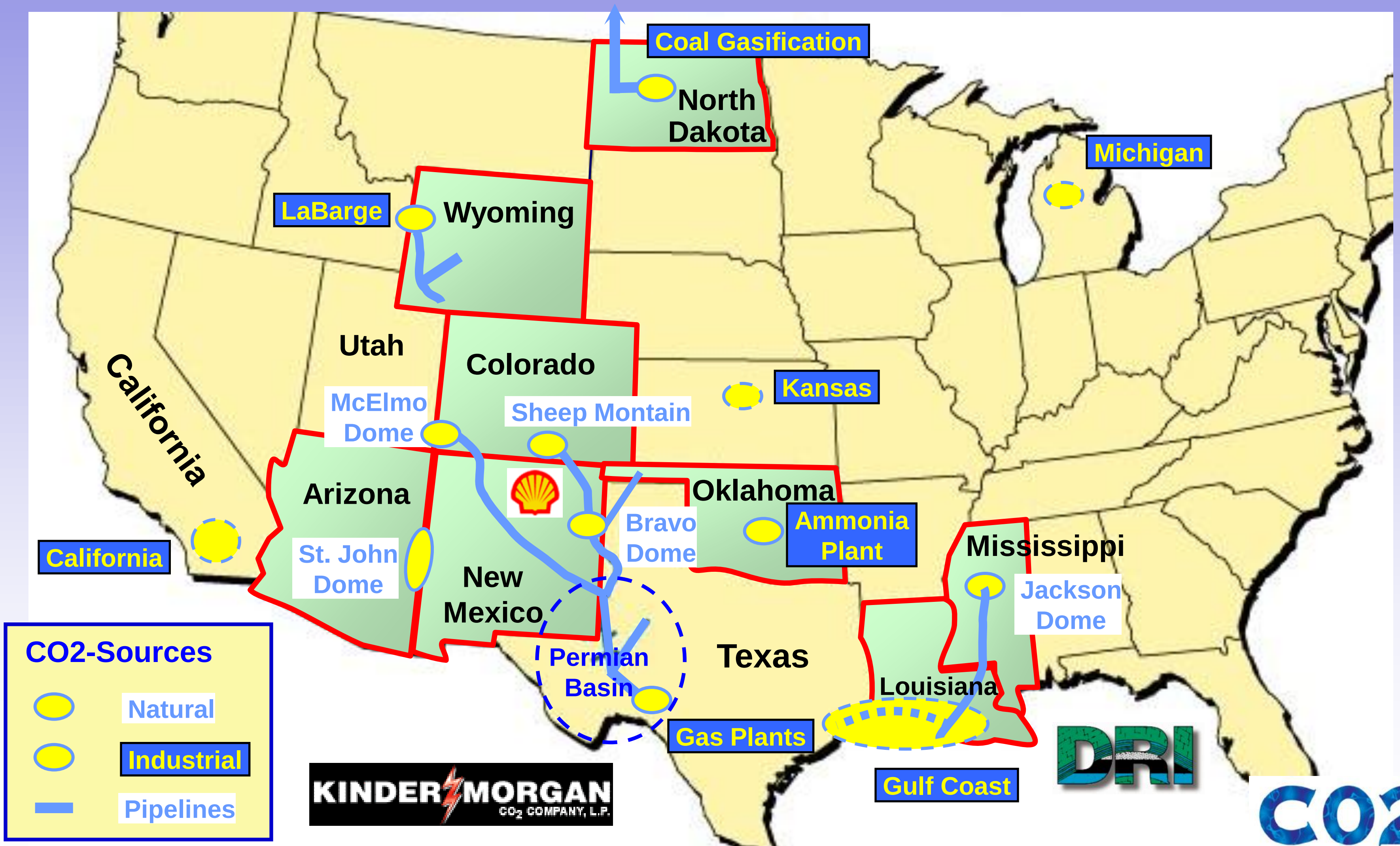
CO2-Global

At the ACI Optimising EOR Strategy 2009

Park Plaza County Hall, London, UK

On 11th – 12th March 2009

The United States -- An Established Business: ~220,000 bbls/day in >70 CO2-floods



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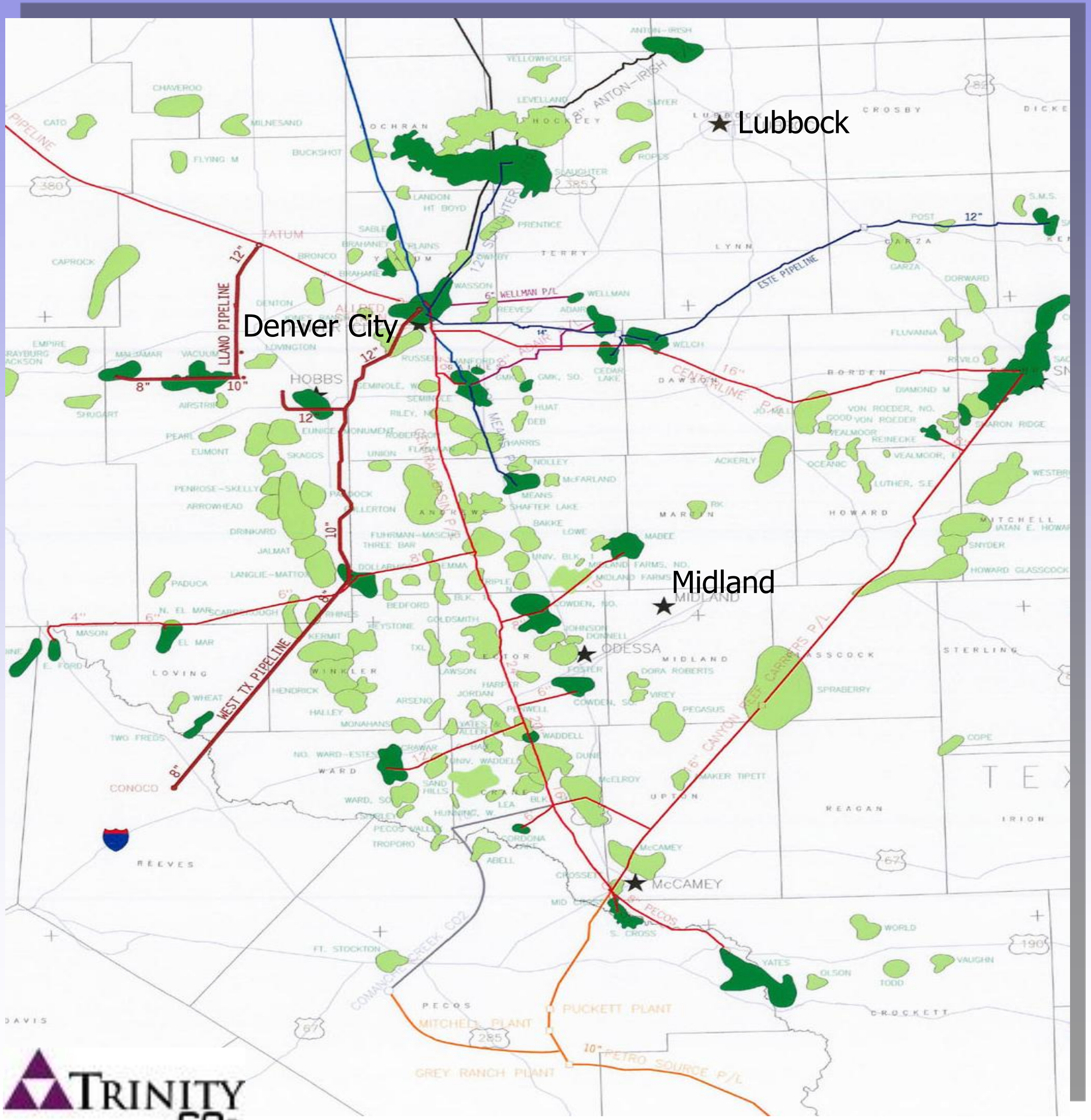
The Permian Basin in West Texas & New Mex.



- The Permian Basin is a prolific CO2 arena with ~70% of global CO2-EOR production.
- Current supply is 1.6 bcfd CO2 yielding ~180,000 bbl of incremental oil per day.
- Map shows an area covering ~ 40,000 sq miles in West Texas and the SE part of New Mexico;
  - Dark green represents existing CO2-floods.
  - Light green are the new recognised opportunities.
- The “ring main” pipeline ensures some flexibility of supply, but ....
- Region is short!

TRINITY CO2

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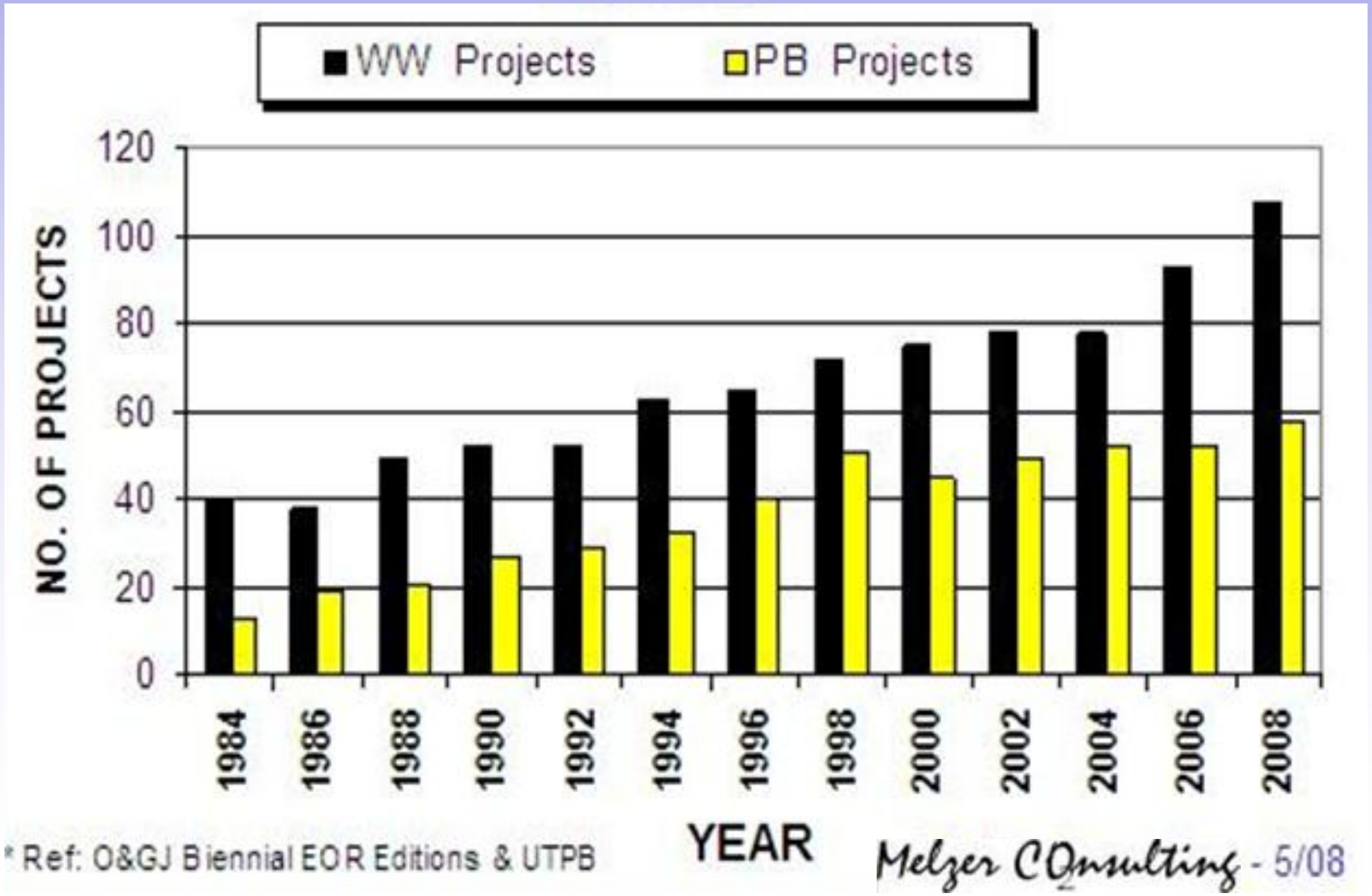
Growth of CO2-EOR in the Permian Basin

- The Permian, West Texas has a strong engineering community with “hands-on” experience for managing all aspects of CO2-flooding. This includes;
  - Overall process design and implementation.
  - Plant integration with existing and new CO2-floods.
  - Operation & Maintenance covering;
    - Corrosion management
    - Recycle of CO2
    - Measurement & monitoring
  - Optimal sub-surface use of injected CO2.
  - Texas under-stands legal aspects of mineral rights and pore space!



* Ref: O&GJ Biennial EOR Editions & UTPB

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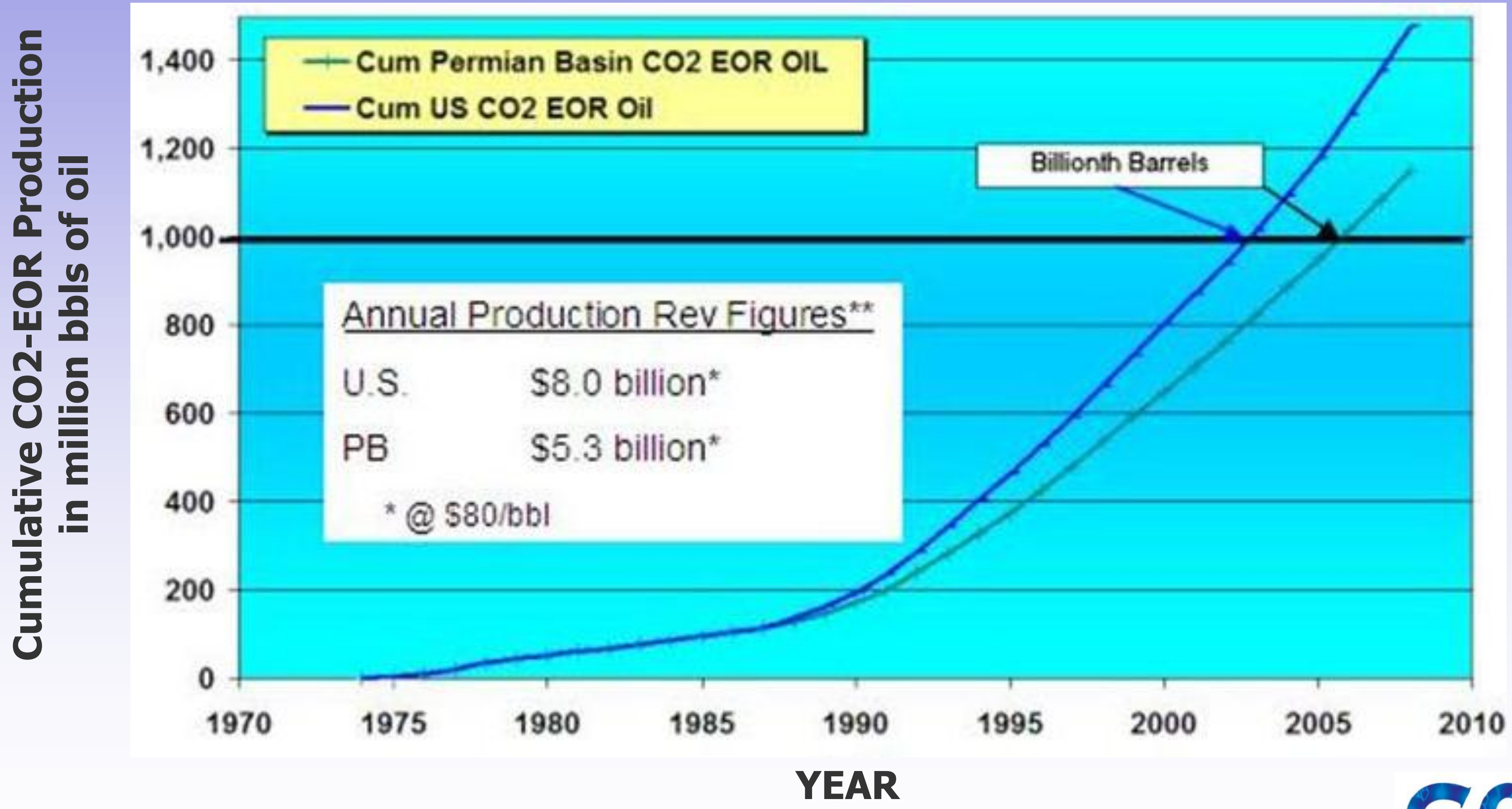
Cumulative CO2-EOR Oil Production

- Cumulative CO2-EOR oil production in the Permian Basin passed ONE billion barrels in 2006 representing ~80% of total U.S. capacity.



Annual Production Rev Figures**

U.S.	$8.0 billion*
PB	$5.3 billion*

* @ $80/bbl

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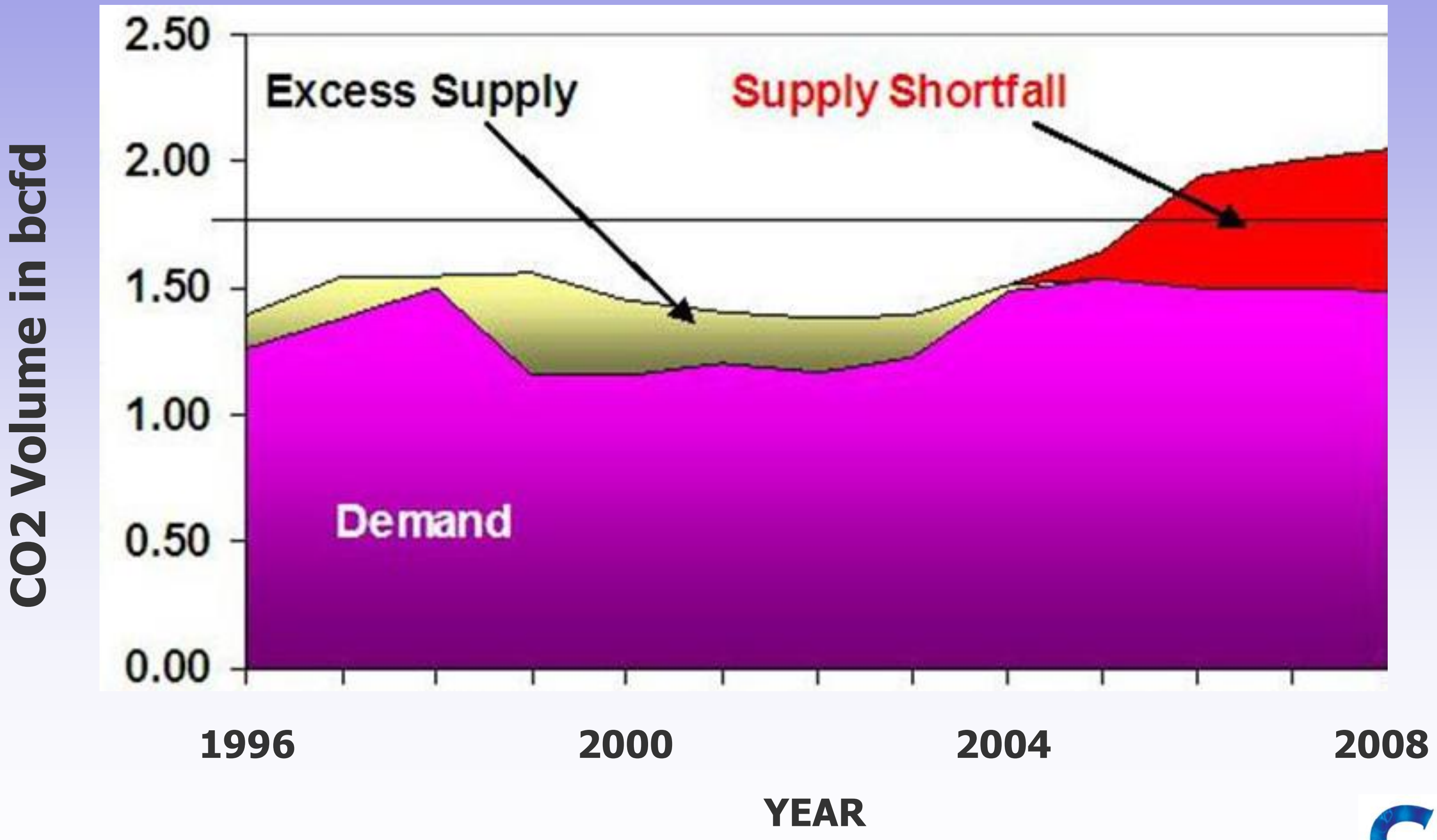
Historical Variation of Supply & Demand

- A changing market with current shortfall of ~550 MMcfd of CO2 supply.



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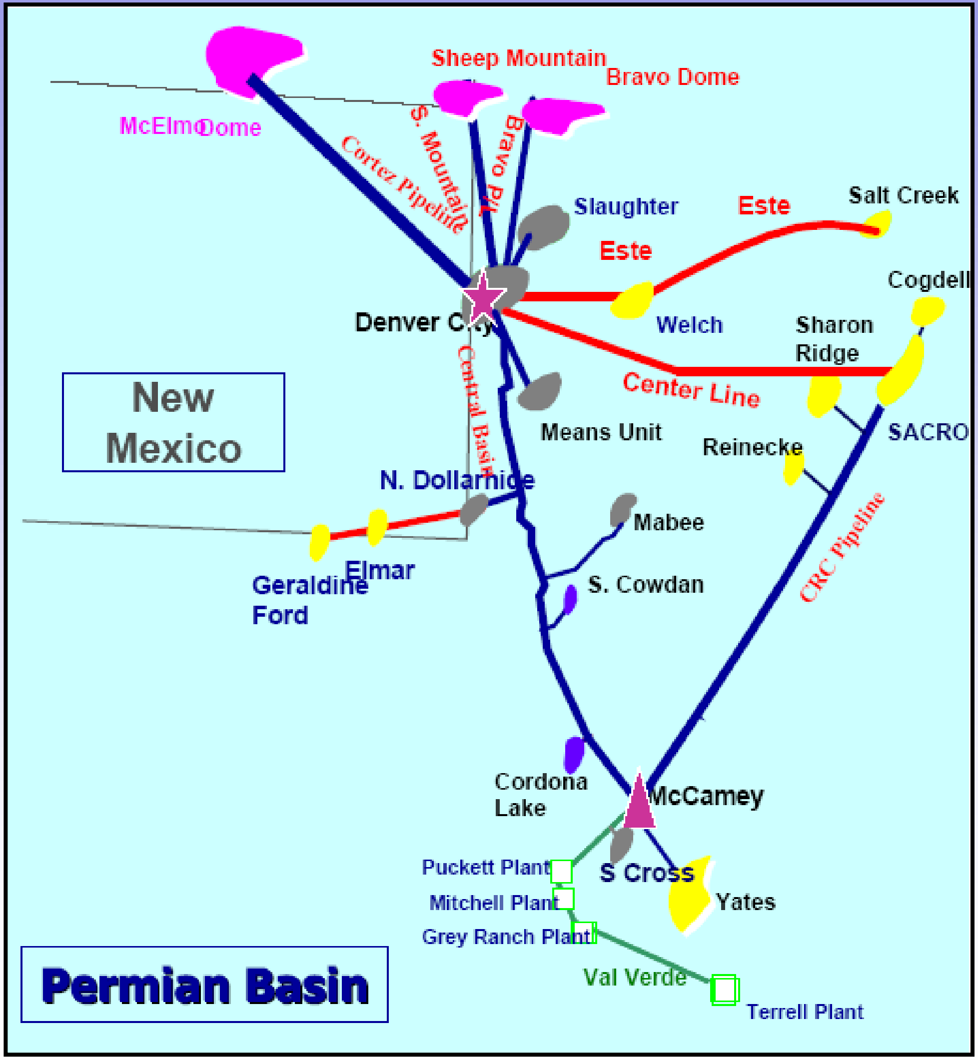
Pipeline Development during 1975 - 2005



Map by courtesy of David L. Coleman

- **Constructed over 30 years**
- **Economic Drivers**
  - Oil Price
  - Tax Incentives to ensure "Security of Supply"
- **90% Natural CO2 Supply**
- **Built by Shell & Mobil**
- **Main Players are now;**
  - ExxonMobil
  - Oxy-Permian
  - Kinder Morgan CO2
  - Denbury Resources
  - Trinity CO2

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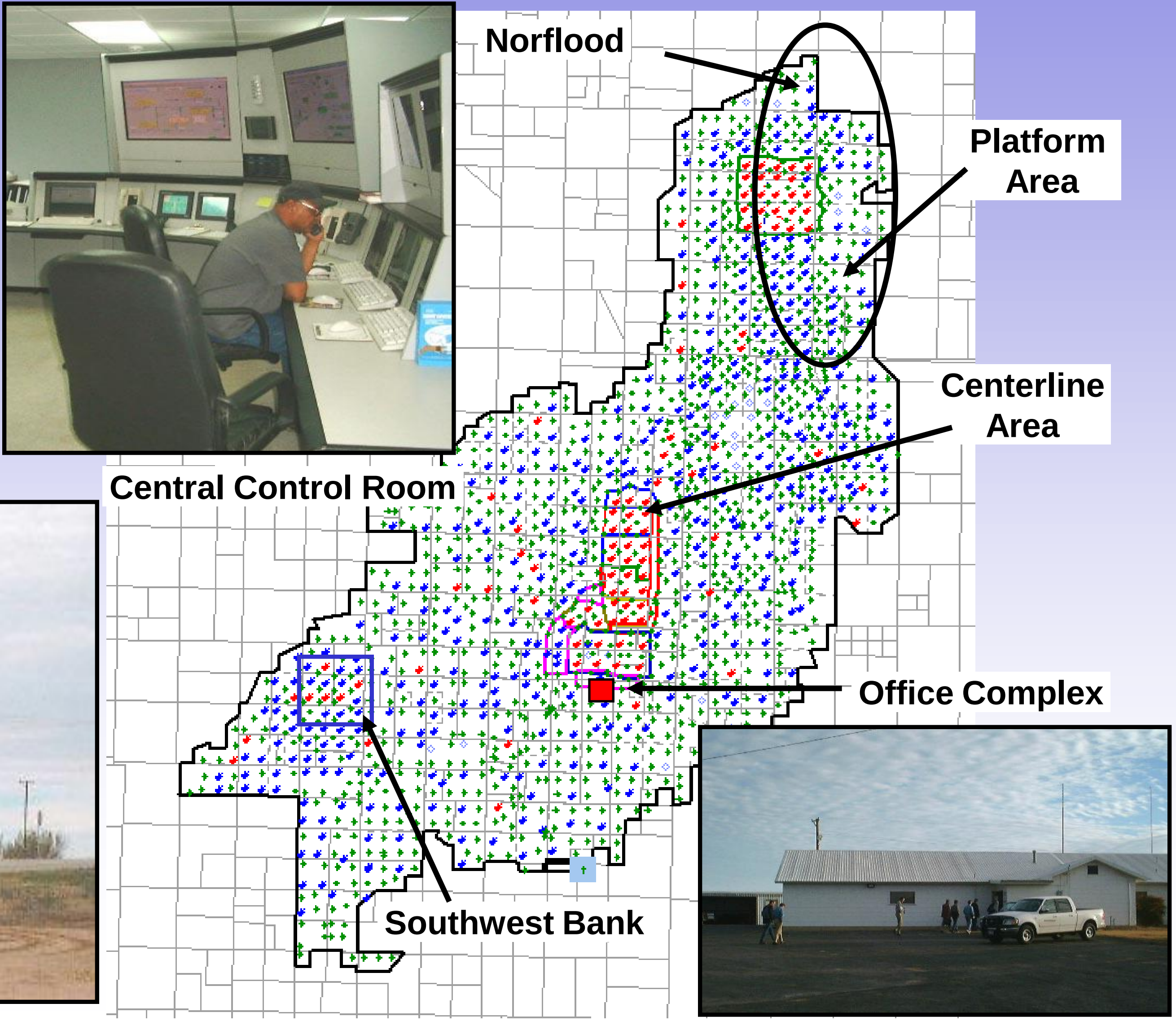
Status of Supply into the Permian Basin

- Present CO2 supply is 1.6 bcfd with ~180,000 bbls EOR production;
  - Market is significantly short with depletion in main supply domes
  - Estimated 0.5 - 1.0 bcfd shortfall leaving “pent-up” demand ...
  - Releasing this is very dependent upon timing!
  - ... but larger volumes of CO2 from power generation is difficult to integrate with current EOR opportunities despite the short market
  - Long-term supply and demand of both CO2 and power is therefore difficult to match.
- New focus on “CO2-rich” NG is opening supply-side, but also ...
  - Creating higher demand for compression power
  - Necessitates identification of a pathway for further expansion of the infrastructure
  - But can enable early transition from natural to anthropogenic CO2.
- Field operators need time and confidence regarding availability of future supply to invest in processing, handling and compression equipment.

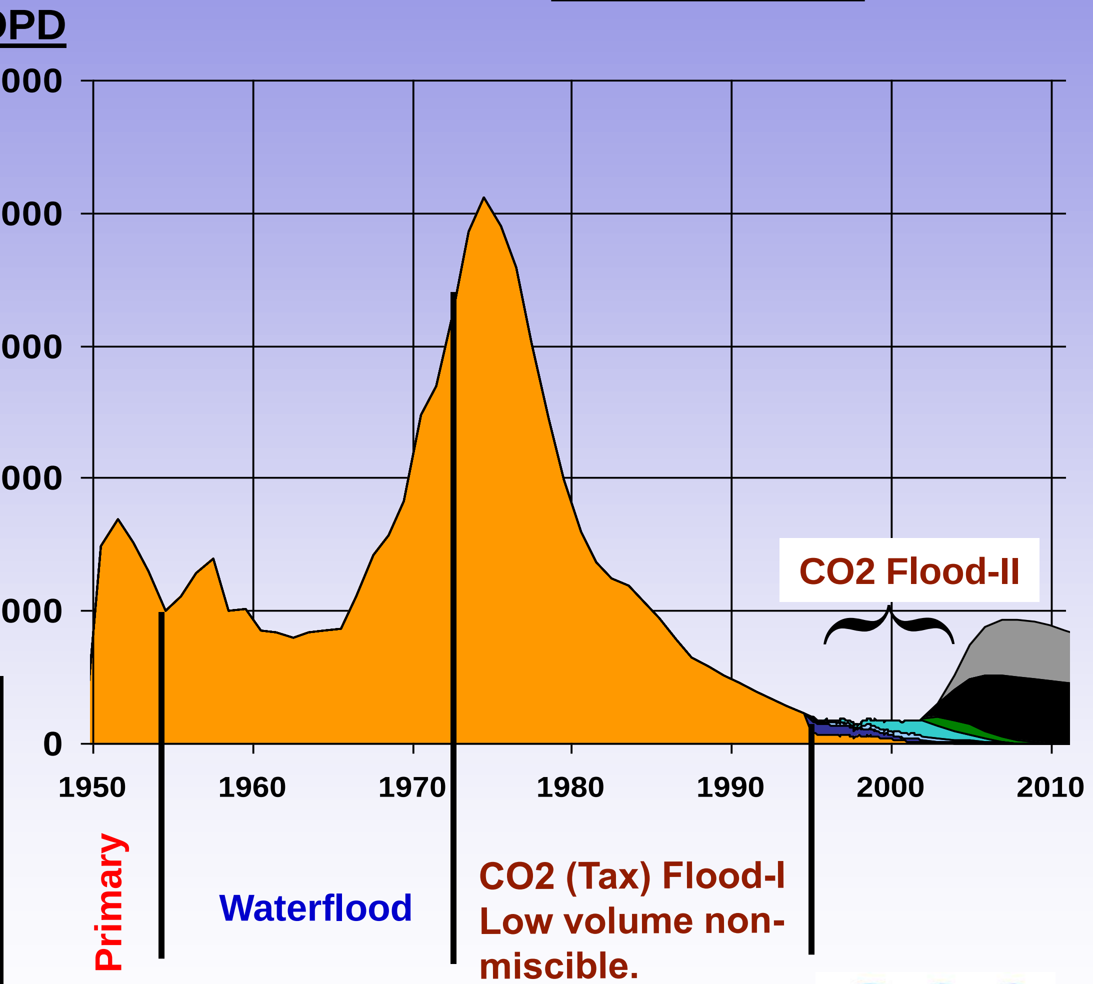
Case Study: CO2 - EOR at SACROC

- Discovered in 1948
- 81 square miles
- US 7th largest field
- 2.8 bn bbl OOIP
- Max. 211,000 BOPD
- ~1,700 wells



SACROC Production History

- **2003 Production**
  - **12,000 BOPD**
  - **94 MMscf/D**
  - **165,000 BWPD**
- **2003 Injection**
  - **200,000 BWPD**
  - **3.5 mtCO2/yr**
- **Tertiary Recovery**
  - **First injection 1972**
  - **CO2 from vent stacks (associated gas)**



Injector well with both CO2 and water for WAG EOR

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Producer Well Head Treatment


(1) Producer Well


(3) Oil and Gas Separator Tanks


(2) Well Header Manifold

CO2 Management & Recycling

Membrane module is packed with 5 micron diameter fibres providing a maximum contact area.

Membrane Separation System

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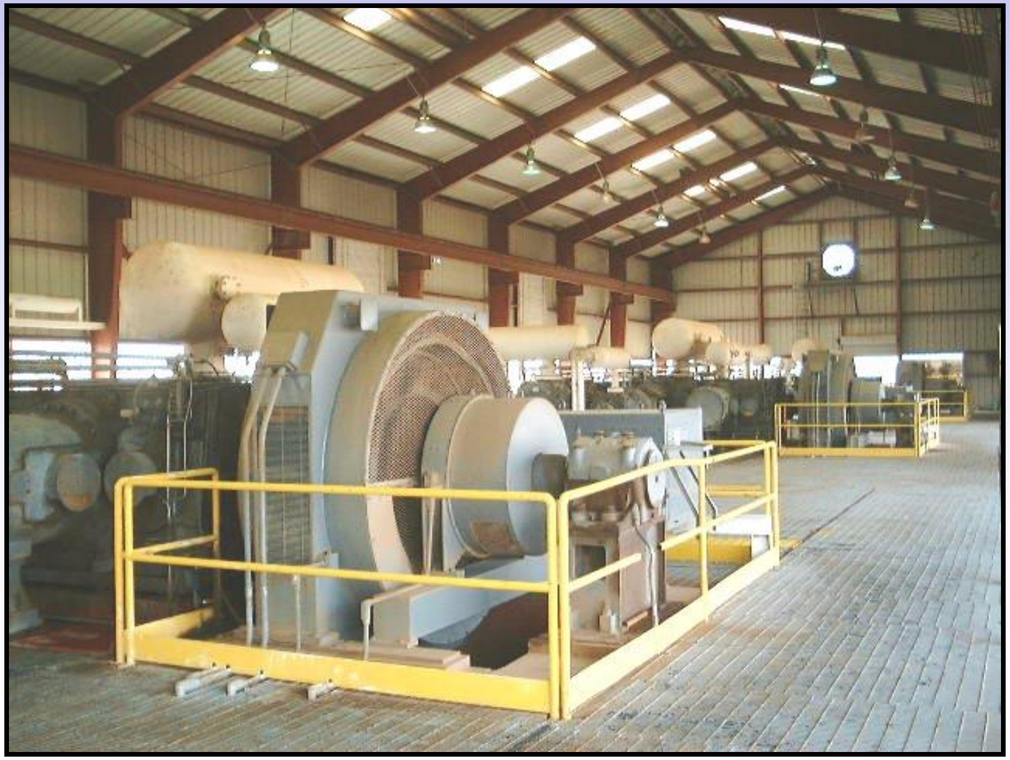
CO2 Compression Facilities

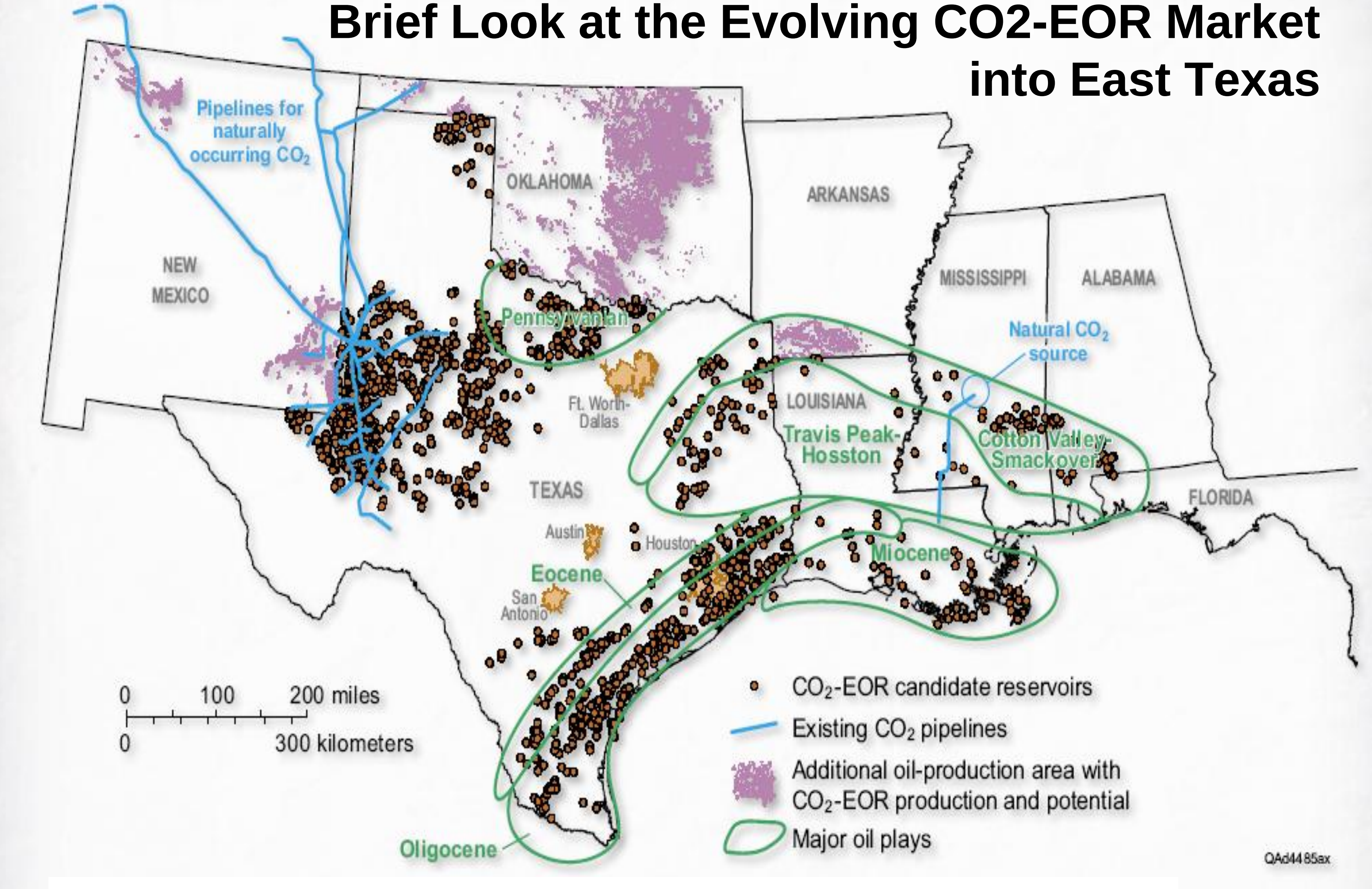

Termination of the CRC Pipeline into SACROC.

The CO2 Recompression Plant (in 2002)

- Ten compressors
- 30,000 H.P. installed
  - 1 at 2,000 H.P.
  - 4 at 2,250 H.P. each
  - 4 at 3,500 H.P. each
  - 1 at 5,000 H.P.
- Electric drive (synchronous)
- 90 mmscfpd (1.8 mt/yr) capacity
  - 20 mmscfpd at 7 PSIG
  - 70 mmscfpd at 40 PSIG
- 40 mmscfpd expansion on-going



Brief Look at the Evolving CO2-EOR Market into East Texas



- **House Bill 3732** provided tax incentives from 2008 for both anthropogenic CO2 and Advanced Clean Energy Projects.
- **Bailout Bill** included $10 credit per ton anthropogenic CO2-EOR

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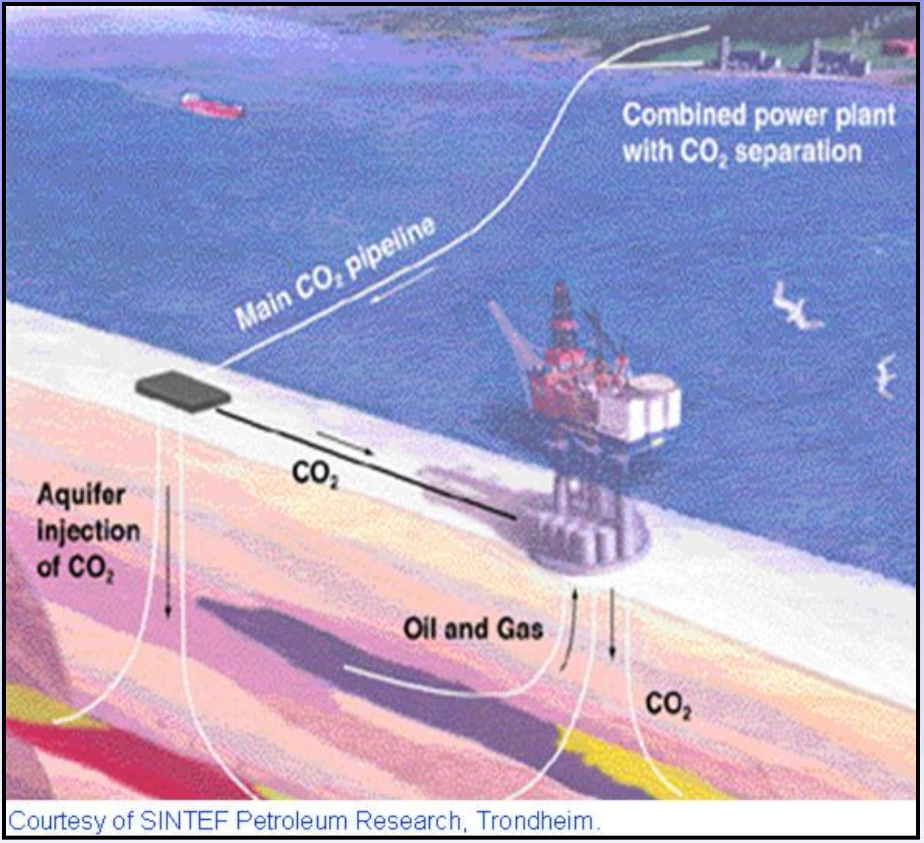
Early North Sea Infrastructure Concepts



Courtesy of SINTEF Petroleum Research, Trondheim.

Image taken from work by Torleif Holt & Erik Lindeberg, SINTEF (1999).

From *"The Norwegian CO2 Infrastructure Initiative: A Feasibility Study"* by Hustad, CO2-Norway AS. Presented at GHGT-5, Cairns, 2000.

Early NS CO2-EOR Concepts (1998)

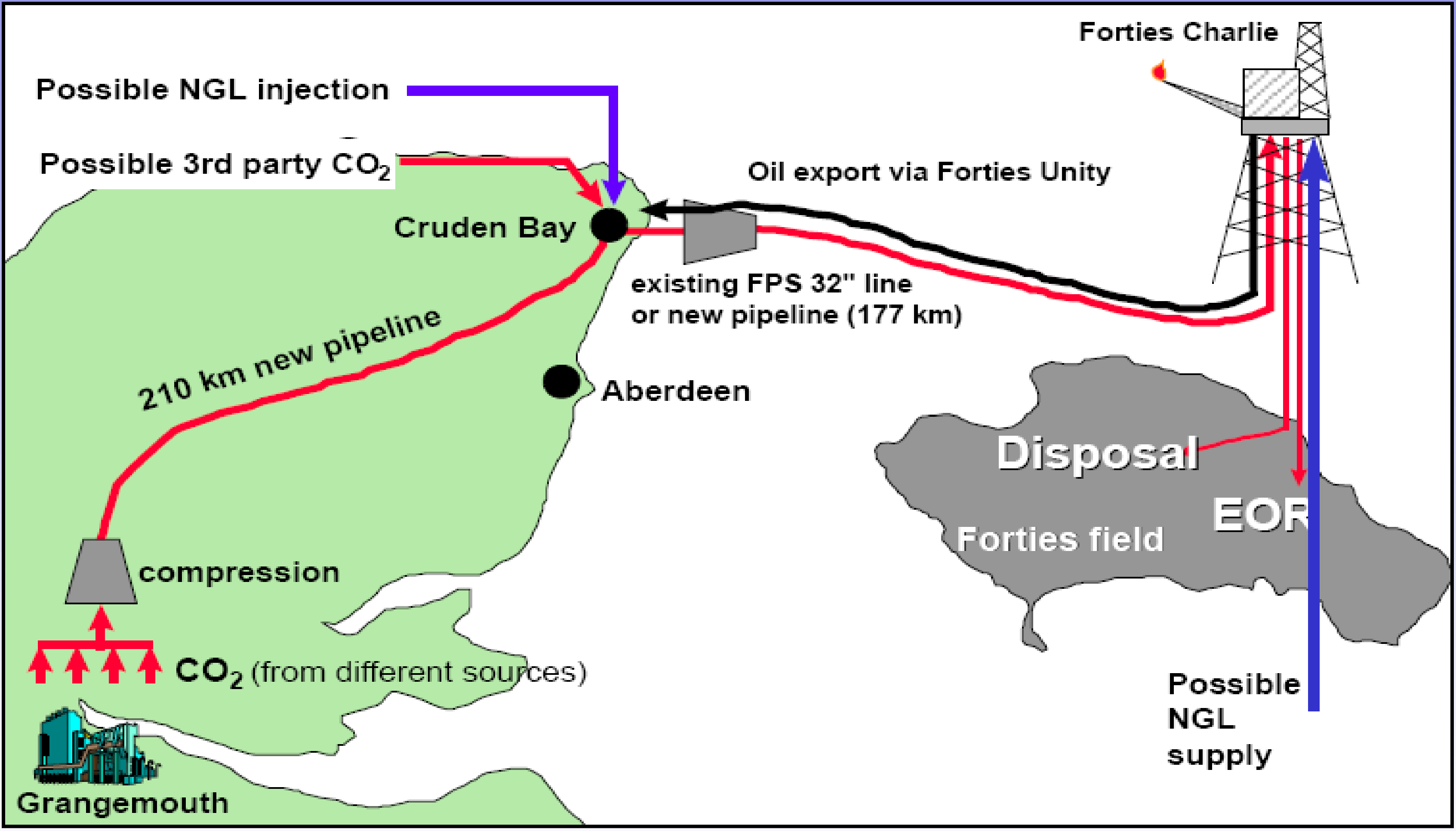


Image from *"Options for Establishing a North Sea Geological Storage Hub"* by Tony Espie, BP Amoco Exploration. Presented at GHGT-5, Cairns, 2000.

Elsam

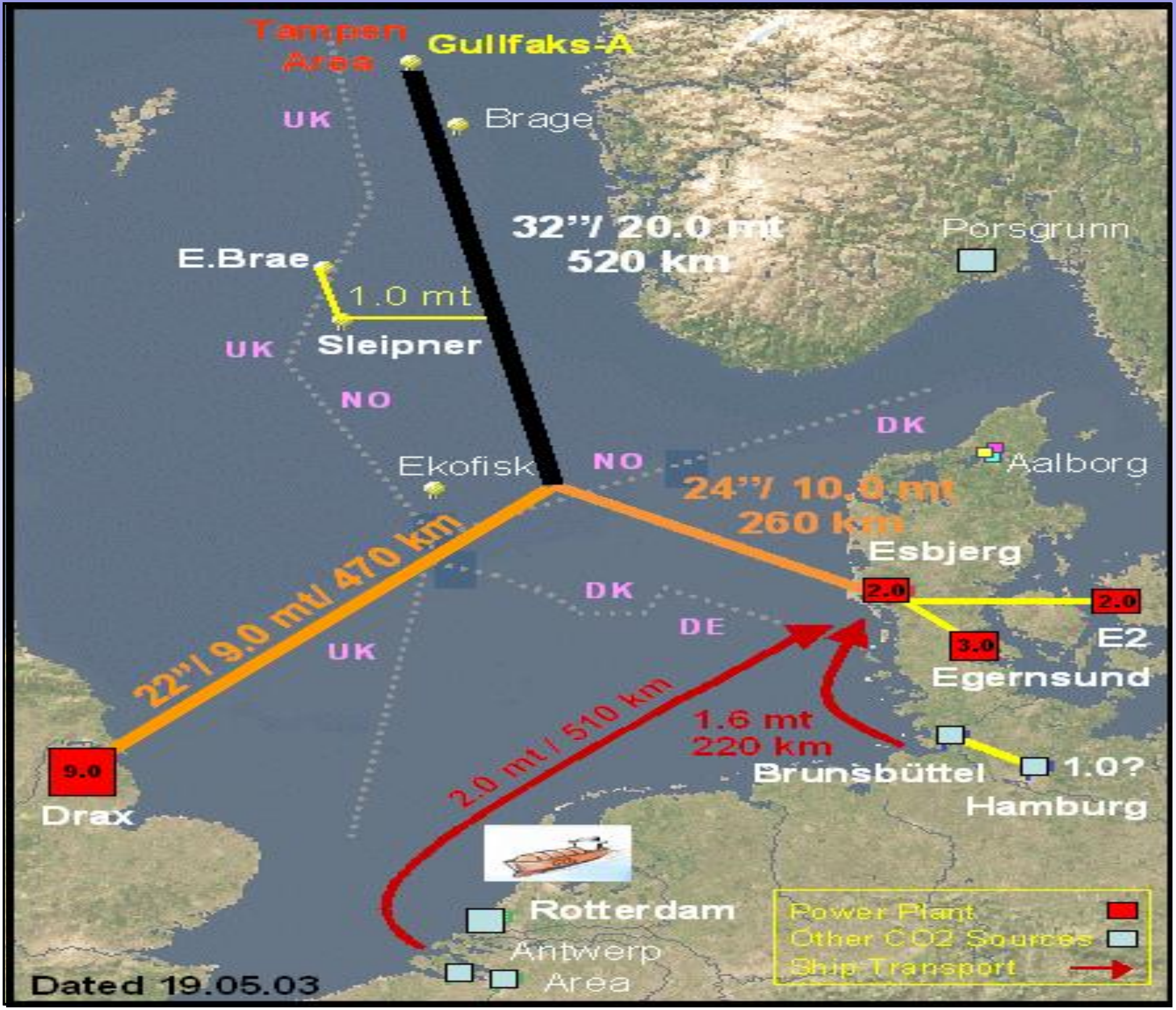
KINDER MORGAN CO$_2$ COMPANY, L.P.

Snøhvit

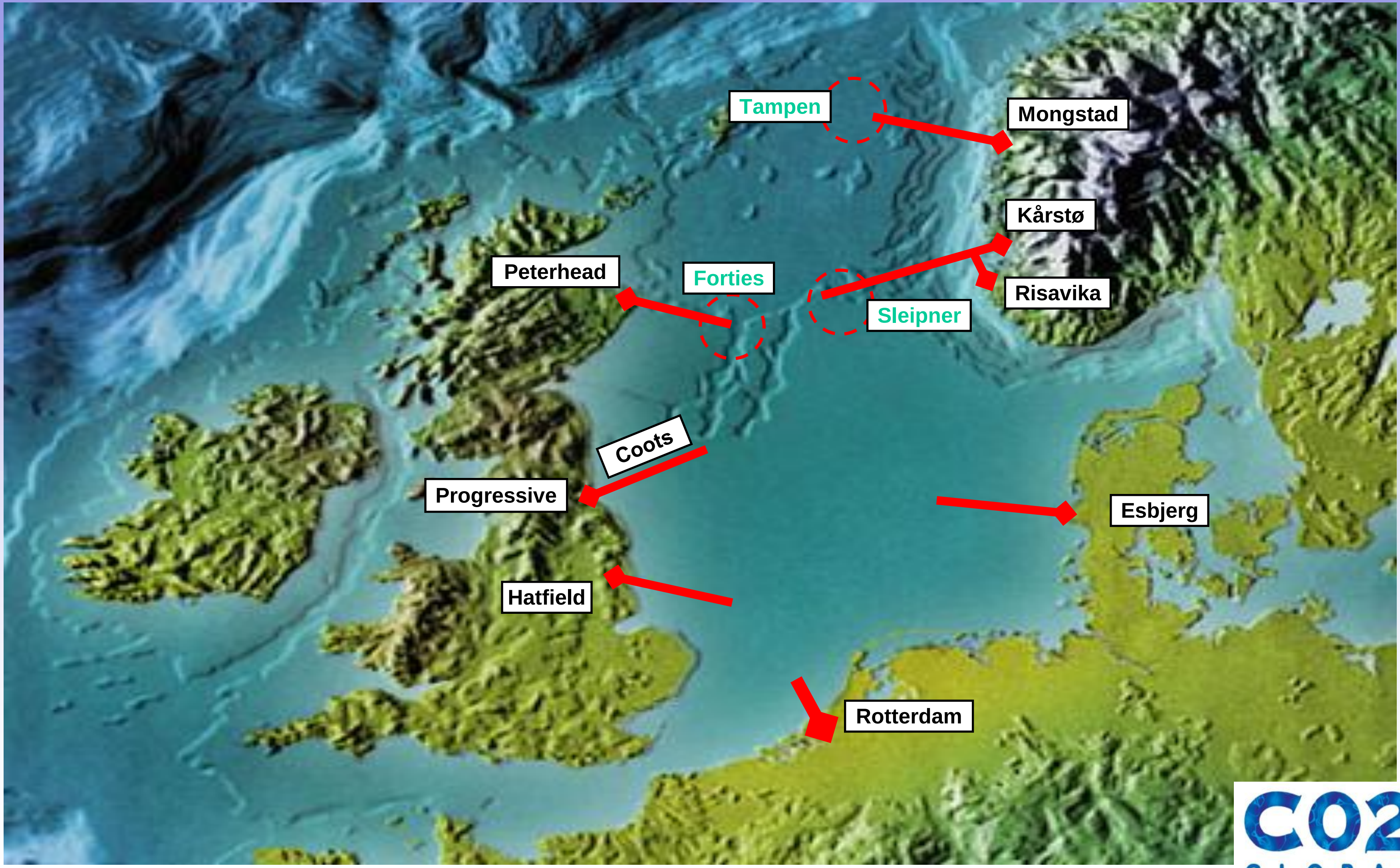
CENS Project (2001-2004) CO2 - EOR in the North Sea

- Potential delivery of CO2 for EOR through infrastructure at cost of ~ $35 /tCO2 (2002).
- Screening of the most mature EOR fields indicated potential of > 30 mtCO2/yr for +20 year period.
- A combination of pipelines and ship transportation enhanced flexibility and economics for initial EOR projects.

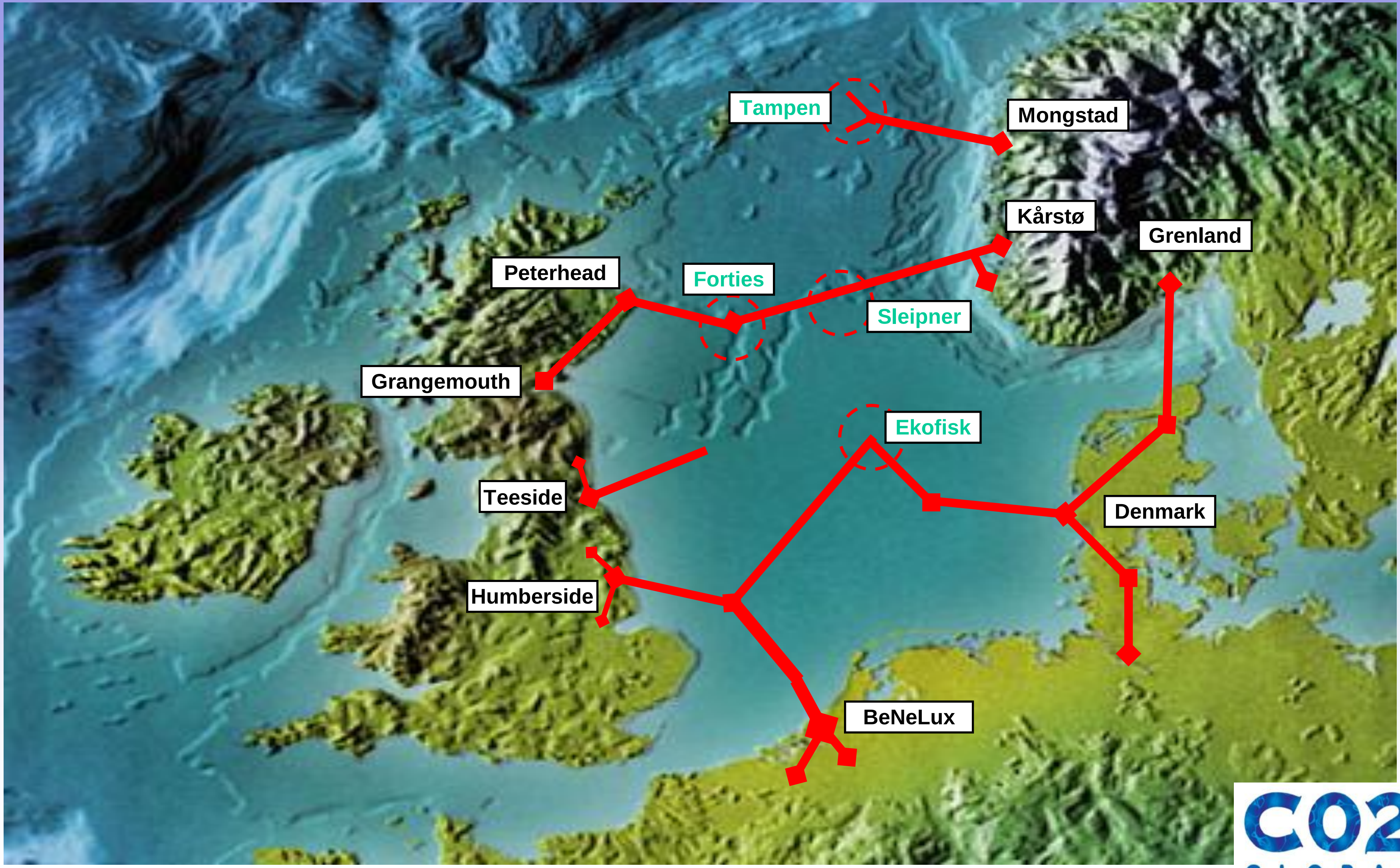
† Designated fields were “potential” CO2-floods.



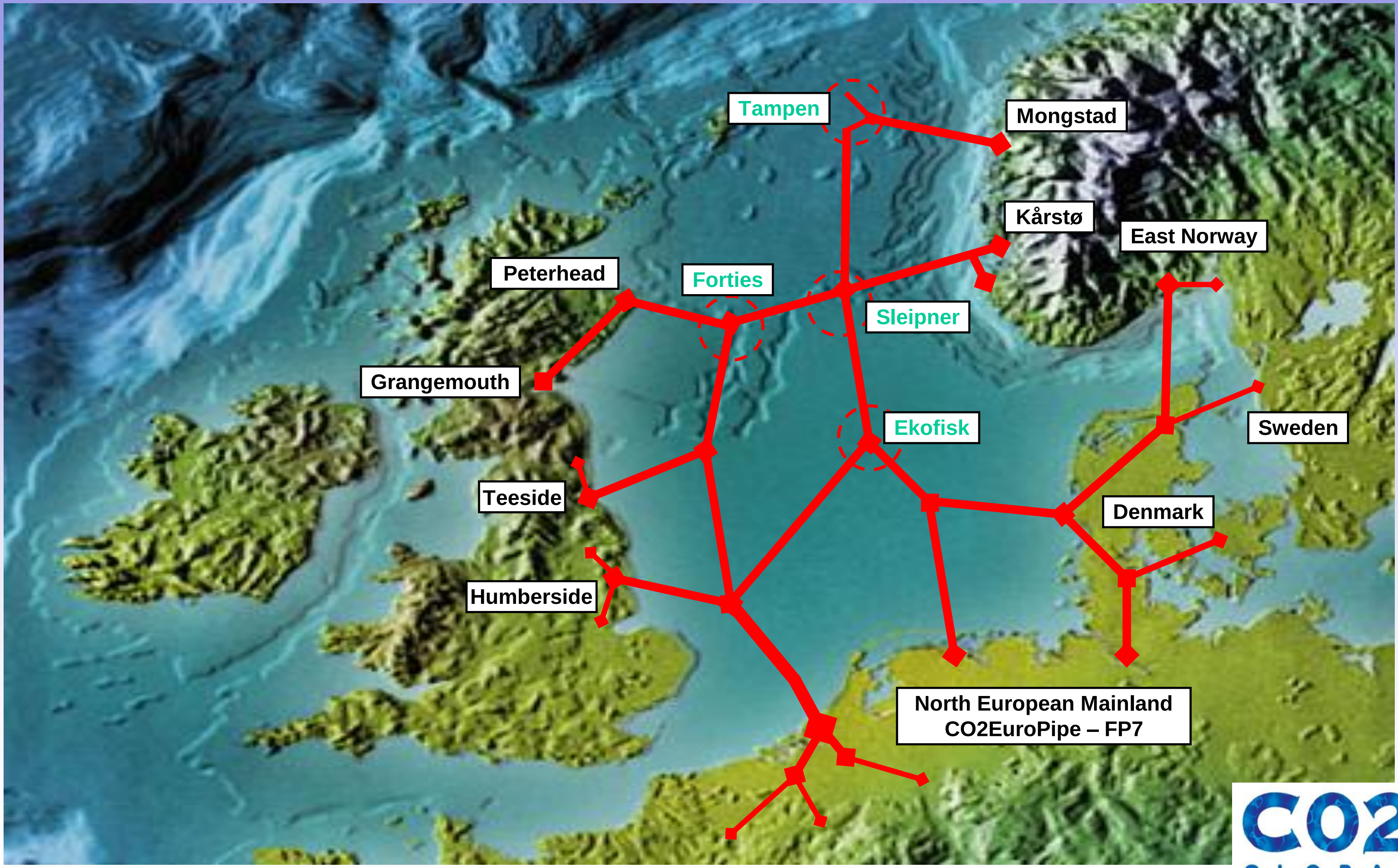
Future Roadmap: CENS Phase-1 Early Projects (2012 – 2015)



Future Roadmap: CENS Phase-2 Interconnections (2015 – 2025)



Future Roadmap: CENS Phase-3 System Looping (2025 – 2035)



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Deployment of Zero-Emission CES Power Plants for CO2-EOR in the Permian Basin

Project Development Presentation

November 2008

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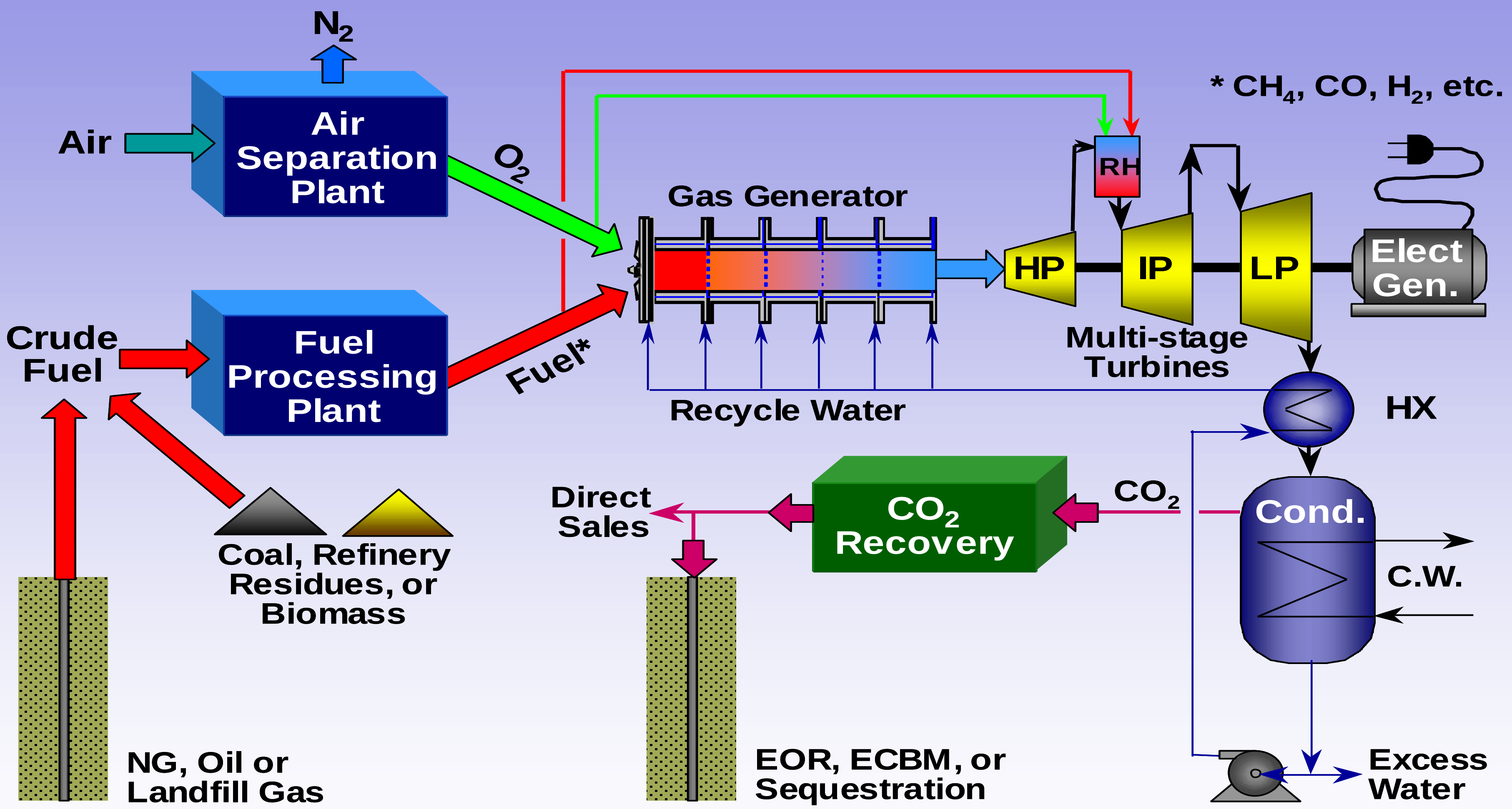
Overview of Presentation

- **The CES Zero Emission Power Plant**
  - The Multi-Fuel Oxy-Power Generation Concept
  - The Kimberlina Demonstration Power Plant
  - The 170 MW_t CES Gas Generator
  - Integration with the reconfigured GE J79 oxy-turbine expander
  - Technology Development Roadmap
- **Commercial Deployment of CO2 with Power**
  - Unique features needed for success
  - Managing project risk and upsides
  - Opportunities for future growth
  - The development team and partnership

Schematic Overview for the Multi-Fuel Capability of the CES Power Plant



Clean Energy Systems Inc.
Sacramento, Ca.

The CES Demonstration Power Plant

- Since 2005 CES have deployed the technology at their 5 MW_e Kimberlina Power Plant, nr. Bakersfield, Ca.;
  - First generation 20 MW_t Gas Generator has completed +1,500 hr.
  - More than 300 start / stop sequences
  - Demonstrated extensive multi-fuel capability (incl. “low-btu” gas)
  - Received insurance cover in 2006
  - Supplies no-NOx power to PG&E.


Kimberlina Power Plant - 2005

- Second generation 170 MW_t Gas Generator is currently being tested for commercial delivery starting 2010;
  - Extensively skid-mounted
  - All-up plant Capex is $125 – $150 m inclusive of ASU & CO2-compression
  - Can be fully installed on-site in the Permian Basin by late-2010.

- Key performance parameters are;
  - 50 MW_e power available for export
  - 15 MMBtud fuel-gas used
  - 15 – 30 MMcfd (supercritical) CO2 available for export
  - 160,000 galls/day water produced
  - 28 MMcfd Nitrogen.

The CES Zero Emission Power Plant

- Installation of the170 MW_t CES Gas Generator on-site at Kimberlina;
  - Design and production started in 2006.
  - Installed and first-firing 3Q-2008.
  - Gas Generator is fully containerised and skid-mounted.
  - Undergoing final verification and endurance testing during 2009 prior to commercial deployment.

Kimberlina Oxy-Test Facility - 2008

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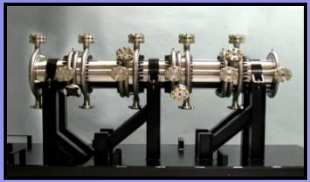
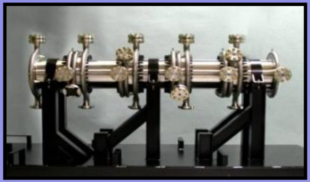


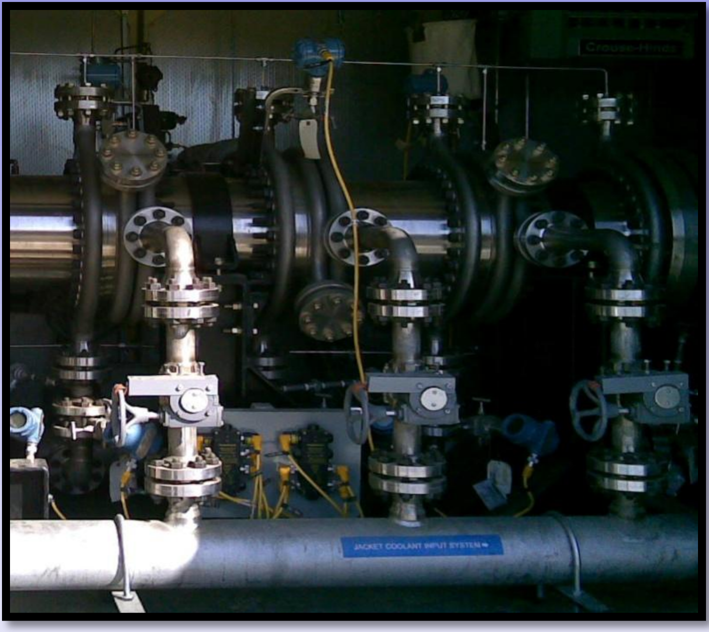
The CES 170 MW_t Gas Generator

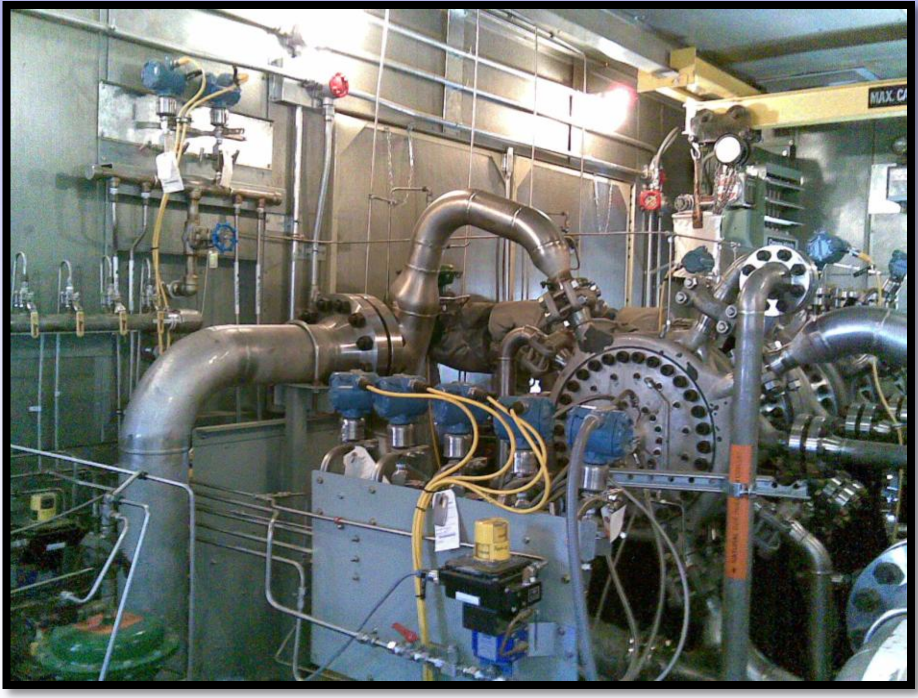
- A unique oxygen and fossil-fuel combustor based on well-proven rocket propulsion technology;
  - Very compact design with no moving parts
  - Easily interchangeable components
  - The 20 MW_t prototype has been operating in the demonstration plant since 1Q-2005.
- More than $100 million investment in development work since 1998;
  - Funded by California Energy Commission (CEC) and U.S. Dept. of Energy
  - Collaborating with major industrial gases, energy and power companies
  - CES also have private investment capital to commercialise the technology.



The CES 170 MW_t Gas Generator

- Detail below showing Gas Generator “in-situ” inside container with main feed lines for fuel gas, oxygen and water entering into the combustor section.

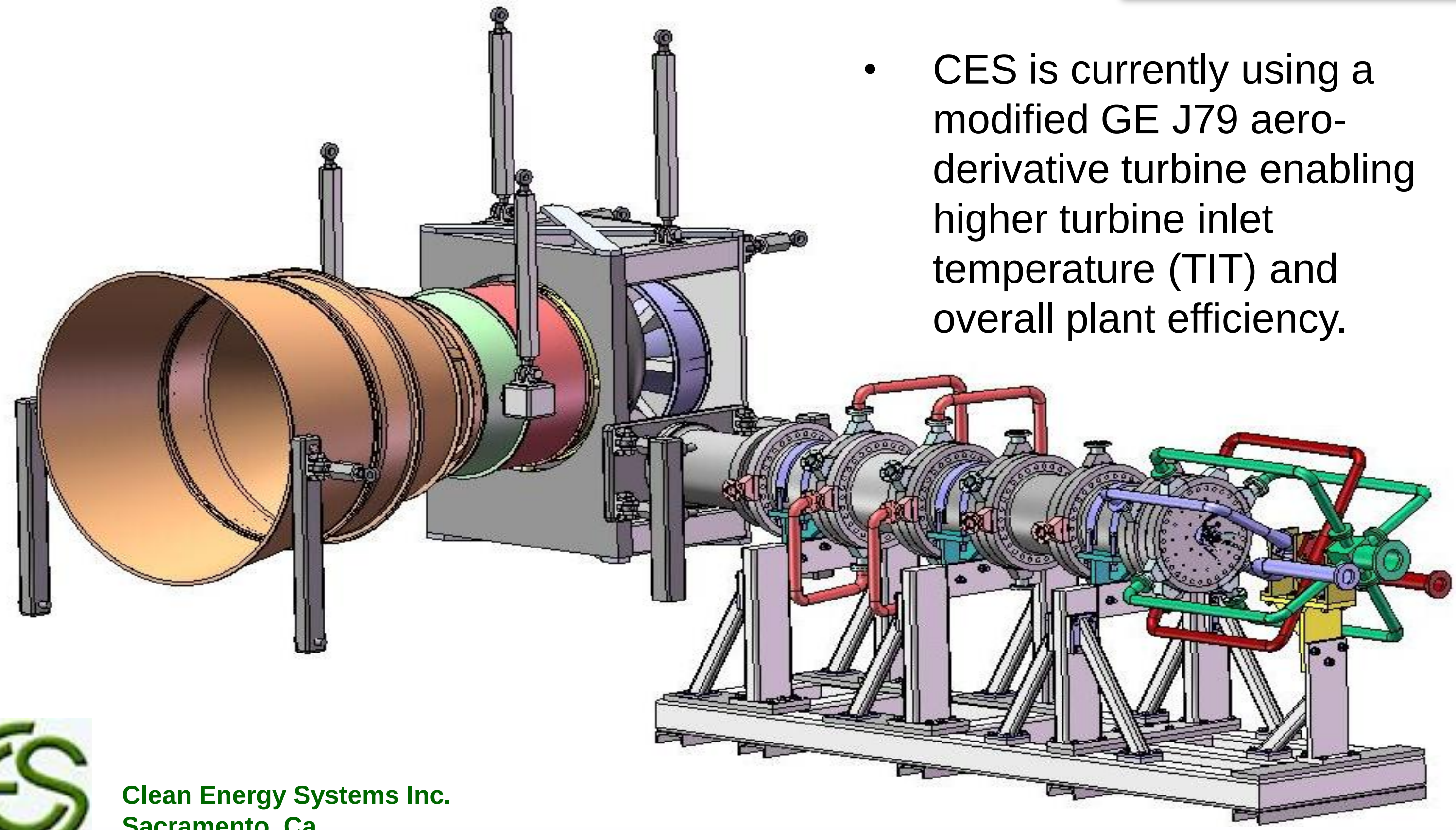




- Detail above showing multiple staged-cooling sections (with water injection) to control temperature before entering the turbine expander.

The Oxy-Turbine Expander

- The Gas Generator produces high-pressure and high-temperature steam (with ~10%-mol CO_2).
- To date CES have been expanding this through a conventional steam turbine (shown right).



- CES is currently using a modified GE J79 aero-derivative turbine enabling higher turbine inlet temperature (TIT) and overall plant efficiency.

The CES Kimberlina Oxy-Test Facility

- The GE J79 Oxy-Turbine was installed during 4Q-2008 following successful initial commissioning of the Gas Generator that was undertaken during 3Q-2008.
- Image (from Sept 2008) shows foundations with tie-in to the Gas Generator in container and exhaust stack.

- The Kimberlina Oxy-Test Facility is currently limited by fuel and Oxygen supply to max. 80 MW_t input representing 40% of the Gas Generator power capability.
- A full-size 170 MW_t power plant is being constructed on site for operation in 2011 as part of the Dept. of Energy Carbon Sequestration Program.

Clean Energy Systems Inc.
Sacramento, Ca.

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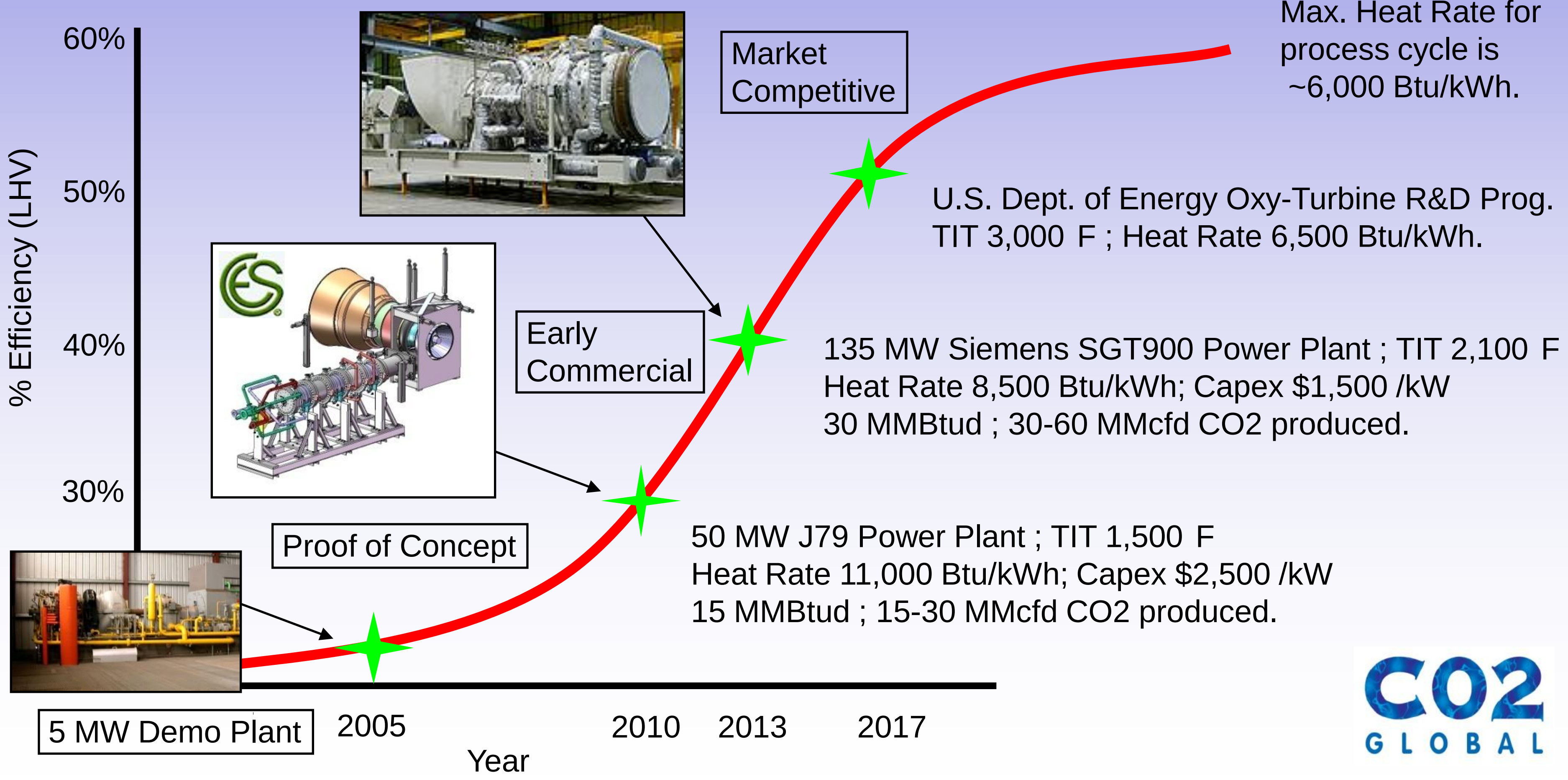
Technology Development Roadmap

- The Zero Emission CES technology has an identified commercial pathway to higher efficiency and reduced costs in order to become competitive with established coal and NG power generation.



Max. Heat Rate for process cycle is ~6,000 Btu/kWh.

U.S. Dept. of Energy Oxy-Turbine R&D Prog.
TIT 3,000 F ; Heat Rate 6,500 Btu/kWh.

135 MW Siemens SGT900 Power Plant ; TIT 2,100 F
Heat Rate 8,500 Btu/kWh; Capex $1,500 /kW
30 MMBtud ; 30-60 MMcfd CO2 produced.

50 MW J79 Power Plant ; TIT 1,500 F
Heat Rate 11,000 Btu/kWh; Capex $2,500 /kW
15 MMBtud ; 15-30 MMcfd CO2 produced.

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Unique Features Needed for Success

- The First Generation CES Power Plant will exploit unique niche market opportunities in the Permian for near-term commercial deployment;
  - Use of low-quality “CO2-rich” untreated fuel-gas
  - Strategically site power plants in order to take advantage of CO2 demand
  - Initial opportunity for CO2 supply is independent of pipeline investment ...
  - But long-term will want to access the CO2-pipeline infrastructure
  - Can supply “Base-load” power at outer edges of the ERCOT electricity grid.
- A detailed knowledge of the Basin is therefore necessary to identify and get access to such special locations.
- There is a clear “First-Mover” advantage obtained by providing anthropogenic CO2 to the region.
- The CES Power Plant will also open other “new” and larger project opportunities for partners and investors in the future.

Managing Project Risk & Upsides

- Deployment of zero emission power generation combined with CO2 capture for EOR has not been done commercially before ...
- However Technology Risk is low because the core new component comprising the CES Power Unit is;
  - Modularised, flexible and predominantly skid-mounted
  - Represents only ~25% total plant investment capex
  - The ASU is well proven and represents ~35% total capex
  - Penalty for oxygen production will reduce in the future due to an increasing demand for large-scale oxygen plants in industrial processes
  - Remaining Balance of Plant is based on standard components.
- Market Risk needs to be reduced through long-term contracts;
  - For power and fuel this is feasible
  - For CO2 it is possible with a dedicated CO2-transporter managing risk and volume fluctuations throughout power plant project life.
  - Increased shortfall of CO2 in the Permian Basin is a market driver.
- Commercial Risk is manageable despite general engineering cost-fluctuations and early implementation of zero-emission power plant technology but that will also target future market for CCS.

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The CO2-Global Development Team

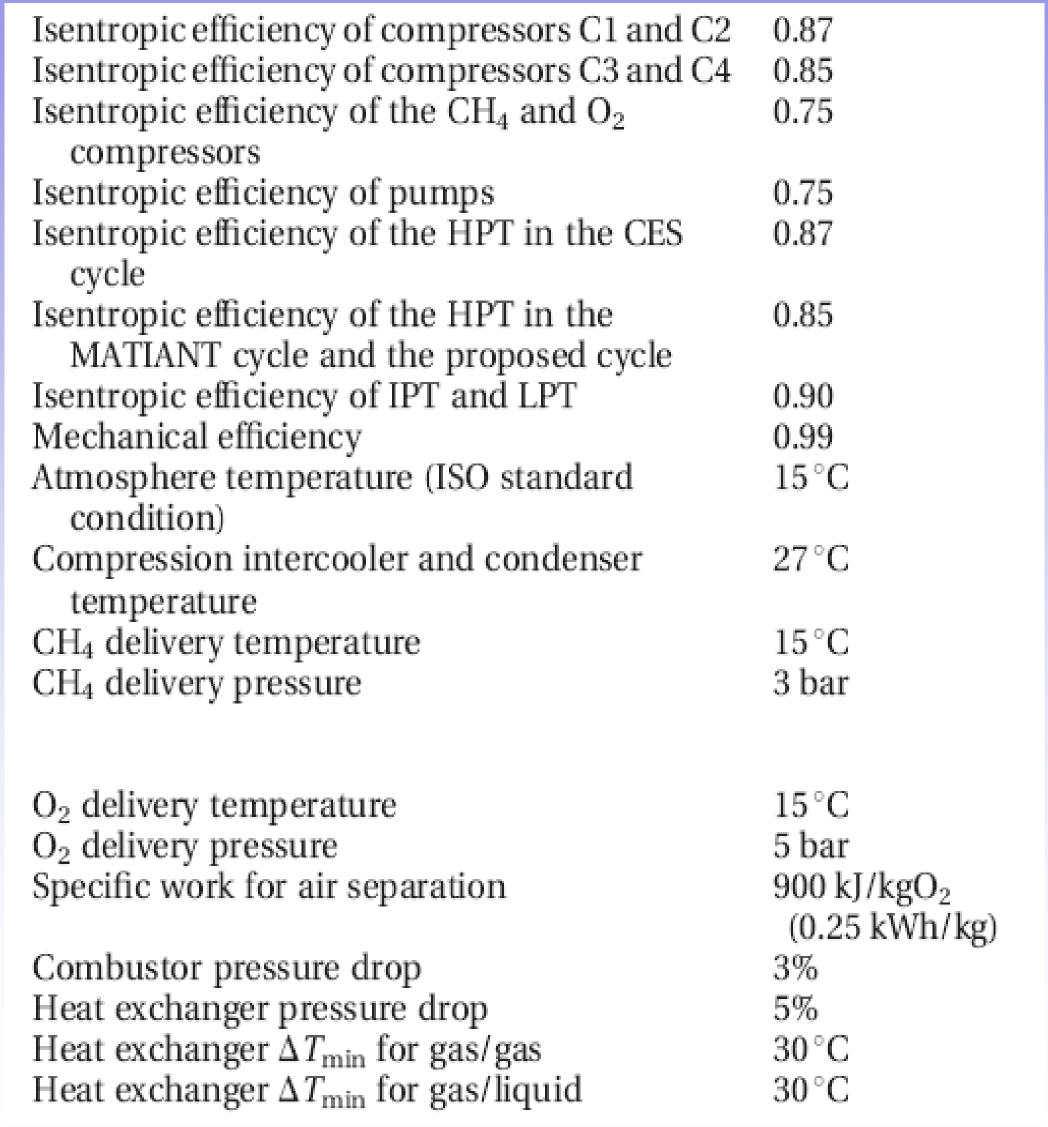
- CO2-Global has a core management team with in-depth experience from following areas;
  - Power plant & commercial contract development
  - CCS technology (RD&D) + commercialisation
  - Power and energy market trading
  - Corporate and Senior Board experience
  - Strong investor backing
- CO2-Global has long relationship with CES including;
  - Unique rights of technology deployment for CO2-EOR in the Permian Basin
  - Non-circumvention for other identified projects
- CO2-Global is collaborating with key companies in the Permian;
  - Nicholas Consultancy Group is a leading surface plant process design and CO2 engineering company based in Midland, Tx.
  - Trinity CO2 Company has extensive assets in the Permian Basin;
    - Owns and operates over 200 miles CO2 pipeline
    - Buys, sells and transports 200 MMcfd CO2

Overview of Recent Comparisons for Advanced Oxyfuel Cycles

Main Oxyfuel Cycles Considered

- Original MATIANT CO2 Cycle (1994)
- Basic CES Water Cycle (2003)
- S-Graz Cycle (2004)
- LP Reheat Cycle (2005)
- LP Reheat Regenerative (Recycle) Cycle (2006)
- ZENG LP-Twin Cycle (July 2007)
- CES – ZENG Cycle (Aug 2007)

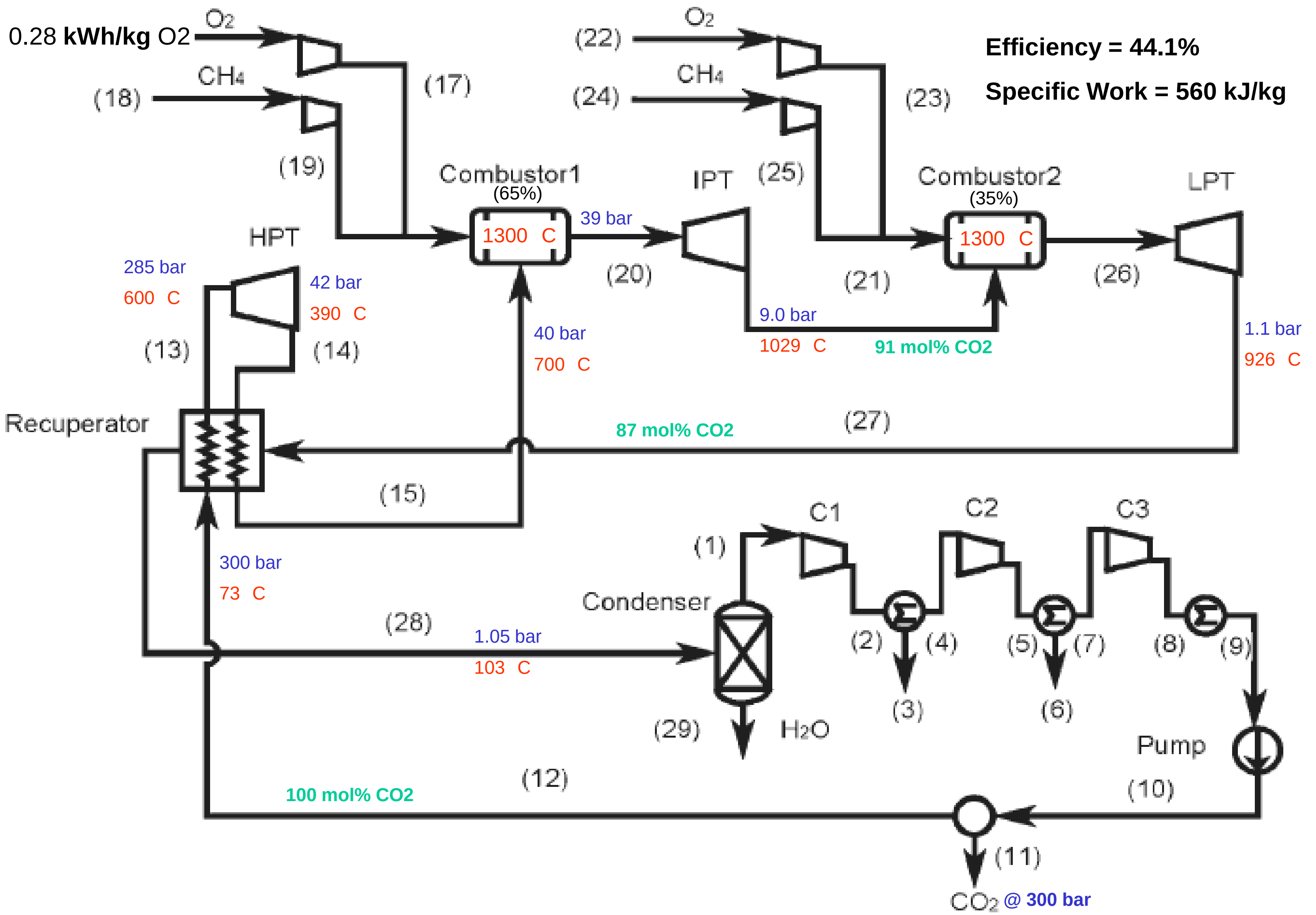
Computational Assumptions



Isentropic efficiency of compressors C1 and C2	0.87
Isentropic efficiency of compressors C3 and C4	0.85
Isentropic efficiency of the CH_4 and O_2 compressors	0.75
Isentropic efficiency of pumps	0.75
Isentropic efficiency of the HPT in the CES cycle	0.87
Isentropic efficiency of the HPT in the MATIANT cycle and the proposed cycle	0.85
Isentropic efficiency of IPT and LPT	0.90
Mechanical efficiency	0.99
Atmosphere temperature (ISO standard condition)	15 °C
Compression intercooler and condenser temperature	27 °C
CH_4 delivery temperature	15 °C
CH_4 delivery pressure	3 bar
O_2 delivery temperature	15 °C
O_2 delivery pressure	5 bar
Specific work for air separation	900 kJ/kgO_2 (0.25 kWh/kg)
Combustor pressure drop	3%
Heat exchanger pressure drop	5%
Heat exchanger ΔT_{min} for gas/gas	30 °C
Heat exchanger ΔT_{min} for gas/liquid	30 °C

- Aspen Plus Simulator Code
- Peng - Robinson EOS
- Max. Combustor Exit Temp. (CET) is 1300 C
- Heat loss and blade-cooling reduced efficiency ~2%-point
- CO2 compressed to 300 bar
- C2 and C3 have PR=8.9
- Condenser pressure 0.11 bar

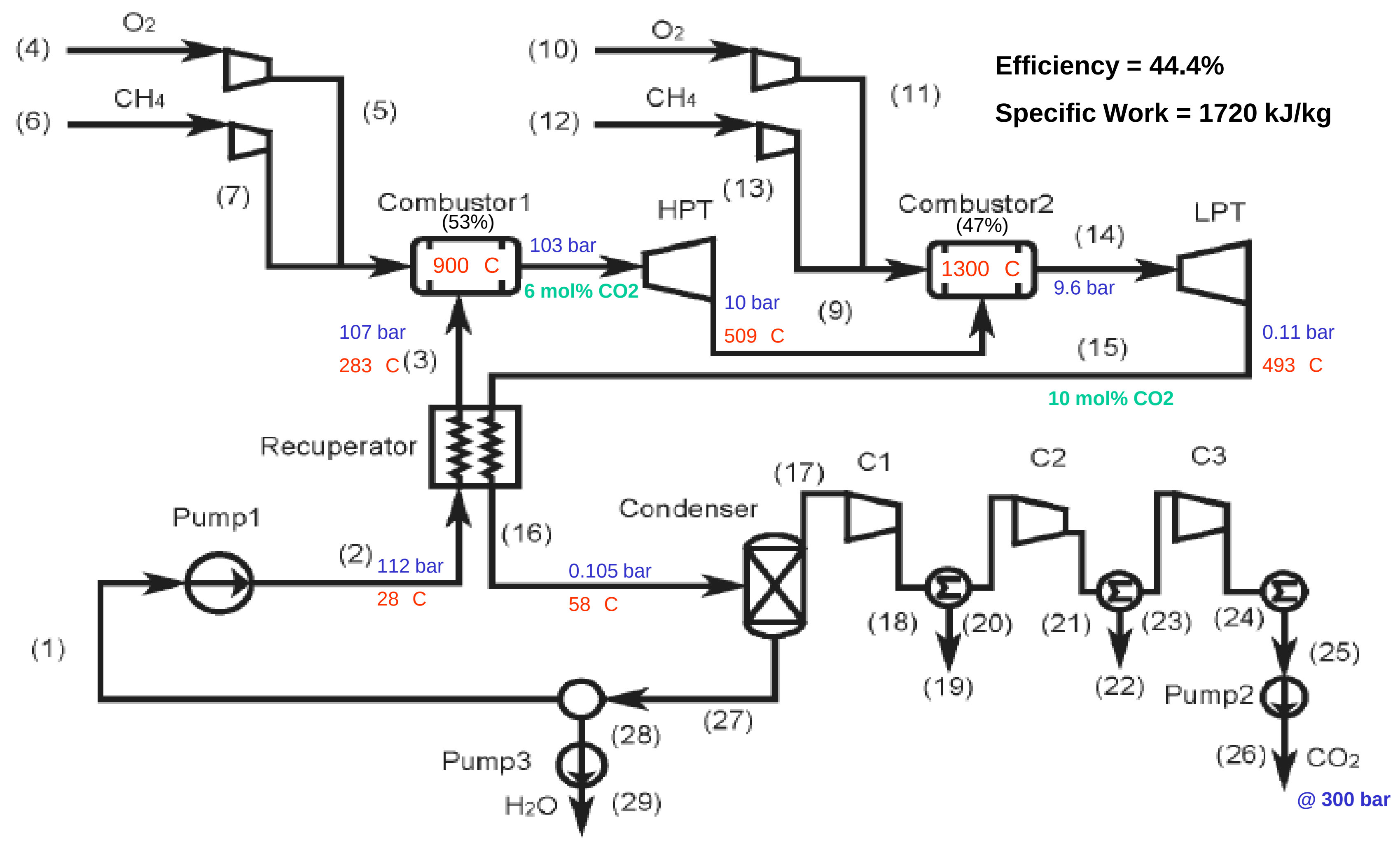
The MATIANT CO2 Cycle



Efficiency = 44.1%

Specific Work = 560 kJ/kg

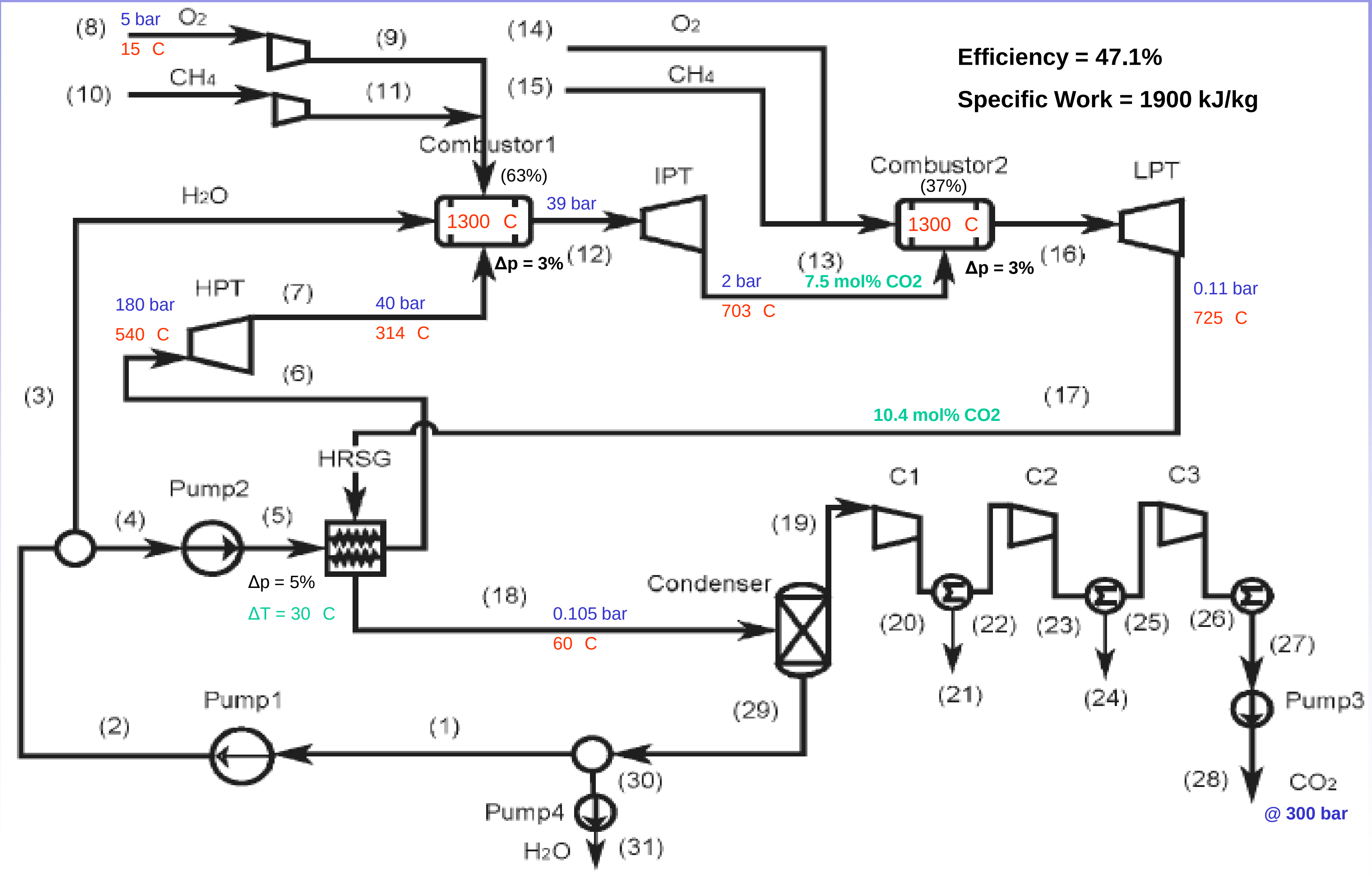
Basic CES Water Cycle



Efficiency = 44.4%

Specific Work = 1720 kJ/kg

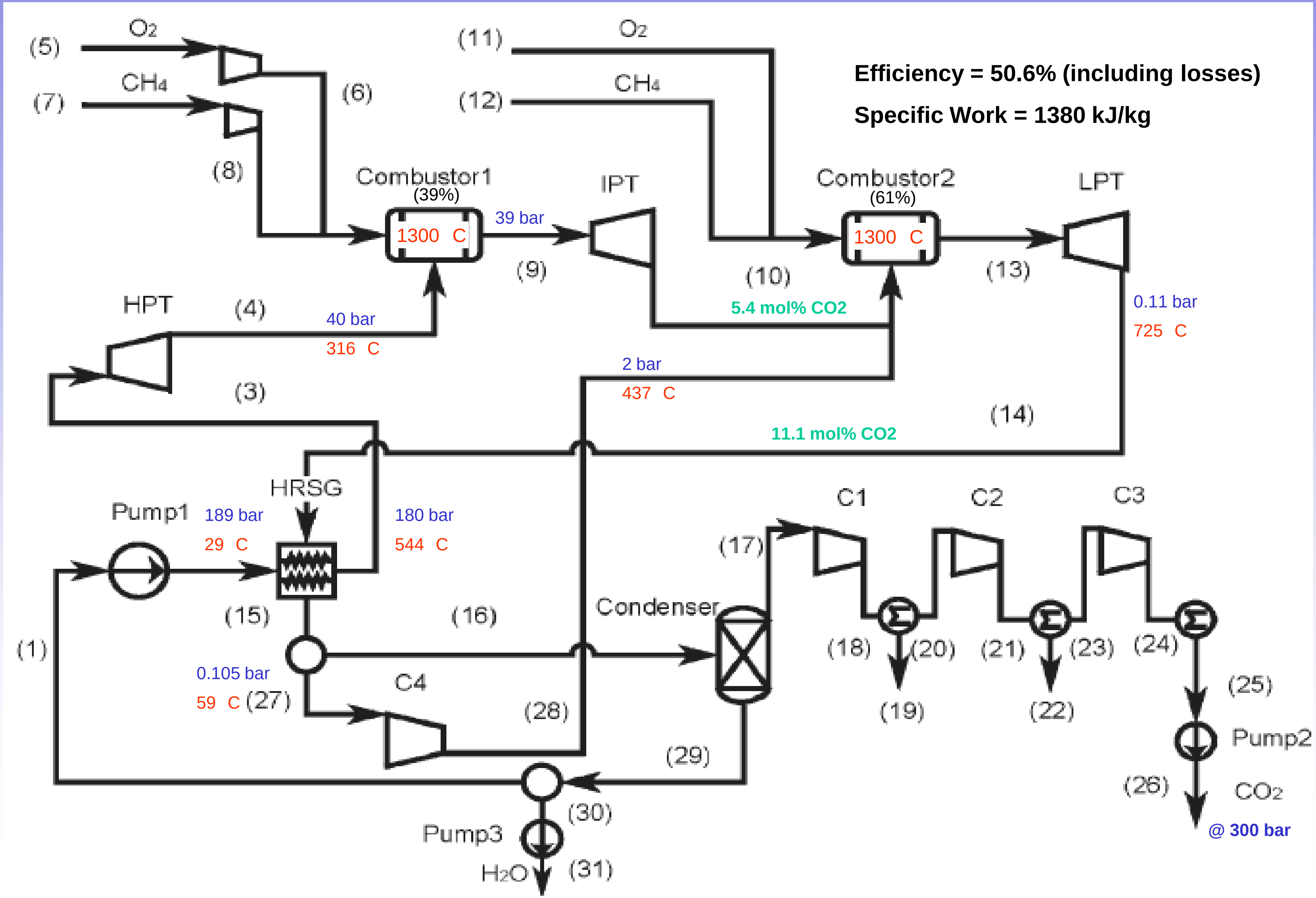
Low Pressure (LP) Reheat Cycle



Efficiency = 47.1%

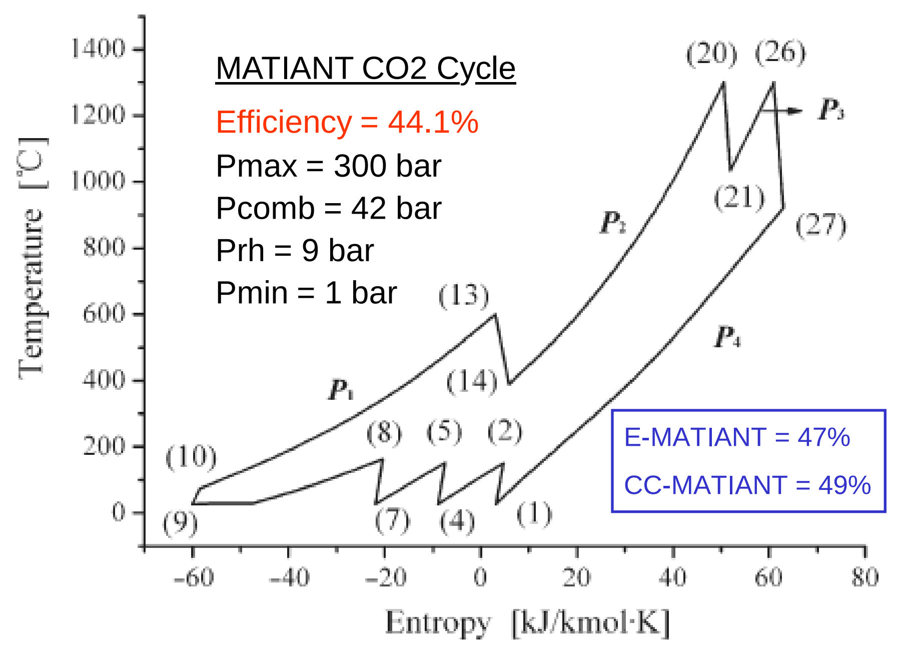
Specific Work = 1900 kJ/kg

LP Reheat (RH) Regen Cycle



Efficiency = 50.6% (including losses)

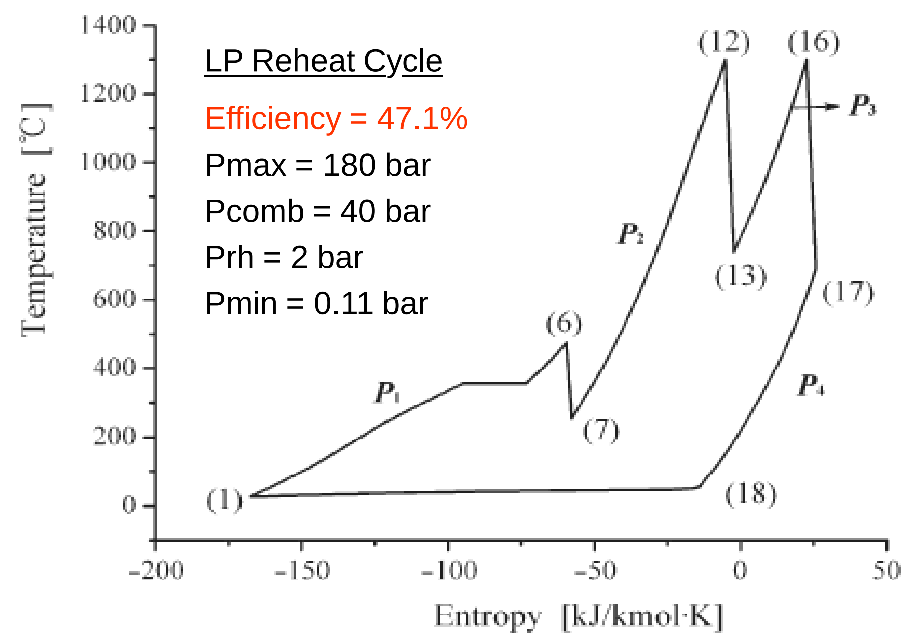
Specific Work = 1380 kJ/kg



MATIANT CO2 Cycle

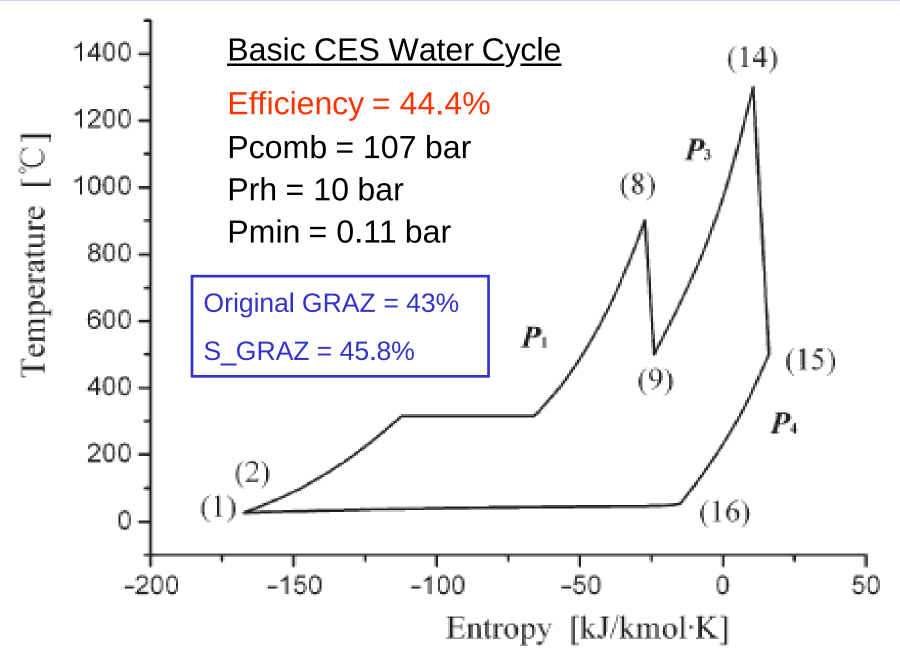
Efficiency = 44.1%
Pmax = 300 bar
Pcomb = 42 bar
Prh = 9 bar
Pmin = 1 bar

E-MATIANT = 47%
CC-MATIANT = 49%



LP Reheat Cycle

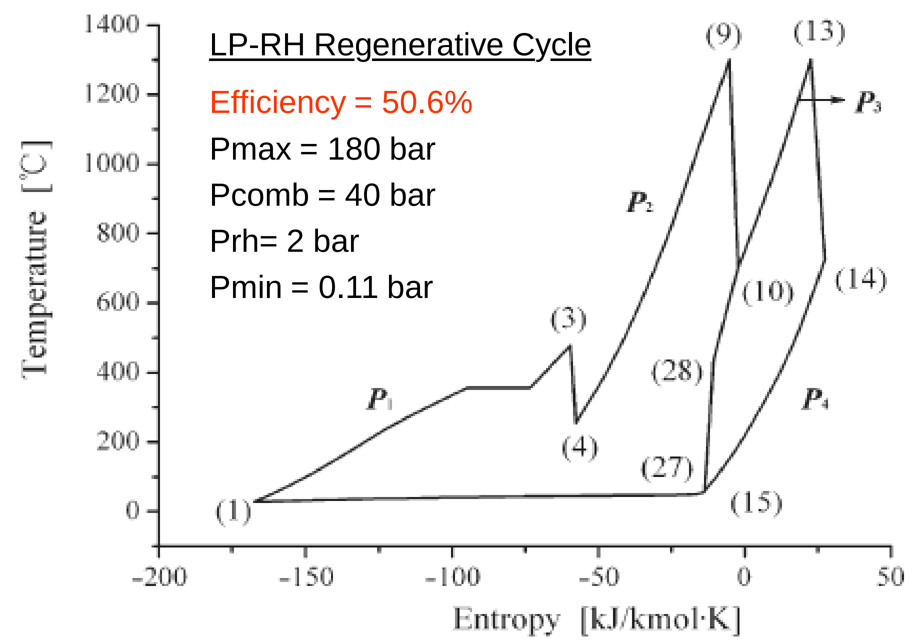
Efficiency = 47.1%
Pmax = 180 bar
Pcomb = 40 bar
Prh = 2 bar
Pmin = 0.11 bar



Basic CES Water Cycle

Efficiency = 44.4%
Pcomb = 107 bar
Prh = 10 bar
Pmin = 0.11 bar

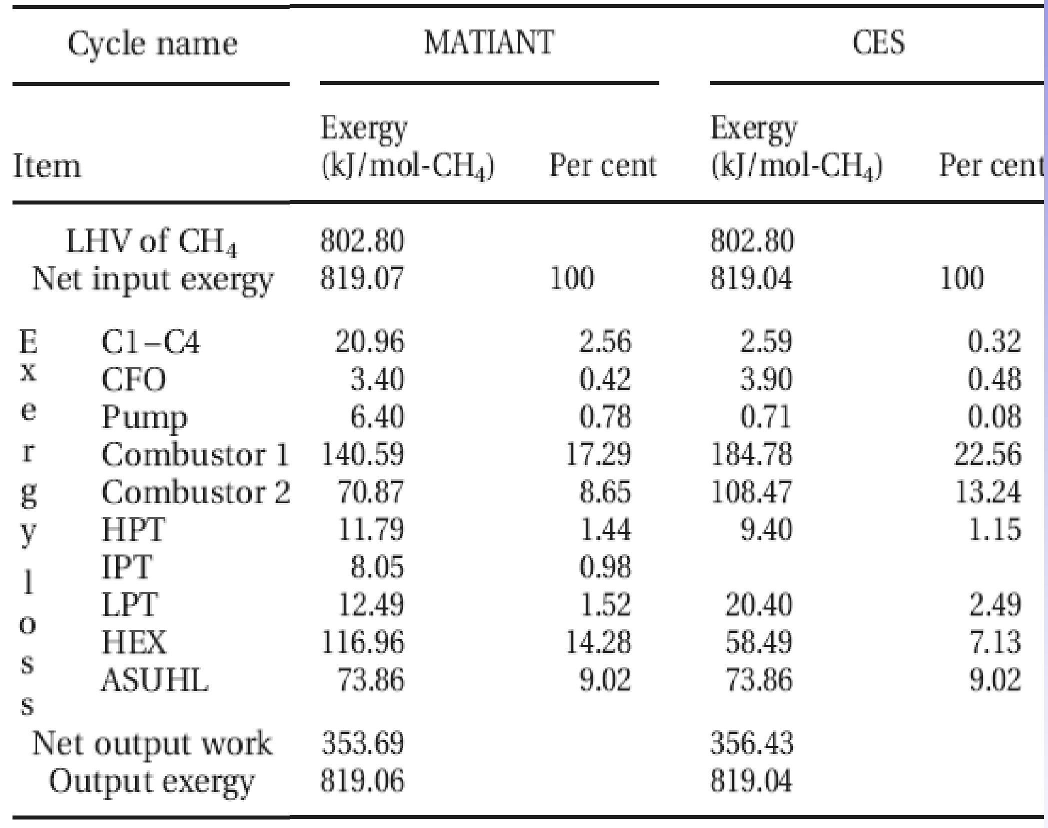
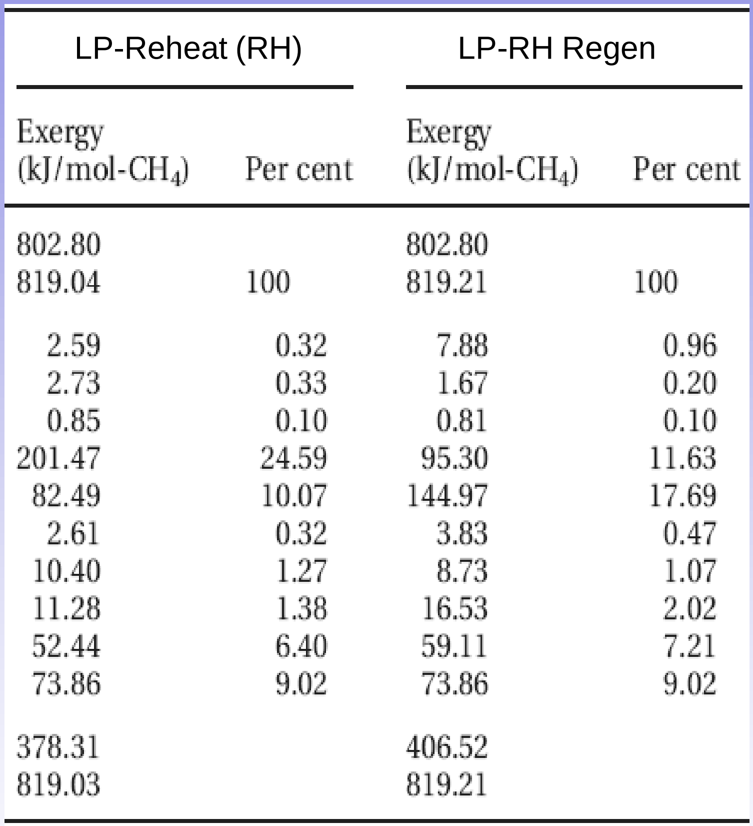
Original GRAZ = 43%
S_GRAZ = 45.8%



LP-RH Regenerative Cycle

Efficiency = 50.6%
Pmax = 180 bar
Pcomb = 40 bar
Prh= 2 bar
Pmin = 0.11 bar

Exergy Analysis of Cycles

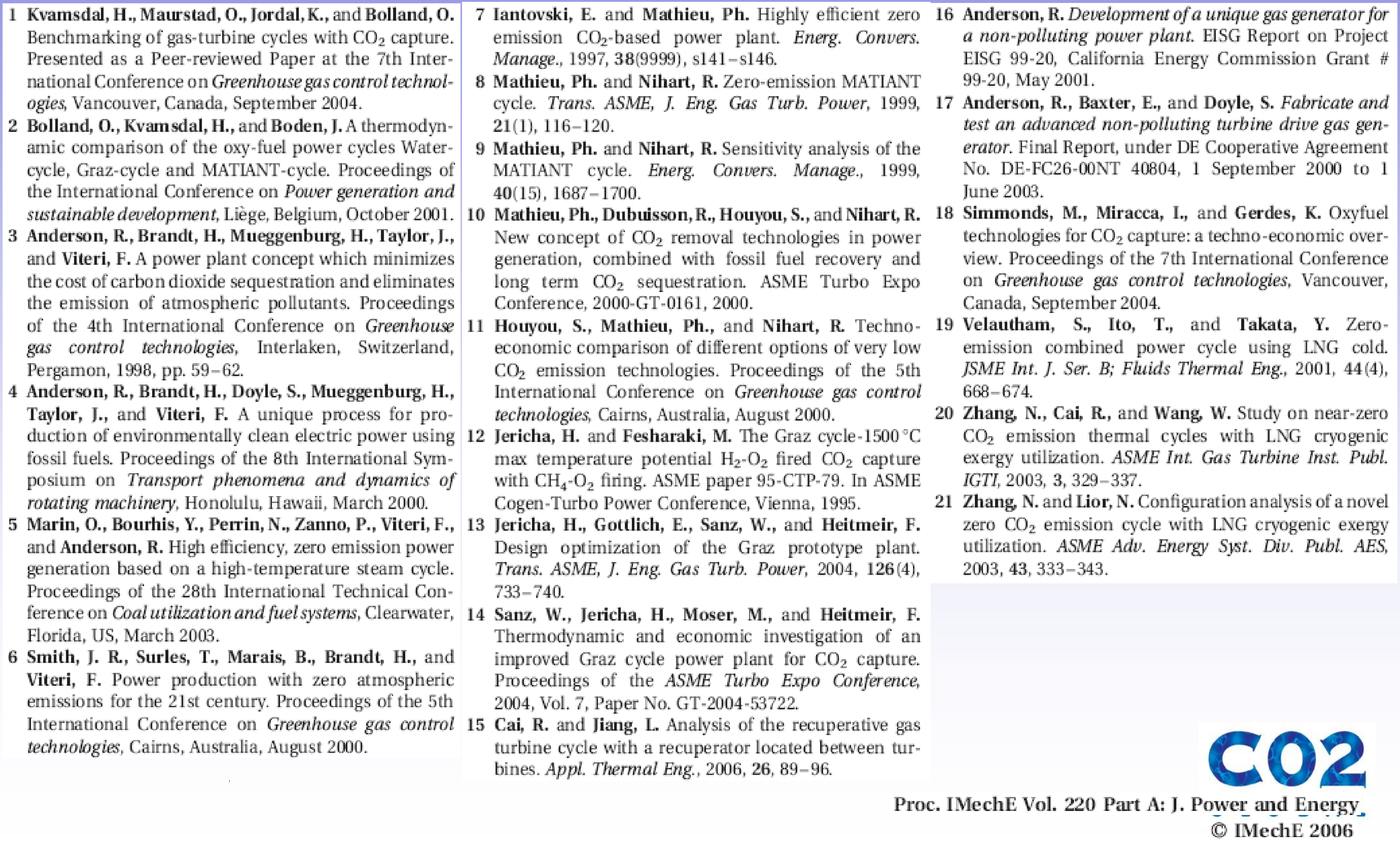



Cycle name		MATIANT		CES		LP-Reheat (RH)		LP-RH Regen	
Item		Exergy (kJ/mol-CH_4)	Per cent	Exergy (kJ/mol-CH_4)	Per cent	Exergy (kJ/mol-CH_4)	Per cent	Exergy (kJ/mol-CH_4)	Per cent
LHV of CH_4		802.80		802.80		802.80		802.80	
Net input exergy		819.07	100	819.04	100	819.04	100	819.21	100
Exergy loss	C1–C4	20.96	2.56	2.59	0.32	2.59	0.32	7.88	0.96
	CFO	3.40	0.42	3.90	0.48	2.73	0.33	1.67	0.20
	Pump	6.40	0.78	0.71	0.08	0.85	0.10	0.81	0.10
	Combustor 1	140.59	17.29	184.78	22.56	201.47	24.59	95.30	11.63
	Combustor 2	70.87	8.65	108.47	13.24	82.49	10.07	144.97	17.69
	HPT	11.79	1.44	9.40	1.15	2.61	0.32	3.83	0.47
	IPT	8.05	0.98			10.40	1.27	8.73	1.07
	LPT	12.49	1.52	20.40	2.49	11.28	1.38	16.53	2.02
	HEX	116.96	14.28	58.49	7.13	52.44	6.40	59.11	7.21
	ASUHL	73.86	9.02	73.86	9.02	73.86	9.02	73.86	9.02
Net output work		353.69		356.43		378.31		406.52	
Output exergy		819.06		819.04		819.03		819.21	

Exergy (A) = Internal Energy (U) - Sink Entropy term (T_o S) plus a pressure volume term (P_o v)

Main conclusion is that exergy losses primarily arise in combustors, heat exchangers and ASU plant.

Referenced Documentation



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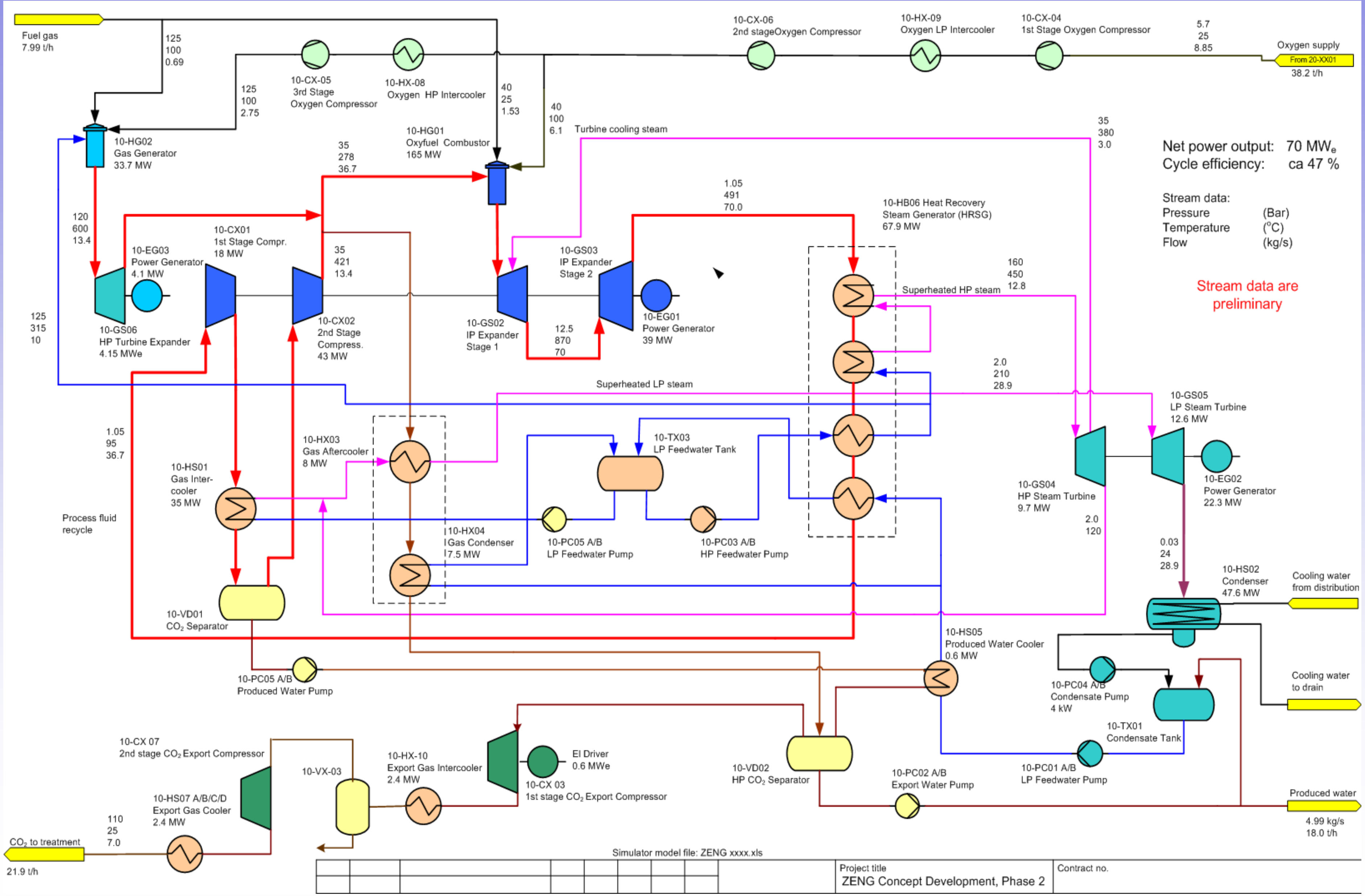
Basic CES Water Cycle - Revised

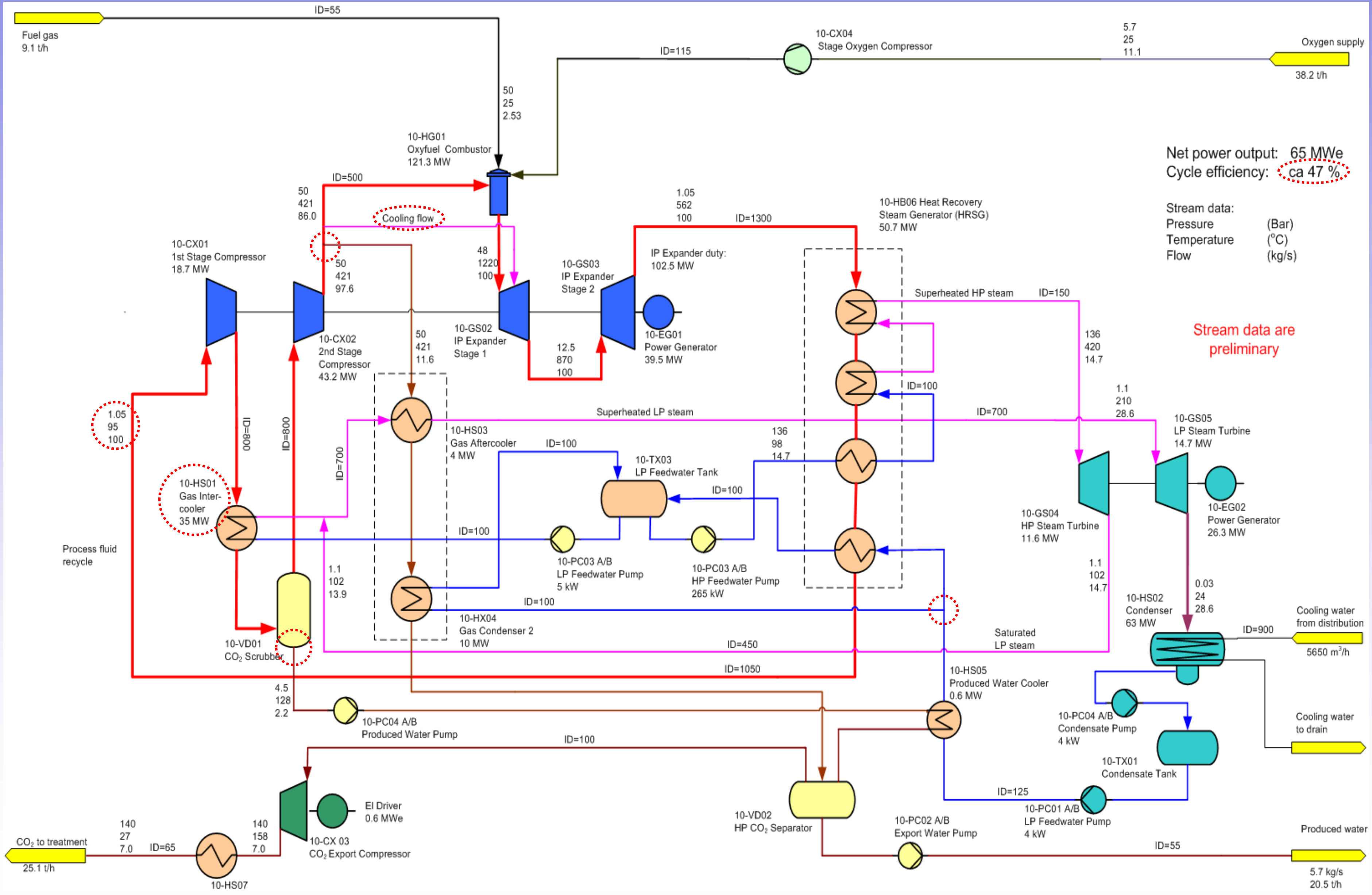


Net power output: 70 MW_e
Cycle efficiency: ca 47 %

Stream data:
Pressure (Bar)
Temperature (°C)
Flow (kg/s)

Stream data are preliminary

ZENG Low Pressure Twin Cycle



Net power output: 65 MWe
Cycle efficiency: ca 47 %

Stream data:	
Pressure	(Bar)
Temperature	(°C)
Flow	(kg/s)

Stream data are preliminary

Thoughts for Advanced Compressors

- **CO2 Compressor Technology Needs**
  - Improved and more accurate Equations of State (EOS) for;
    - CO2 with contaminants
    - CO2 with two-phase steam / water
  - CO2 (with steam) Recycle Recompression
  - Increased Compressor Exit Temperature for enhanced regeneration (compressor blade cooling)

- **Understand the Prevailing Market Conditions**
  - Development Roadmap – identify interim technologies to also create market pull while developing advanced technologies.
  - Identify technology milestones and commercialisation strategy