A pathway towards the use of fossil fuels for power generation and transportation

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creating tomorrow's infrastructure... sustainably

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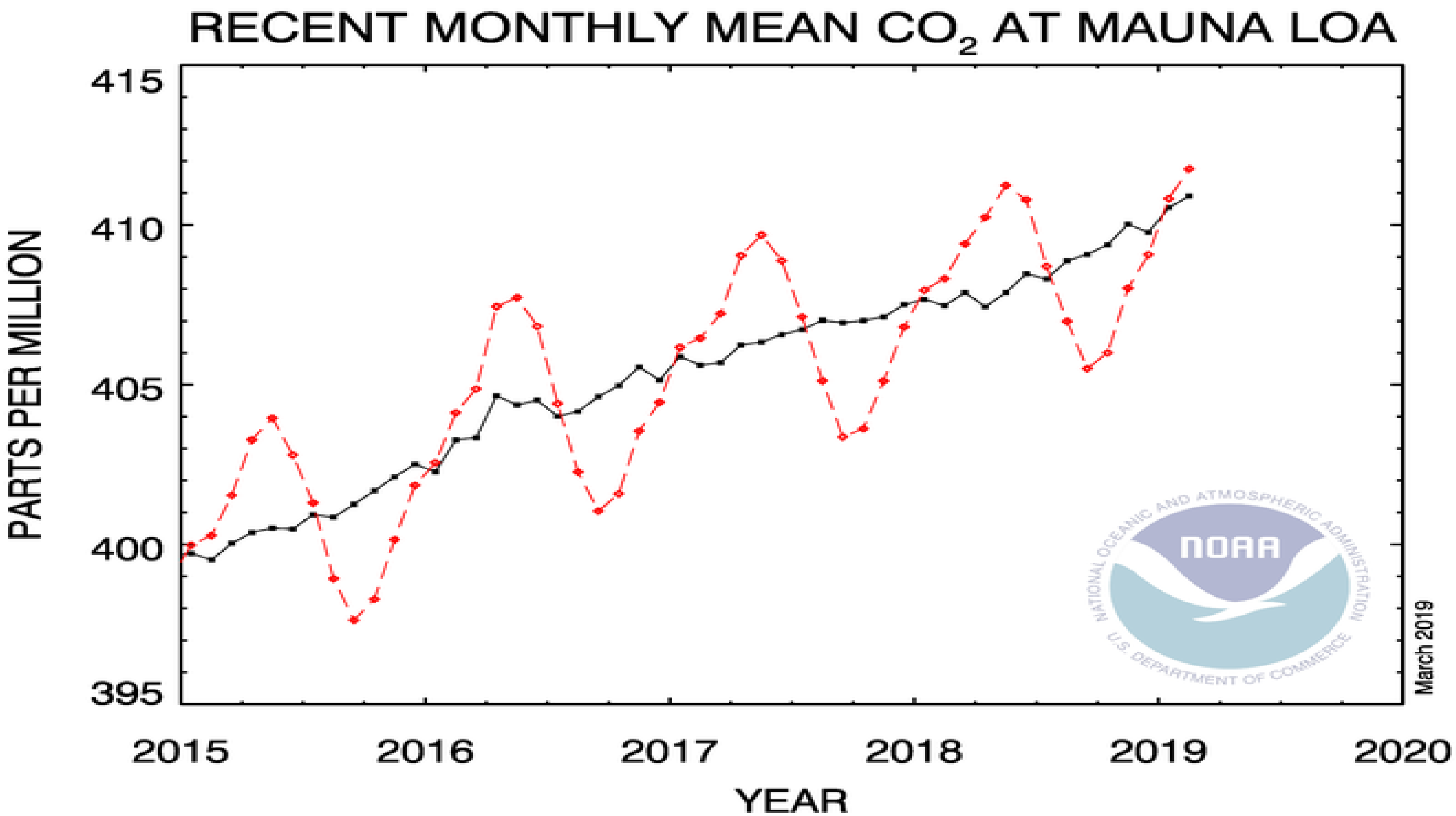
Summary of the talk

- Background
- Development of the Allam Cycle
- Detailed design considerations
- Equipment needed
- Demonstration plant
- Hydrogen production
- Hydrogen fuel for vehicles
- OXY-FUEL conversion of existing coal fired power stations.coal fired power stations
- CONTINUING USE OF FOSSIL FUELS WITH 100% CO_2 CAPTURE IS POSSIBLE

CO_2 level in the atmosphere

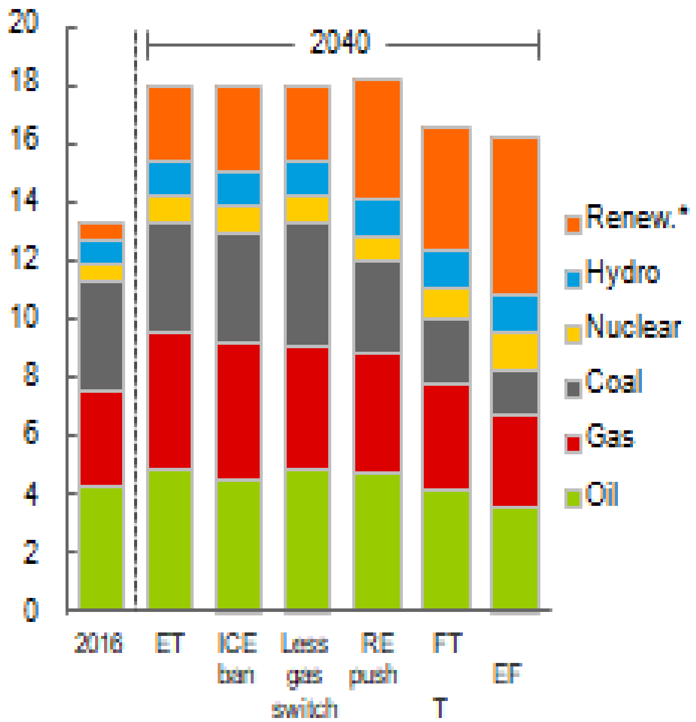
Continuing increase in atmospheric CO_2 levels from fossil fuels



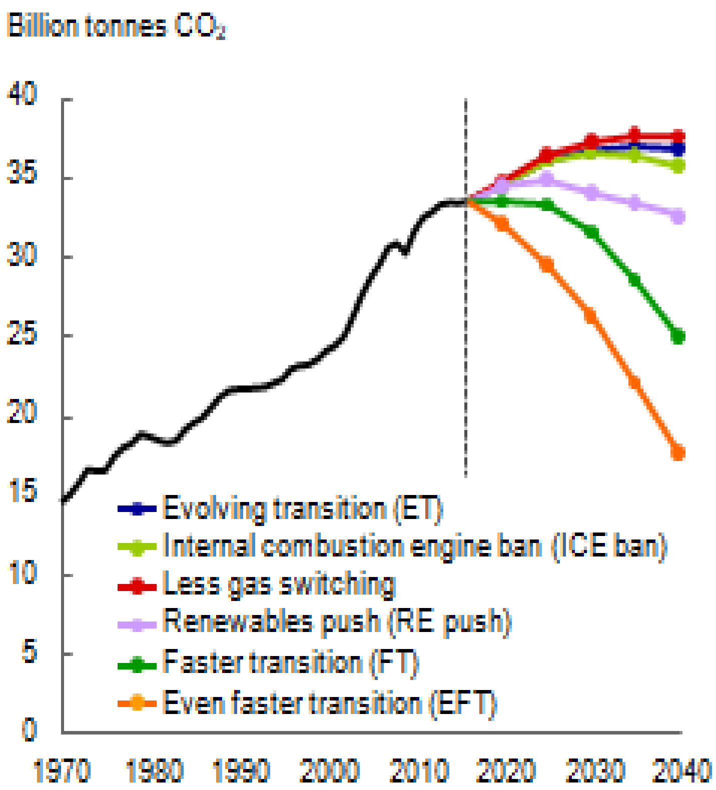
Overview

The Energy Outlook considers a range of scenarios…

Primary energy consumption by fuel



Carbon emissions

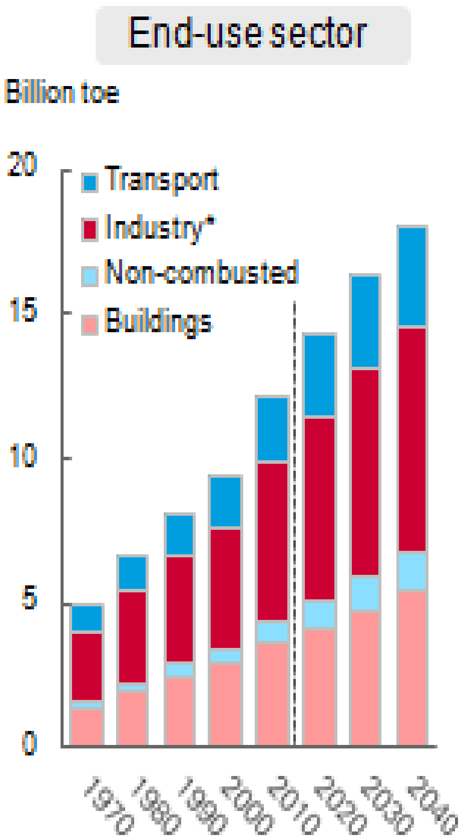


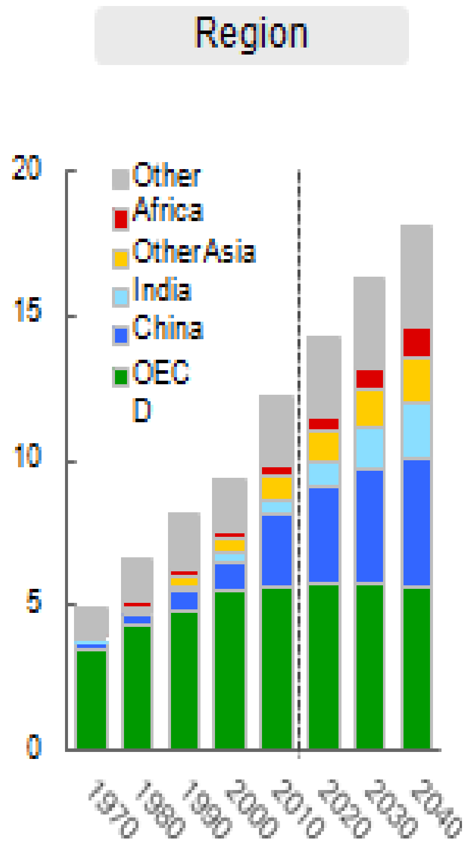
*Renewables includes wind, solar, geothermal, biomass, and biofuels
For full list of data definitions see p122

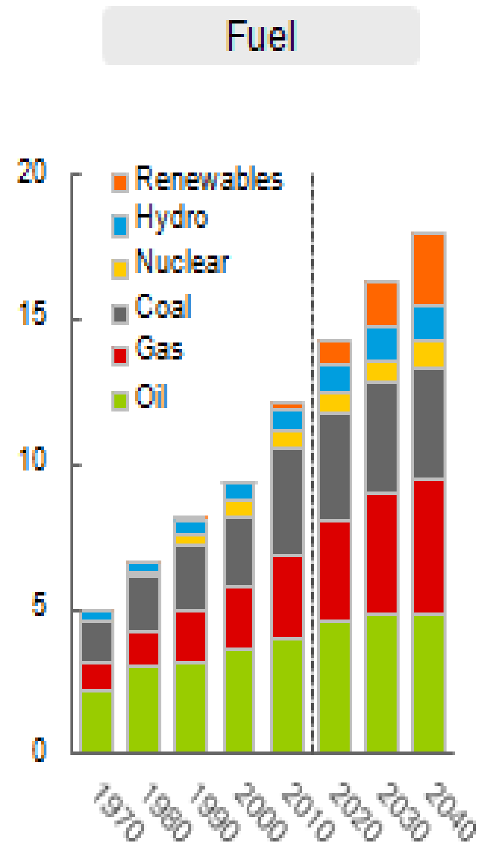
Overview

The Outlook examines the energy transition…

Primary energy demand







*Industry excludes non-combusted use of fuels

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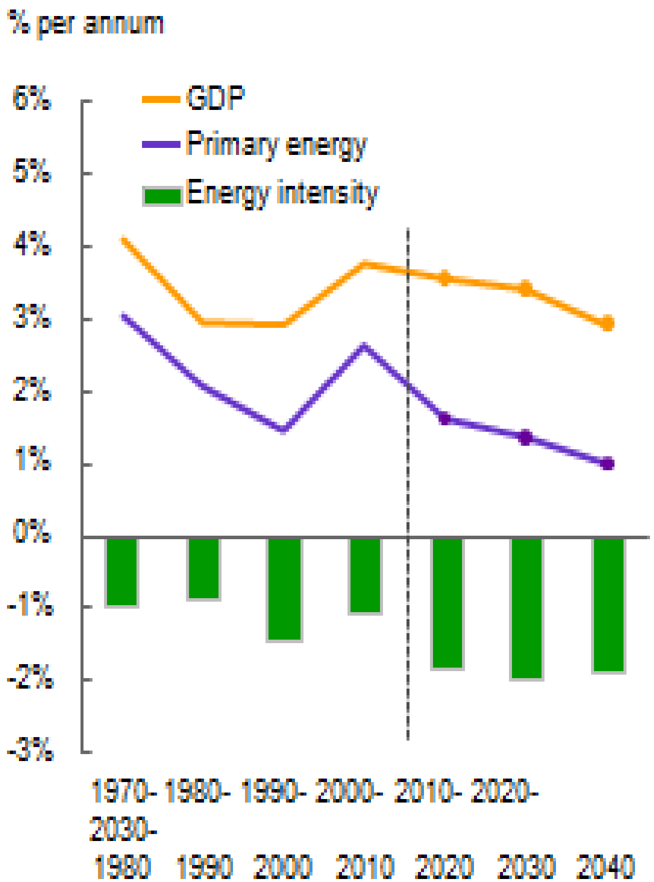
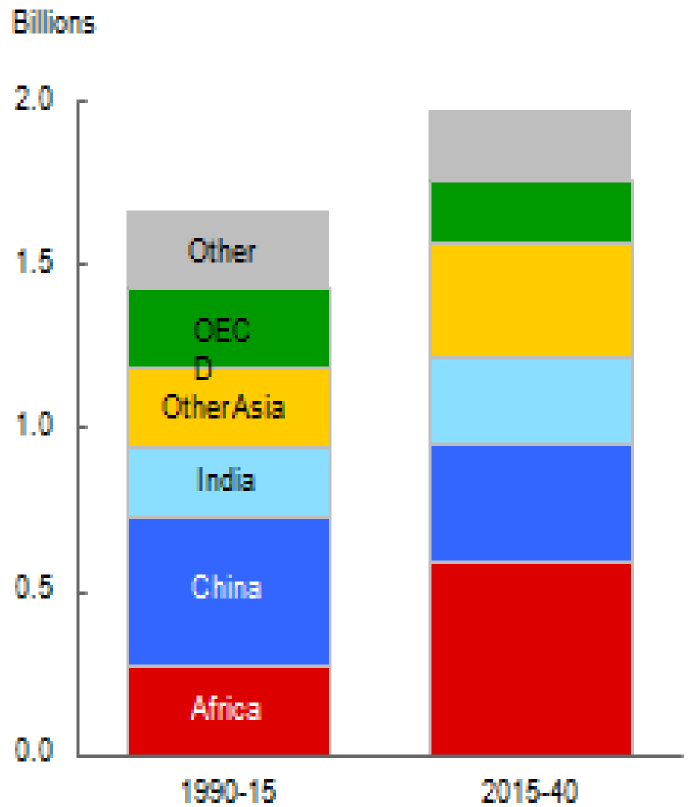
Economic backdrop

Increasing global prosperity drives growth in energy demand…

Growth in GDP and primary energy

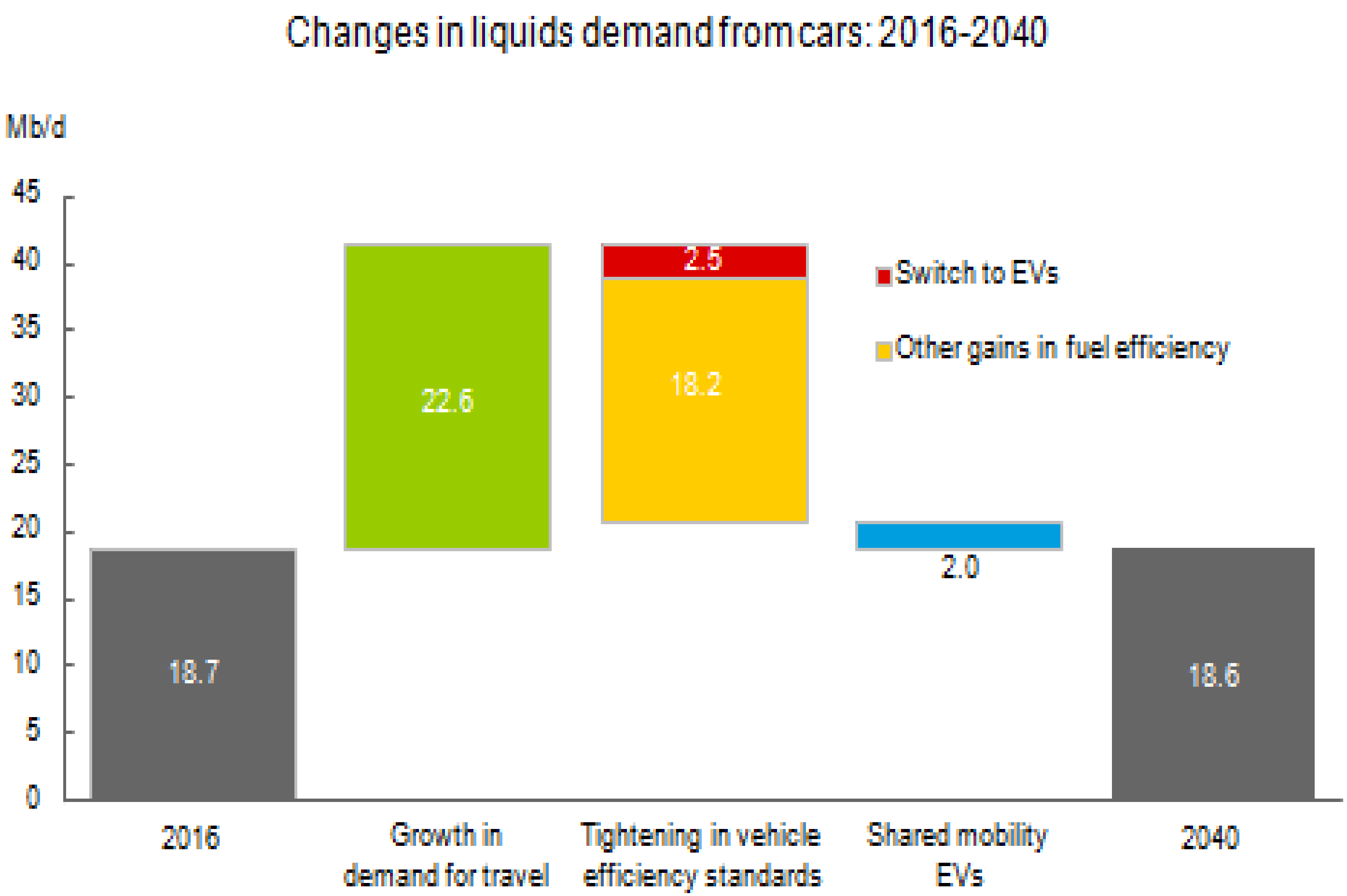


Growth in urban population by region



Sectors: Transport

Liquid fuel use in cars is broadly flat…



2018 BP Energy Outlook

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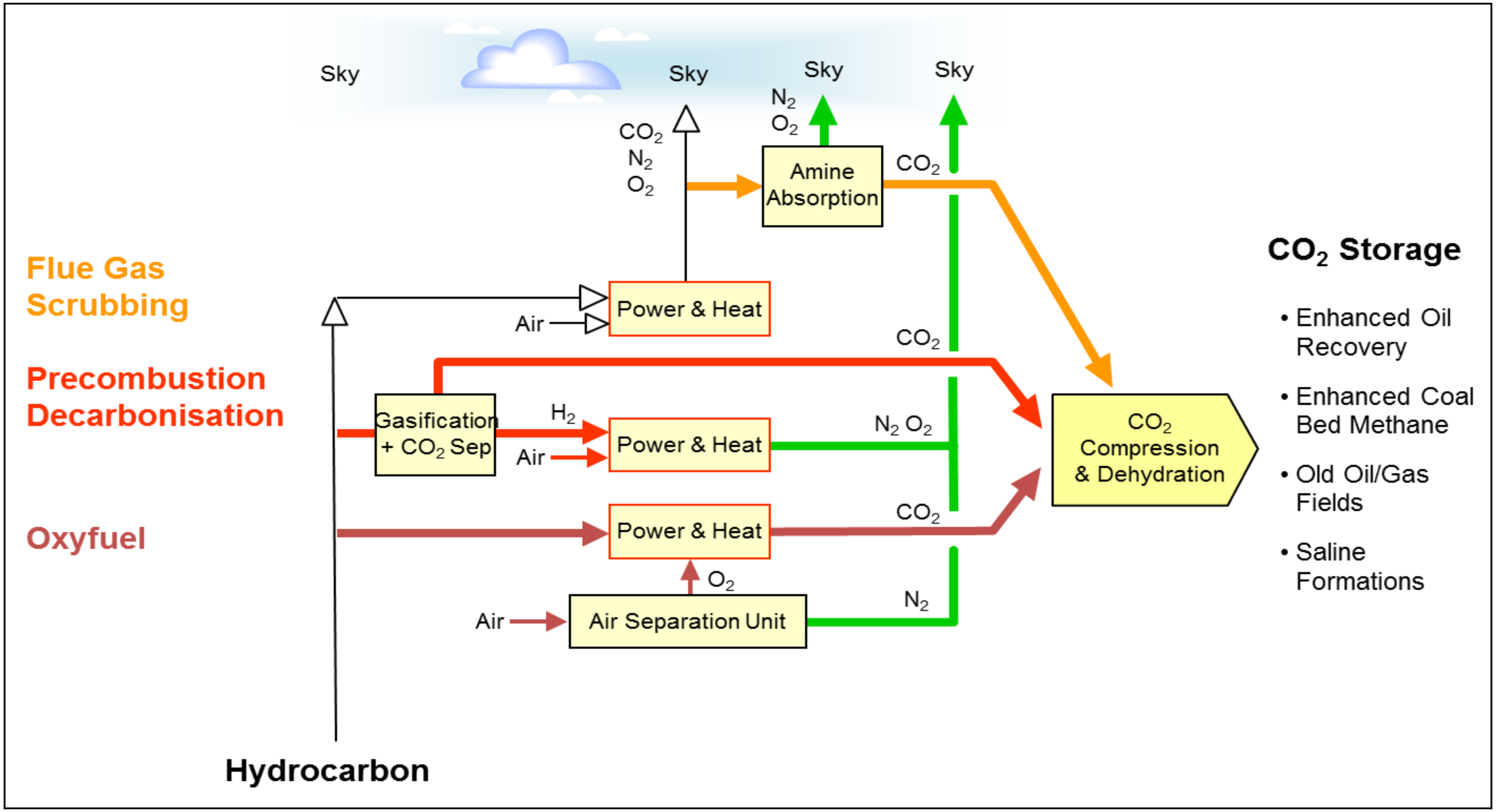
CURRENT OPTIONS FOR CLEAN FOSSIL FUEL POWER PRODUCTION

ALL lead to a 50% to 70% increase in electricity costs



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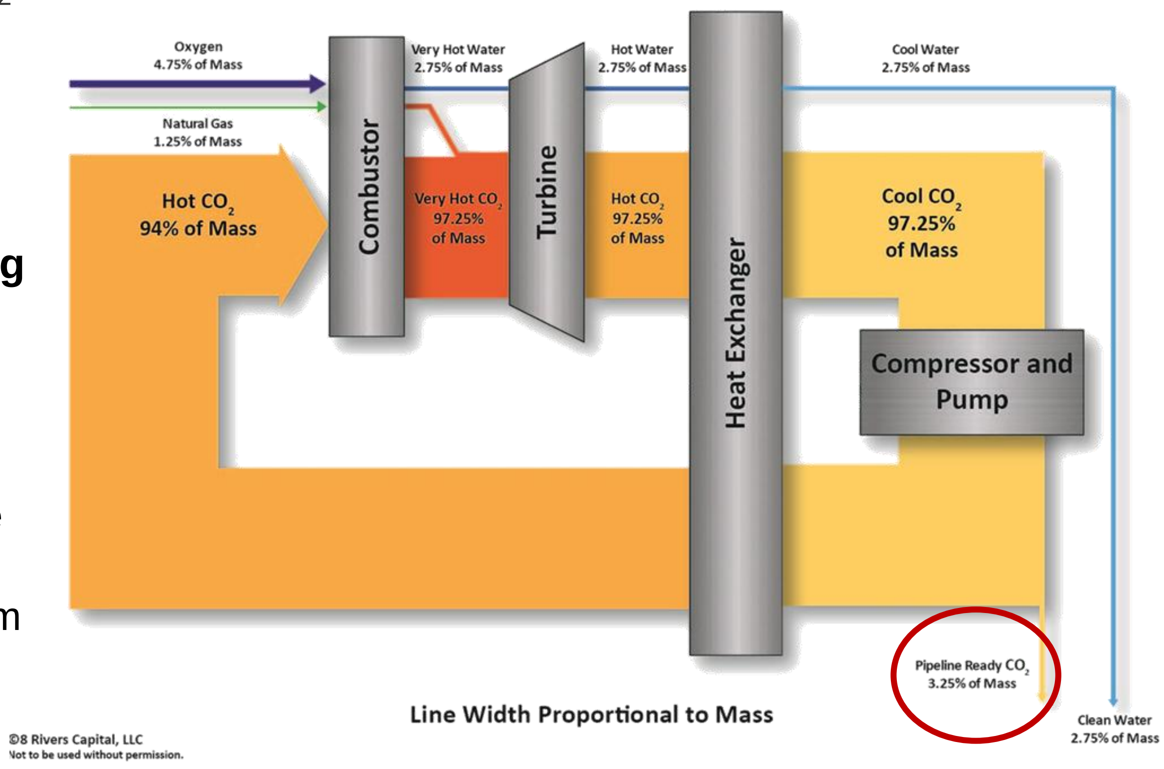
What is the Allam Cycle?

- **The Allam Cycle is**
  - A semi-closed, supercritical CO_2 Brayton cycle,
  - That uses oxy-combustion with natural gas, gasified coal, or other carbonaceous fuels.
- **Historically, CO_2 capture has been expensive, whether using air to combust or oxy-combustion.**
- **The Allam Cycle makes oxy-combustion economic by:**
  - Relying on a more efficient core power cycle.
  - Recycling heat within the system to reduce O_2 and CH_4 consumption, and associated costs of the ASU.



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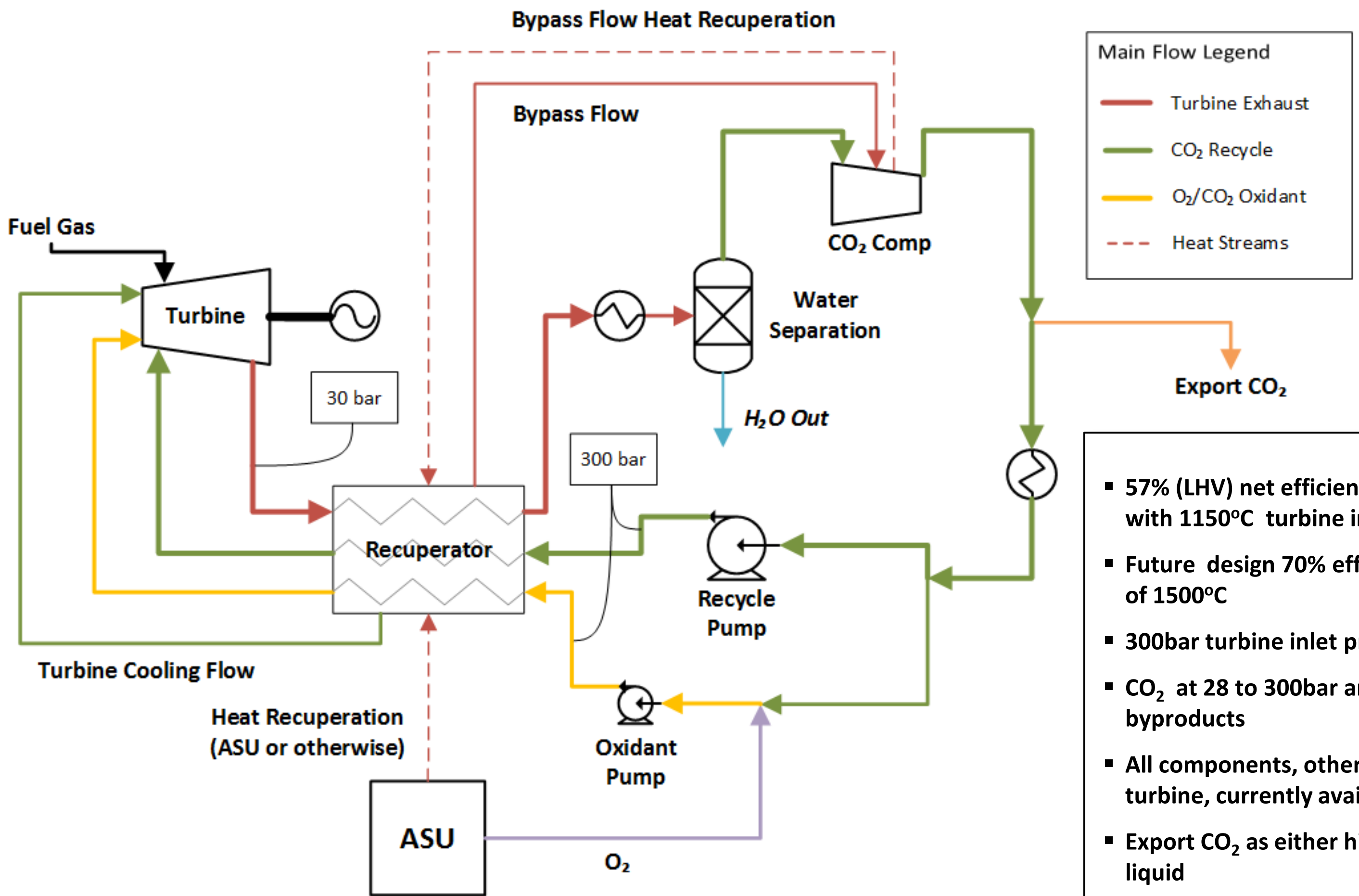
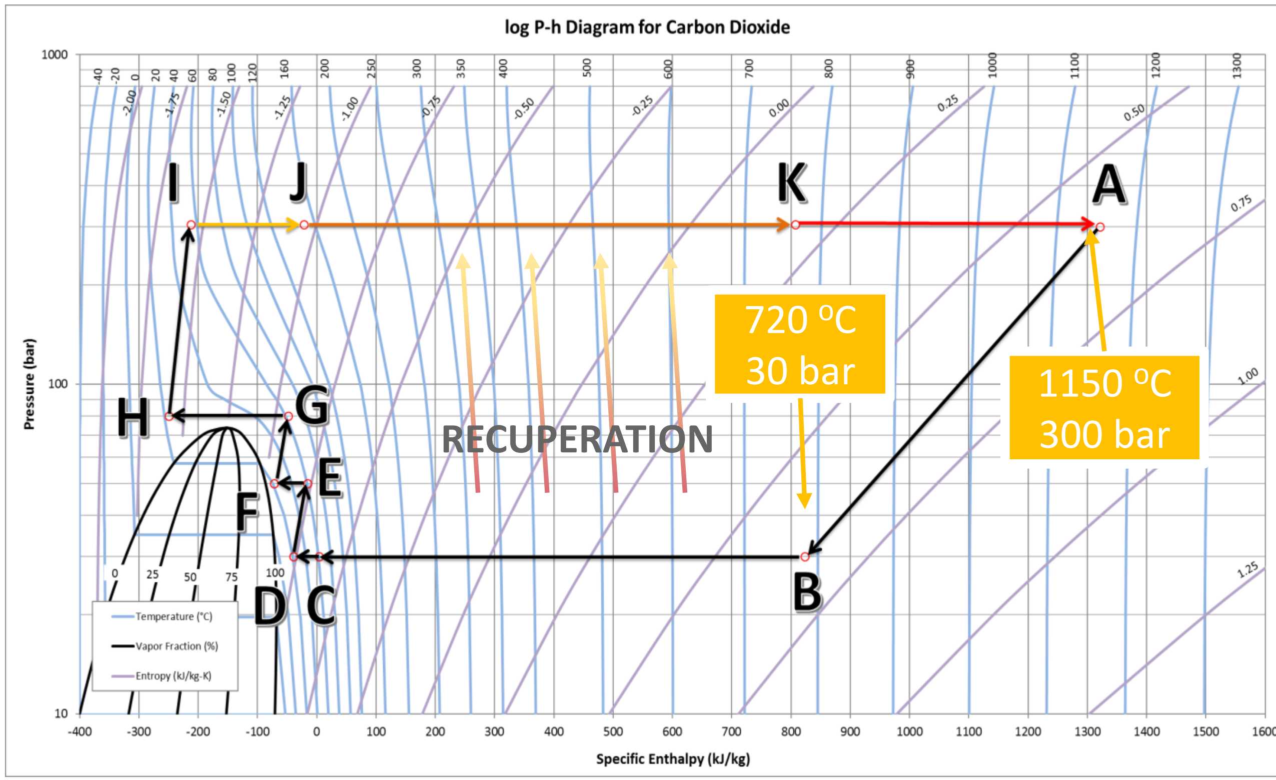
Flow Diagram of the Natural Gas Allam Cycle



- 57% (LHV) net efficiency,100% carbon capture with 1150ºC turbine inlet present design point
- Future design 70% efficiency with a turbine inlet of 1500ºC
- 300bar turbine inlet pressure ratio 10 30bar outlet
- CO_2 at 28 to 300bar and liquid water are the only byproducts
- All components, other than combustor and turbine, currently available
- Export CO_2 as either high pressure gas or a 6bar liquid
- Combustor and turbine developed by Toshiba

Overview of the Allam Cycle. Heat input as fuel plus low grade heat

- Oxy-combustion of natural gas with O_2/CO_2 mixture; adiabatic temp approaching 2000ºC **(K)**
- 300 bar and 1150ºC at the turbine inlet after mixing of combustion exhaust gas with pre-heated recycle CO_2 **(A)**
- 720ºC turbine exhaust preheats 300 bar Recycle CO_2 **(B-C)**
- Separation of condensed water followed by CO_2 compression and pumping **(C-I)**
- 20% of the total heat input is derived from the ASU and CO_2 Recycle Compressor heat of compression which assists in heating recycle CO_2 **(I-J)**
- Pure CO_2 product produced between 30 bar and 300 bar.



A.	Turbine Inlet	G.	Compression
B.	Turbine Outlet	H.	Compressor Aftercooler
C.	Cold End HX	I.	Supercritical Pumping
D.	Cooling to Ambient	J.	Low Temp. Recuperation
E.	Compression	K.	High Temp. Recuperation
F.	Intercooling		

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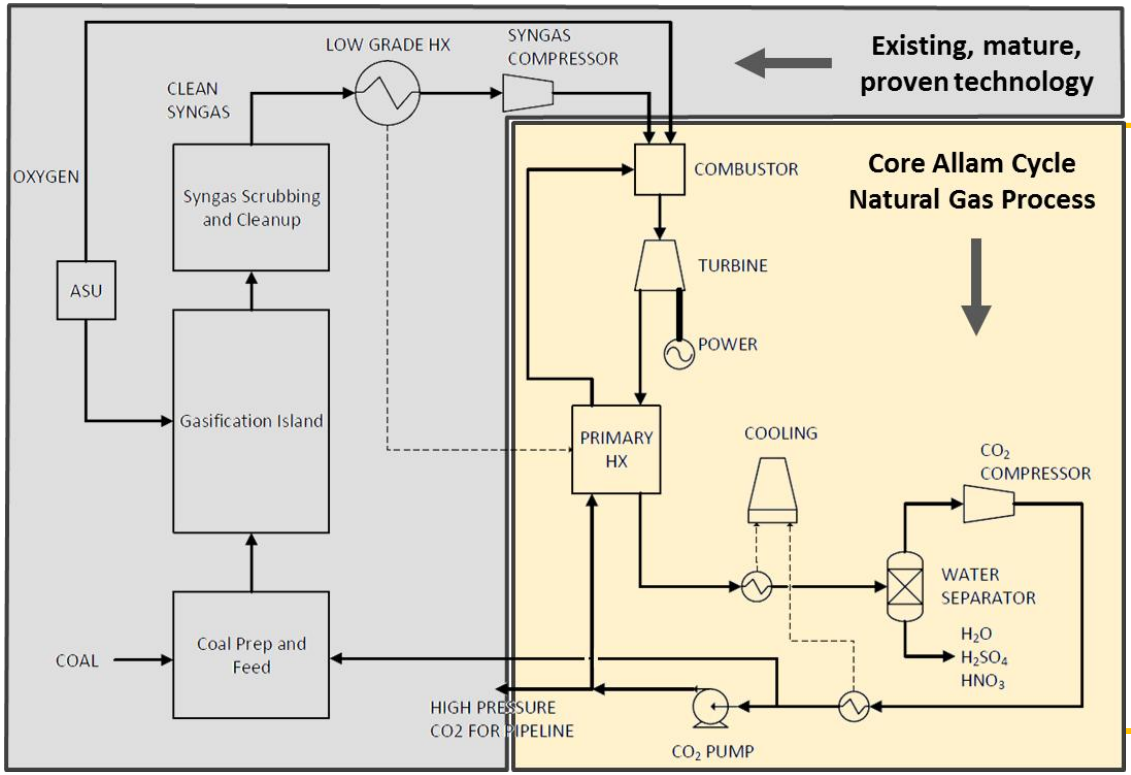
ECONOMICS OF POWER PRODUCTION USING NATURAL GAS

	NET Power	Combined Cycle (without carbon capture)	Combined Cycle with Carbon Capture
Efficiency (portion of energy of gas vs. energy of produced electricity)	57% (1150°C)	55% to 62%	38% to 51%
Percent of CO_2 Captured	100%	0%	85%
NO_X emissions (lb/MWh)	0	0.025-0.026	0.025-0.026
"Levelized" cost of electricity without CO_2 revenues ($/MWh)	$62.9 to $69.4	$64.0 to $72.8	$91.6 to $134.2
"Levelized" cost of electricity *with* CO_2 revenues ($/MWh) at $20/ton	$55.5 to $62.0	$64.0 to $72.8	$85.6 to $128.3

Allam Cycle for Coal or Waste Hydrocarbon Fuels

The Allam Cycle can be used with a range of solid fuels while maintaining the benefits of the core cycle.

Efficiency	LHV	HHV
Gross Turbine Output	76.3%	72.5%
Coal prep & feed	-0.2%	-0.2%
ASU	-10.2%	-9.7%
CO_2, Syngas Comp.	-9.1%	-8.7%
Other Auxiliaries	-6.5%	-6.1%
Net Efficiency	**50.3%**	**47.8%**



- Lowest cost electricity from coal with 100% CO_2 at 28bar to 300bar taken directly from the CO2 recycle compression.
- All impurities are removed from the coal gas prior to combustion or as H_2SO_4 and HNO_3 after combustion.
- Most of the sensible heat in the cleaned coal gas plus steam following water quench is recovered at fuel value in the Allam cycle; directly improving efficiency.
- Process simplification significantly reduces cost vs. IGCC

Other Applications of the Allam Cycle using natural gas

Countries which import LNG can heat the compressed LNG to pipeline temperature and liquefy the ambient temperature turbine exhaust eliminating the CO_2 compressor and increasing the effective efficiency of a 1000Mw power station to about 66% (LHV basis)

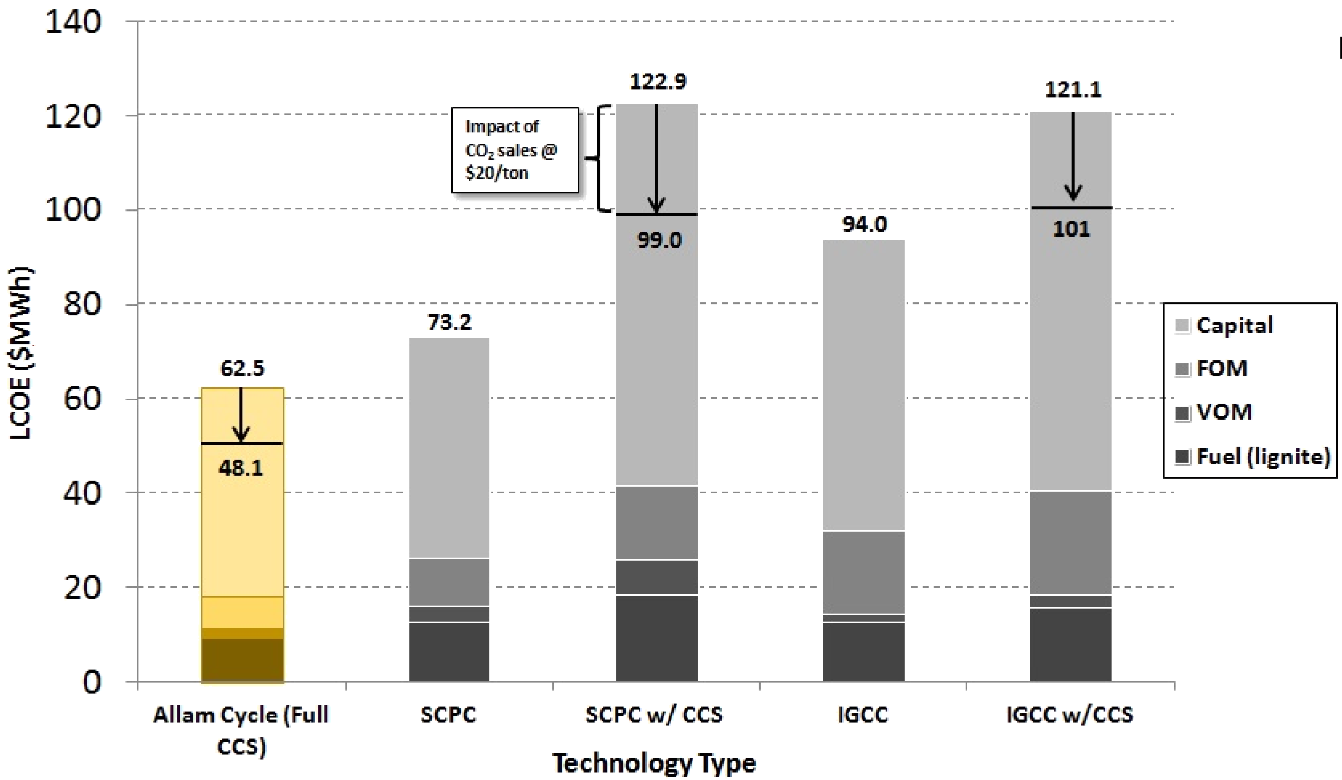
Steam from a supercritical coal fired boiler at typically 300bar and 600°C can be superheated to 720°C in the recuperator heat exchanger giving a large increase in the coal power station efficiency and capturing 100% of the CO_2 produced from the additional fuel required to superheat the steam.

CO2 captured at typically 150bar pipeline pressure can be injected into oil wells for enhanced oil recovery. Associated natural gas separated from the oil which will contain a large quantity of CO_2 can be used directly as fuel for the Allam cycle power system allowing efficient capture and recycling of the CO_2.

Natural gas containing say 25 mol% H_2S can be used as fuel in the Allam cycle. We have developed an effective H_2S removal technology applicable to both natural gas and coal derived POX gas

CO_2 captured can be used for enhanced coal bed CH_4 production.

Increased Performance, Lower Capex, Reduced Complexity Lead to Much Lower LCOE Projections for Allam Cycle Coal



Reduction in costs from removal of:

- Steam turbine
- HRSG
- Steam piping/equipment
- Water-gas shift reactor
- High Temp syngas cooler
- NO_X control unit/SCR unit

Potential removal of:

- AGR/sulfur recovery unit
- COS hydrolysis
- Solvents/catalysts

Notes

- Lu et al. Oxy-Lignite Syngas Fueled Semi-Closed Brayton Cycle Process Evaluation (2014)
- Total Plant Cost and O&M costs were estimated for lignite-fired system in conjunction with EPRI; AACE Class 5 estimate
- Cost data for other technologies is taken from NETL baseline reports (Vol. 3, 2011)

NET Power's Is Demonstrating the Allam Cycle process

50MWth gas plant in La Porte, TX

- Scaled down from 500MWth design
- Construction nearing completion; commissioning in progress.

Includes all core components

- Combustor/turbine, heat exchangers, pumps/compressors, controls, etc.
- Grid connected and fully operable

$140 million (USD) program

- Includes first of a kind engineering, all construction, and testing period
- Partners include Exelon Generation, CB&I, 8 Rivers and Toshiba

Technical Development of the NET Power Demonstration Plant

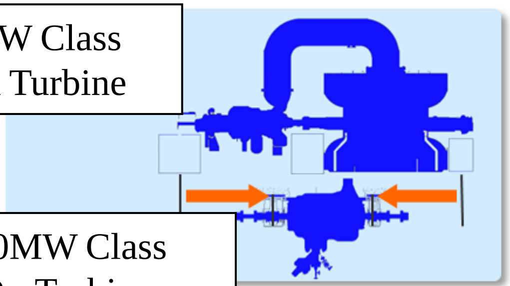
- McDermott (CB&I) led detailed design, procurement and construction and is designing the commercial plant.
- Exelon operate the facility.
- 8 Rivers has provided the proprietary process design, dynamic simulation, and control philosophy with ongoing development.
- Toshiba has developed the novel turbine and combustor.
- The demonstration main process heat exchanger is supplied by Heatric.
- Oxygen is supplied via pipeline from an adjacent Air Liquide ASU.

Technology for supercritical CO_2 Turbine

Gas Turbine Technology

1300-1500°C

Working fluid; CO_2
Pressure;2MPa⇒30MPa



Combustor Technology
1300-1500°C

Working fluid; CO_2
Pressure;2MPa⇒30MPa

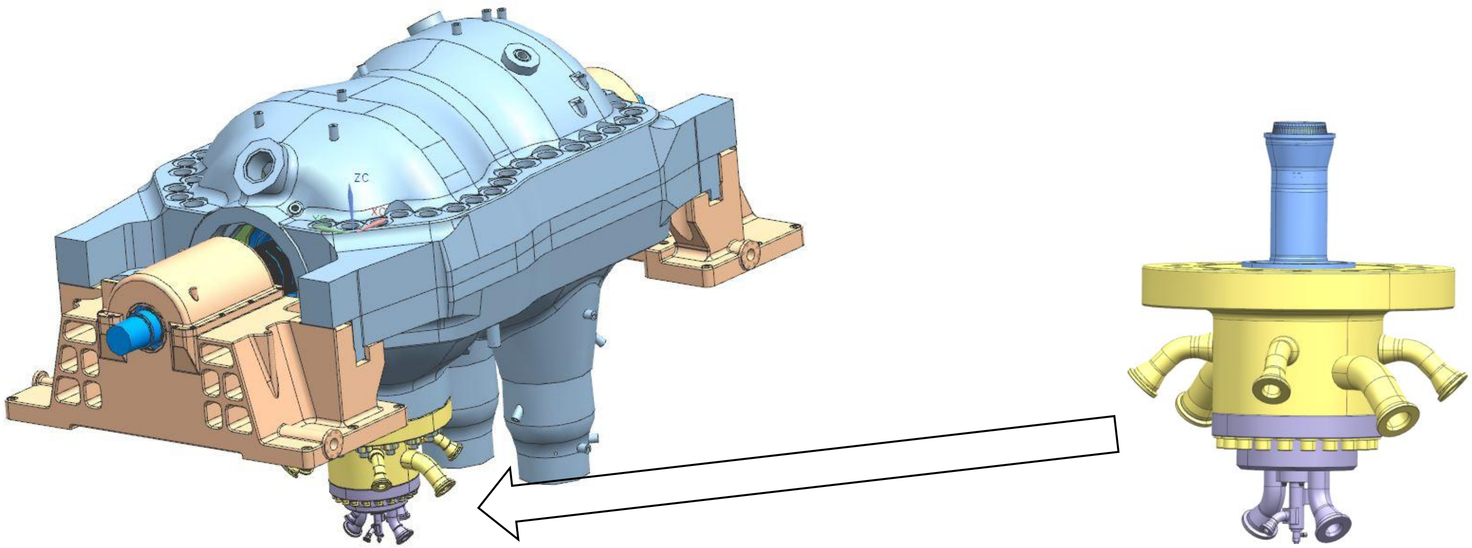
Turbine & Combustor for
Super Critical CO_2 Cycle
Temp. 1150°C
Press. 30MPa

Steam Turbine Technology
USC& A-USC
Pressure; 24-31MPa
Temperature; 600-750°C

Temperature ⇒1150°C

50MWth Combustor

1. First of a kind in view of high pressure and working fluid.
2. Stable diffusion flame can be used since there is no NOx emission.
3. No need of using innovative cooling scheme since temperature is within experience of existing gas turbine.
4. Rig test in order to validate operation has been completed.



Combustor for Demonstration Plant

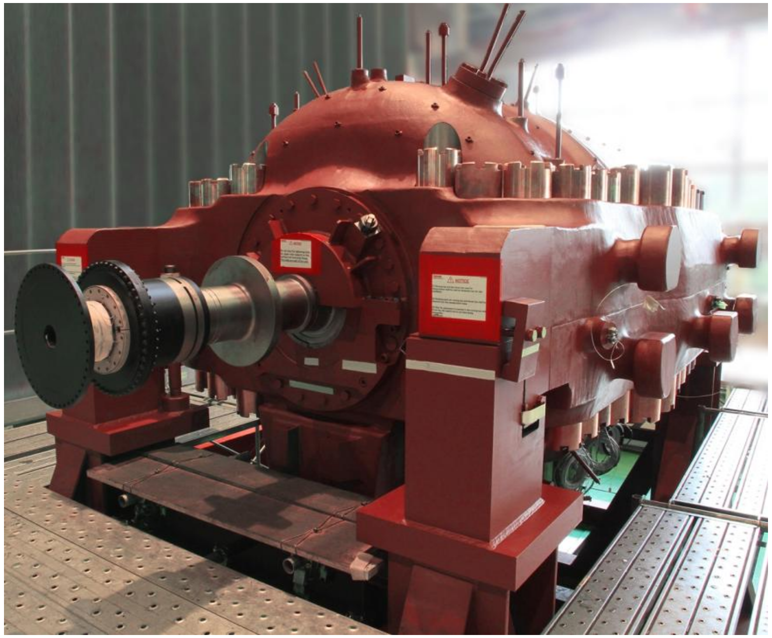
The Toshiba Turbine and Combustor (cont.)

Left: Test stand for a 5 MWth combustor operating at 300bar

Below: Rotor and Outer Casing of Demonstration Turbine (Courtesy: Toshiba)

- Fusion of a USC steam turbine (double casing design) with the design of gas turbine (cooled and coated blades). The inner casing is internally cooled.
- NG and oxidant mixture of 20% O_2 & 80% CO_2 is mixed with 700°C recycle CO_2 to provide a turbine inlet temperature of 1150°C at 300 bar
- 5MW combustor test with 700°C oxidant flow confirmed calculated performance. Diffusion flame, no premixing gives stable combustion conditions.
- 200MWth turbine unit scaled to 50MWth by partial arc admission to the turbine blades, minimizing risk for the commercial-scale turbine
- The use of pure O_2 means very low NO_X formation. Trace NO_X will be formed from fuel-derived N_2 in the natural gas.

The high pressure CO_2 turbine

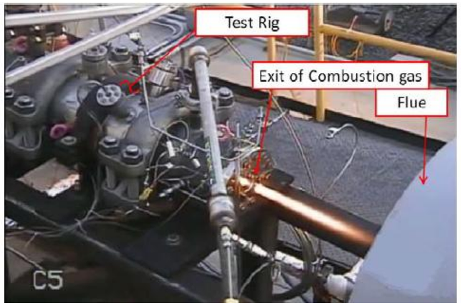


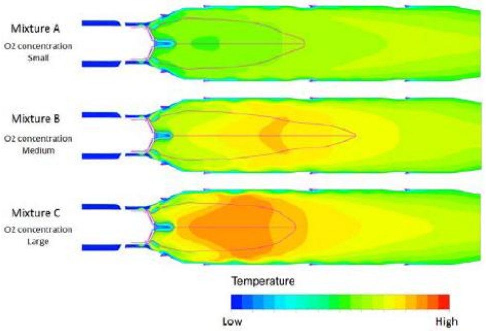
NET Power 5Mw first combustor test

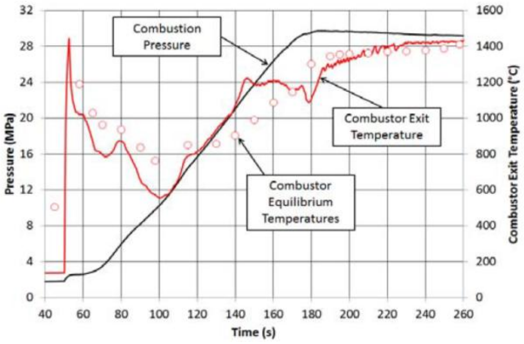
Combustion tests under these conditions have been underway by Toshiba since 2013.[1]

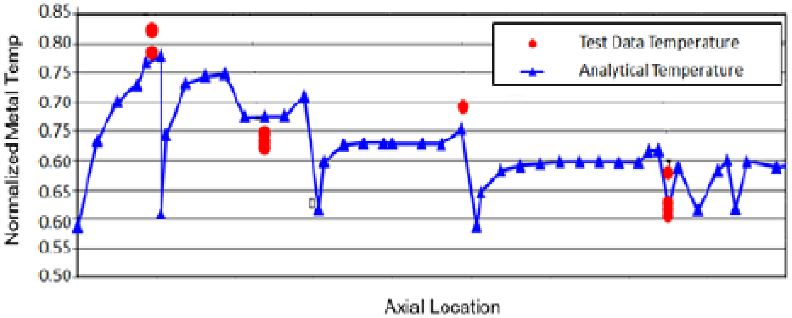
Tests have been conducted under various pressures and CO_2/O_2 ratios all of which were successful and agreed with theoretical models.[1]

Additionally combustor metal temperatures matched well with predictive models.[1]









1. Iwai, Y., Itoh, M., Morisawa, Y., Suzuki, S., Cusano, D., & Harris, M., "Development Approach to the Combustor of Gas Turbine for OXY-fuel, Supercritical CO_2 Cycle", Proceedings of ASME Turbo Expo, **2015**, GT2015-43160

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The High Pressure Combustor Test Vessel

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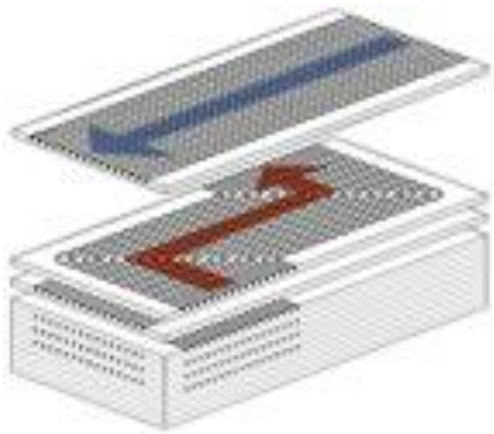
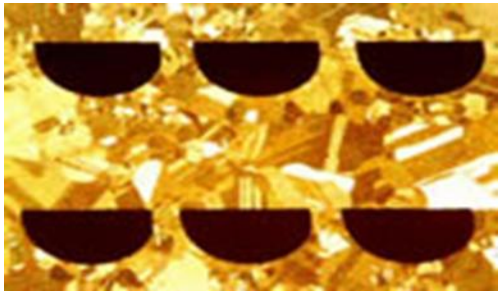
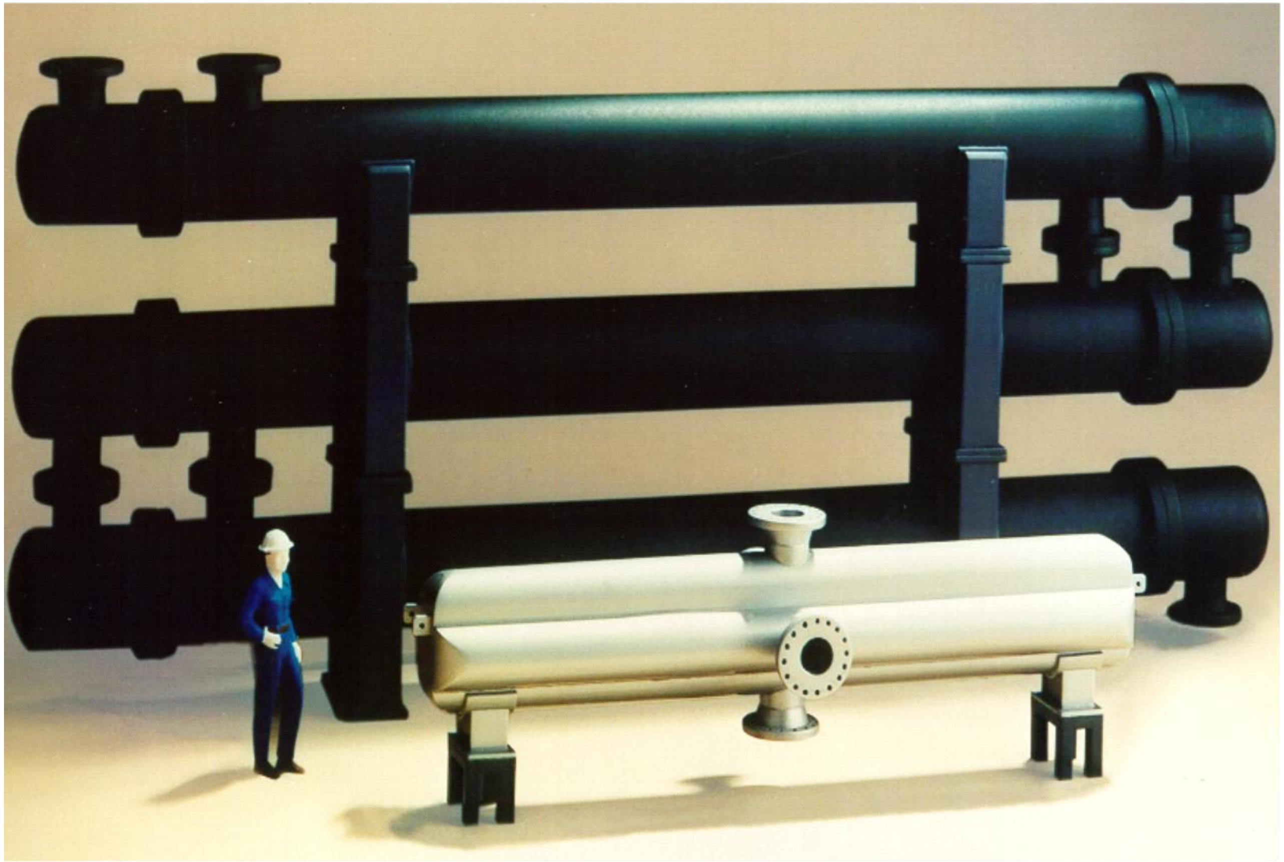
HEATRIC DIFFUSION BONDED PLATE FIN HEAT EXCHANGER

- Plates have chemically etched channels and are stacked then diffusion bonded
- Grain growth occurs between plates during the diffusion bonding process
- Very compact and potentially low cost system
- Headers welded to the outside of the blocks
- Multiple blocks welded to form batteries
- 617 alloy allows operation at >300bar and >700^{o}C





Size and Weight Savings



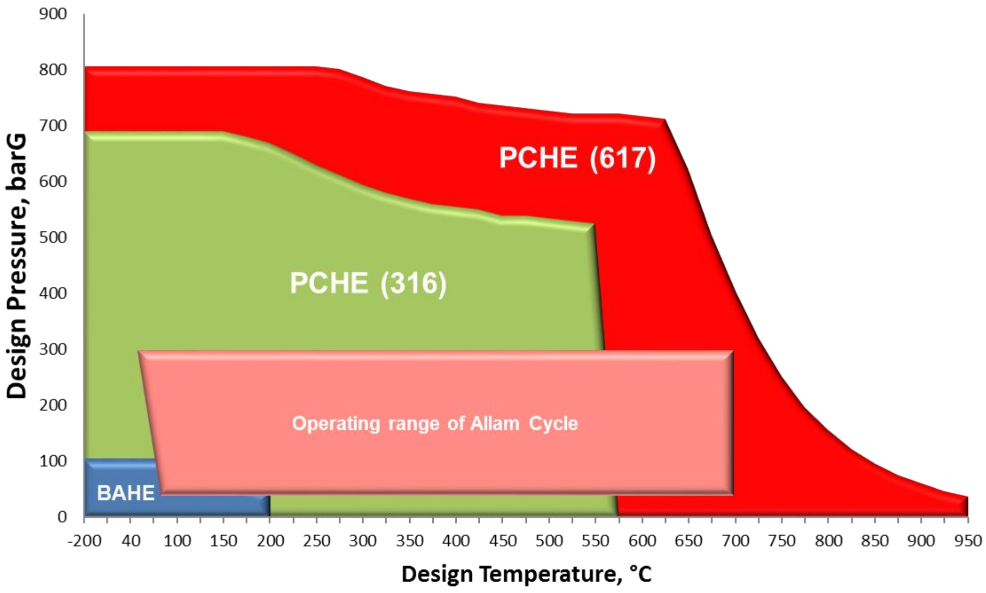
NET Power is near-term deployable – HX

Heat exchanger design is well within Heatric's capabilities

- NP has been discussing recuperators with other manufacturers as well.

HX designed following ASME guides:

- ASME Sec. IID - function of design temperature.
- ASME Sec. VIII, DIV. 1 - pressure vessel design code
- ASME Sec. III NH, DIV. 2- fatigue and creep in high temperature (developed for nuclear power generation extreme conditions).



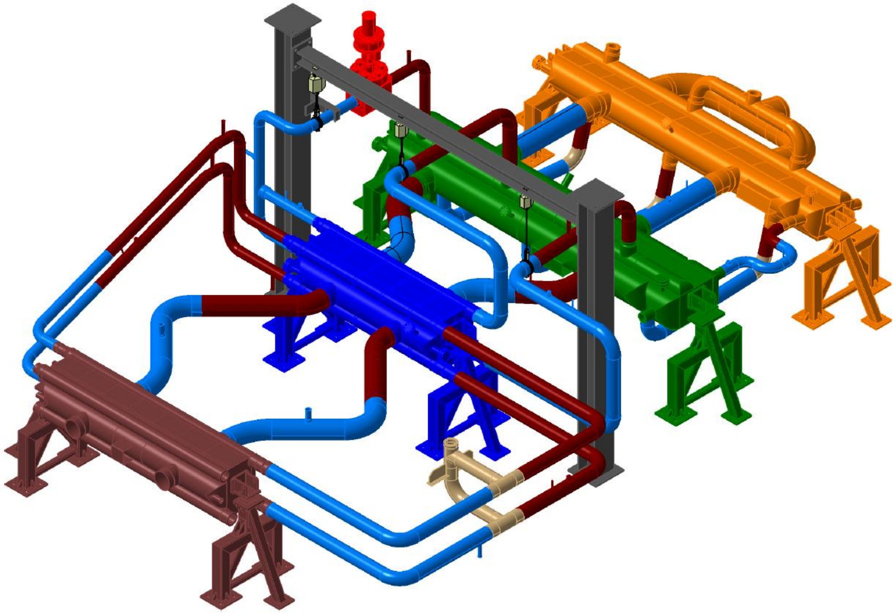
Design of HX train limits nickel alloys to only hottest section, 316 (lower cost material) can be used for the majority while maintaining strength and corrosion resistance

Main Process Heat Exchanger

- The demonstration Printed Circuit Heat Exchanger has been supplied by Heatric
- Large SA/V allows for high P & T operation with tight approach.
- Stacks of 1.6mm thick plates are photo masked then chemically etched to produce complex passage arrangements
- The plates are diffusion bonded at high T to form a homogeneous monolithic block.
- The main recuperator operates over a range from 50ºC to 705ºC . It has a multi-stream configuration in 4 sections
  - 617 alloy for T > 550ºC
  - 316L alloy T < 550ºC.
- The demonstration recycle compressor aftercooler is also PCHE type


Low Temperature Section

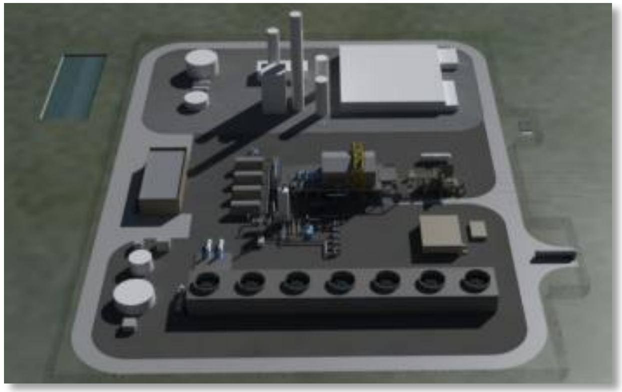

Aftercooler being lowered into position


Demonstration plant main process heat exchanger network (*Courtesy: Heatric*)

Part of the recuperative heat exchanger battery and the recycle CO_2 high pressure pump

Direct contact cooler for turbine discharge gas and the CO_2/O_2 oxidant compressor

The 300MWe Commercial Natural Gas Plant is Currently in Pre-FEED Design



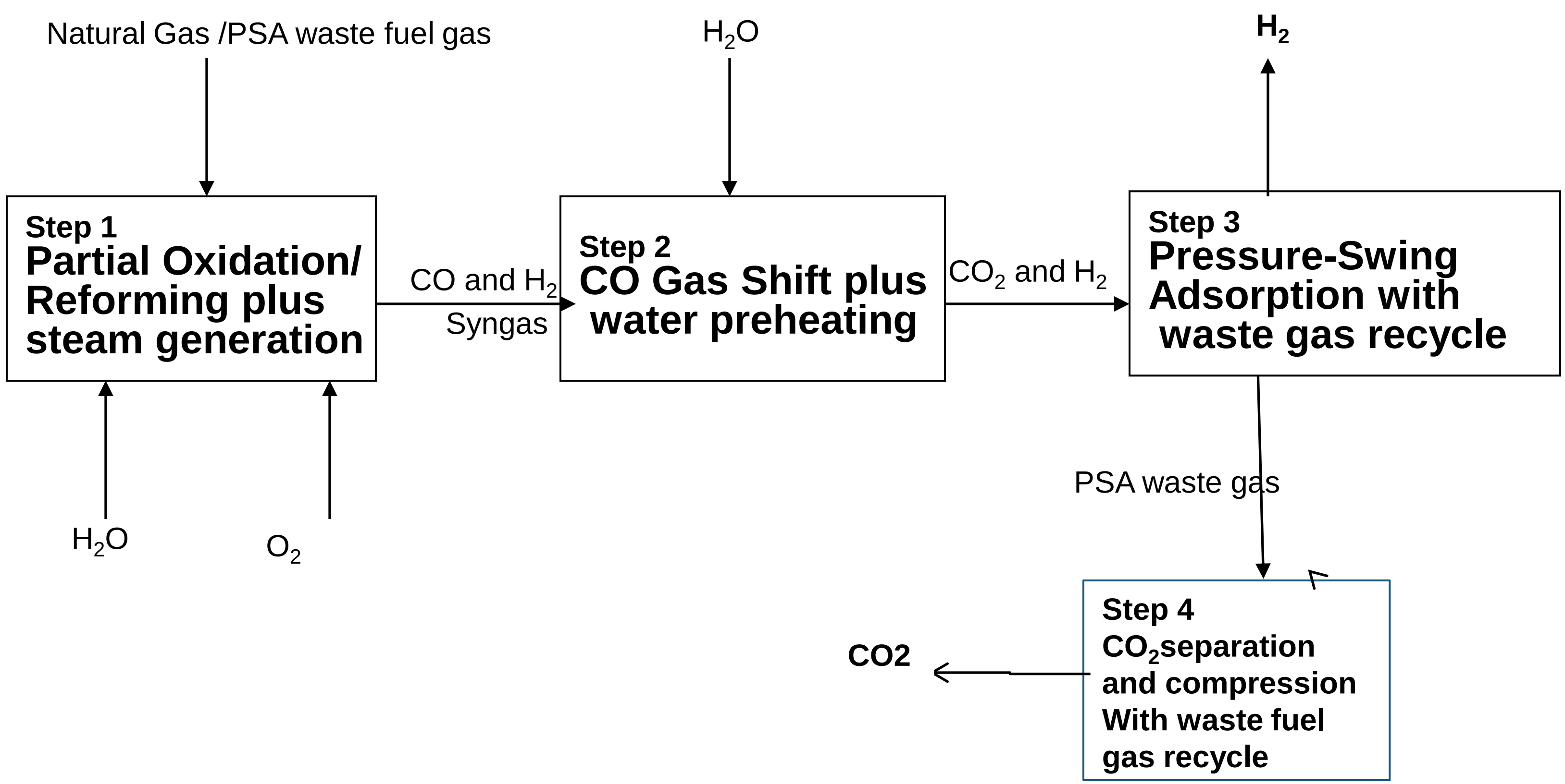
NET Power 300 MWe Commercial Plant (CH4 fuel)	
Net power output	300 MW at ISO Conditions
Natural gas thermal input	526MW
LHV Efficiency	57.0%
Oxygen consumption	3627 MT/day (contained)
CO_2 Produced	2494 MT/day at 150 bar
Turbine outlet flow	923 kg/s
Turbine inlet condition	300 bar at 1158°C
Turbine outlet condition	30 bar at 727°C (approximately)

- **A detailed pre-FEED design study is underway.**
- **Major equipment is in an advanced stage of readiness:**
  - ***Turbine and Combustor:*** The demonstration turbine size allows verification of the design for the 526 MWth commercial turbine.
  - ***Heat Exchanger:*** increase in size and quantity of cores for the commercial system.
  - ***ASU:*** The 3627 MT/day, 99.5% O_2 ASU has been demonstrated at this size by all major suppliers.
  - ***Compressors:*** The physical linkage of the CO_2 compressor and turbine is within the size capability of major compressor vendors.
  - ***Pumps:*** The multistage CO_2 pumps are demonstrated at the design duties required.

Excellent performance at high ambient conditions: 31C Air, 289 MW net

Hydrogen Production Process Overview

A Proven pressurized Process That Converts Natural Gas Oxygen and Steam to Hydrogen



Hydrogen Production Reactions

Partial Oxidation

$CH_4 + ½O_2 \leftrightarrow CO + 2H_2$ endothermic

$CH_4 + 2O_2 \leftrightarrow CO_2 + 2H_2O$ exothermic

$CO + H_2O \leftrightarrow CO_2 + H_2$ exothermic

Convective Heat Reforming

$CH_4 + H_2O \leftrightarrow CO + 3H_2$ endothermic

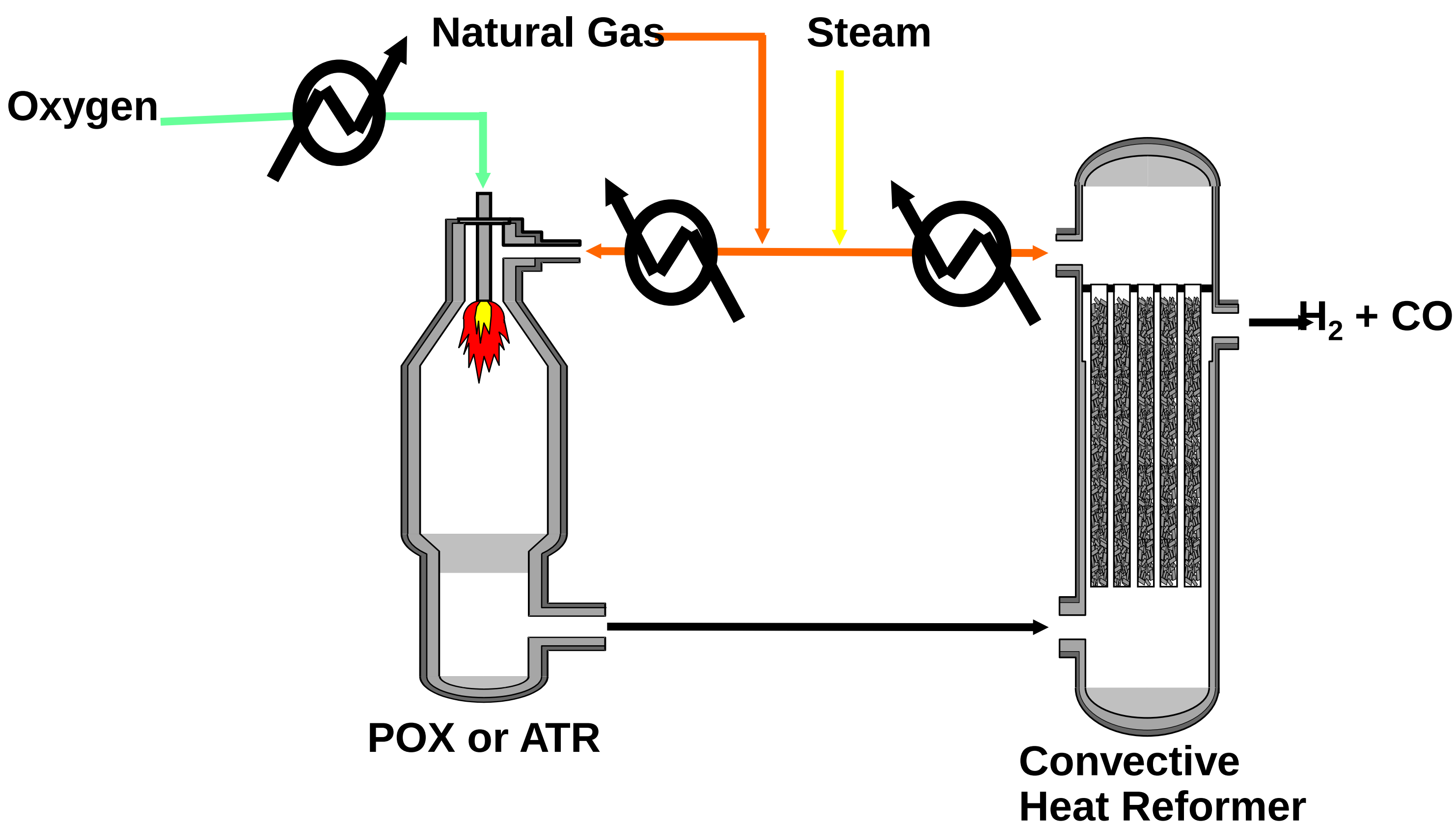
$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$ endothermic

Water-Gas Shift

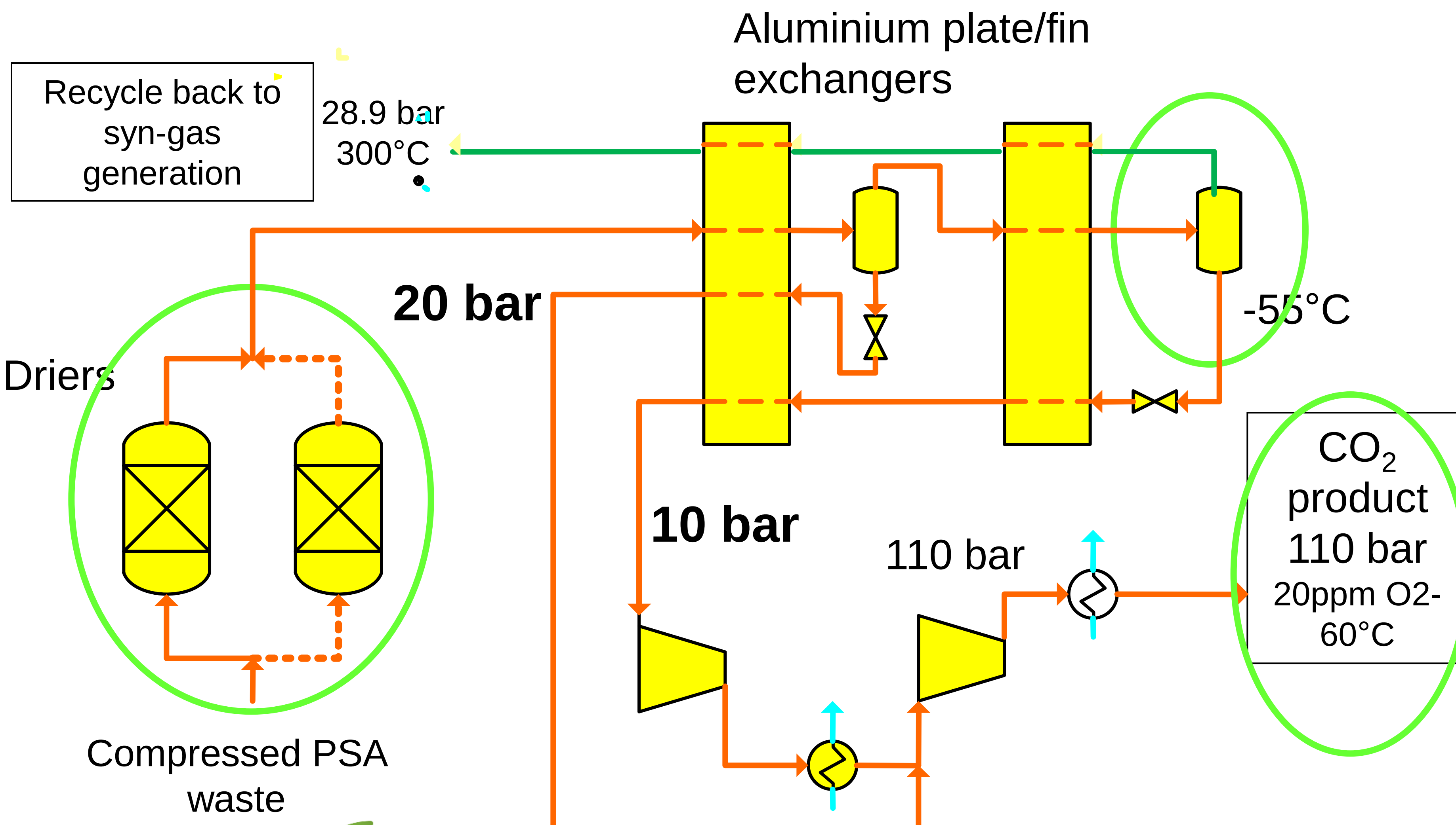
$CO + H_2O \leftrightarrow CO_2 + H_2$ exothermic

Syn-gas System For Hydrogen Production

H2 can be produced at up to 90bar pressure



Low temperature CO2 removal by condensation near the triple point



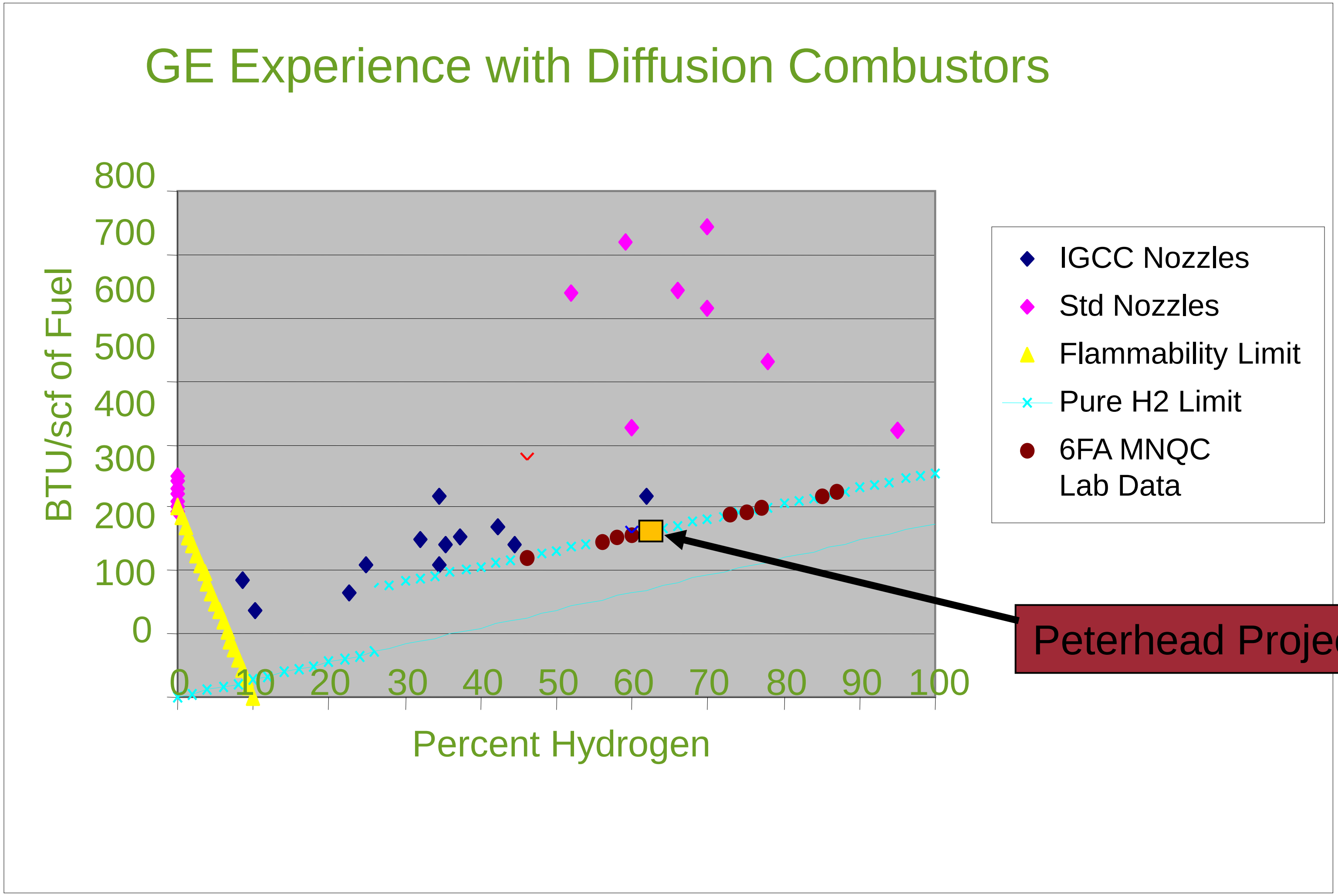
GE F Class Turbines For Hydrogen Power

GE F Class Turbines Have Over 30 Million Hours Of Operations, the Largest, Most Experienced Fleet of High Efficiency Gas Turbines

	PSI Wabash	Tampa Polk	Exxon Singapore	Motiva Delaware
Turbine	7FA	7FA	2x6FA	2x6FA
H_2 (% vol)	24.8%	37.2%	44.5%	23.0%
LHV (BTU/ft^3)	209	253	241	248
H_2/CO Ratio	0.63	0.80	1.26	0.65
Diluent	Steam	N_2	Steam	H_2O/N_2

Feasibility of high H_2 fuel combustion with low emissions has been demonstrated at F class conditions using proven syngas combustor design; reliability, availability and maintainability can be equivalent to natural gas turbines

GE Hydrogen Combustion Experience GE data



INTEGRATED POWER SYSTEM WITH AN ALLAM CO2 CYCLE PLUS A HYDROGEN FUELED COMBINED CYCLE

ALLAM cycle integrated with a GE PG9371(FB) combined cycle power syste

Stand alone ALLAM cycle net power output 290Mw

Stand alone GE PG9371(FB)

Combined cycle net power output 432.25Mw

Gas turbine fuel is 50% H2+50% N2 molar concentration

Total net power output 697Mw Cycle efficiency (LHV) 50.9%

CO2 production (100% capture) at 150bar pressure 6437Metric tons per day

O2 consumption (99.5% purity) 4979Metric tons per day

Approximate capital cost erected £1150/kw installed net capacity

net electricity cost 4.53pence/Kwhr

Capital charges plus operations 17%/year, Natural gas £5/million BTU (LHV), 8000hr/year, CO_2 credit £25/metric ton,

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Commercial Hydrogen Fuelling Installations

BP, Singapore

Air Products' Hydrogen Fuelling Systems

Supplied to major oil companies

Shell, Washington, DC, USA

Underground Liquid Hydrogen Fuelling Tank – Washington, DC, USA

Liquid Hydrogen Tanker

capacity 3600 kg liq H_2

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Oxy-fuel Technology for CO_2 Capture - Definition:

Fuel + oxygen with nitrogen rejected in an air separation plant

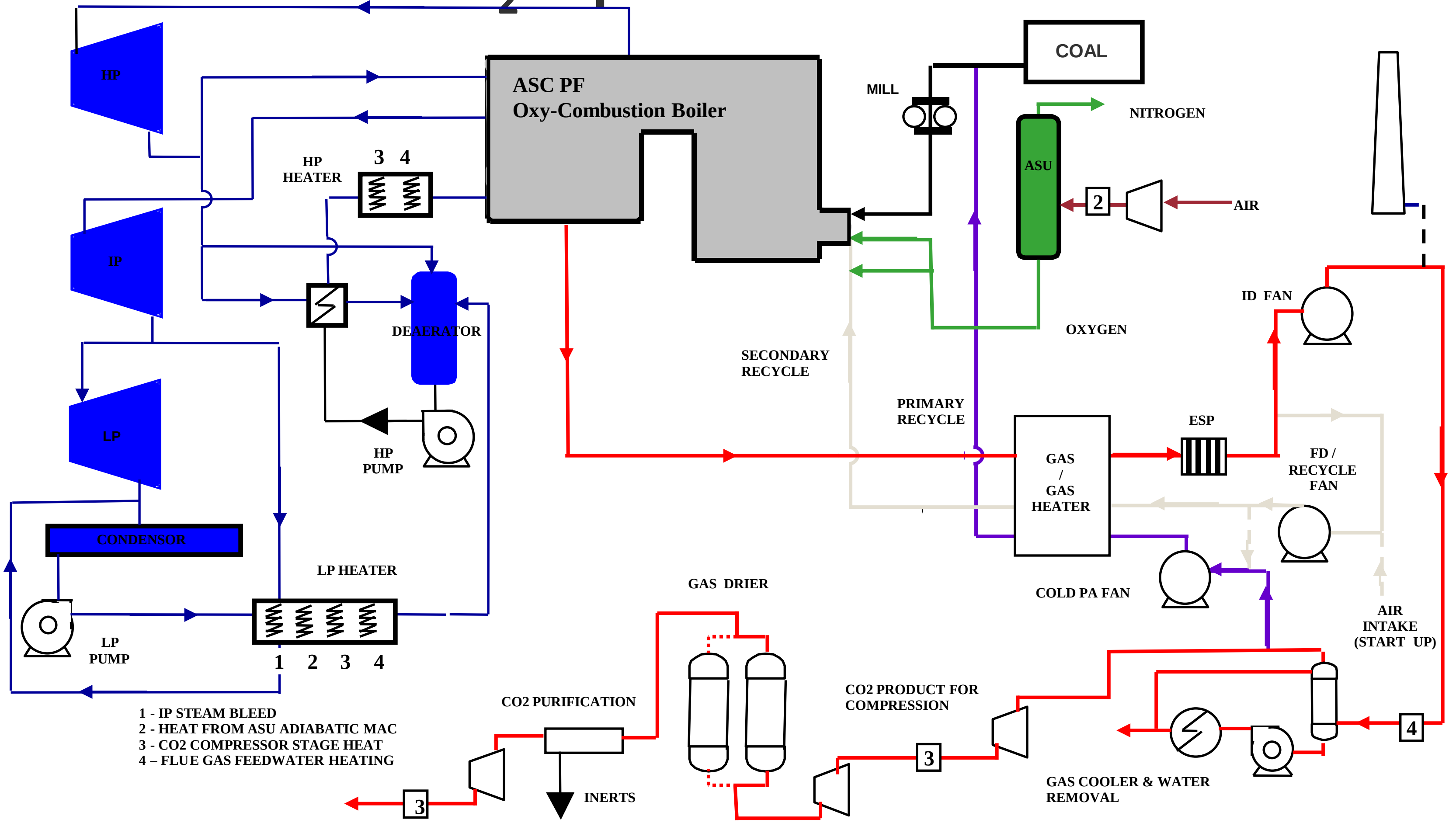
Diluent flow of CO_2 or H_2O or recycled flue gas with fuel to oxygen concentration ratio controlling combustion temperature

Independent control of heat output and combustion temperature

Low power consumption 95% O_2 plants and simple SOX and NOX removal

Minimal existing boiler and turbine plant modification. Demonstrated burner operation. Low risk system

Schematic of Supercritical PF Oxyfuel Power Plant With CO_2 Capture



NOx and SO_2 Reactions in the CO_2 Compression System

SO_2, NOx and Hg can be removed in the CO_2 compression process, in the presence of water and oxygen.

SO_2 is converted to Sulphuric Acid, NO_2 converted to Nitric Acid:

- $NO + \frac{1}{2} O_2$ = NO_2 (1) Slow
- $2\ NO_2$ = N_2O_4 (2) Fast
- $2\ NO_2 + H_2O$ = $HNO_2 + HNO_3$ (3) Slow
- $3\ HNO_2$ = $HNO_3 + 2\ NO + H_2O$ (4) Fast
- $NO_2 + SO_2$ = $NO + SO_3$ (5) Fast
- $SO_3 + H_2O$ = H_2SO_4 (6) Fast

Rate of Reaction 1 increases with Pressure to the 3rd power

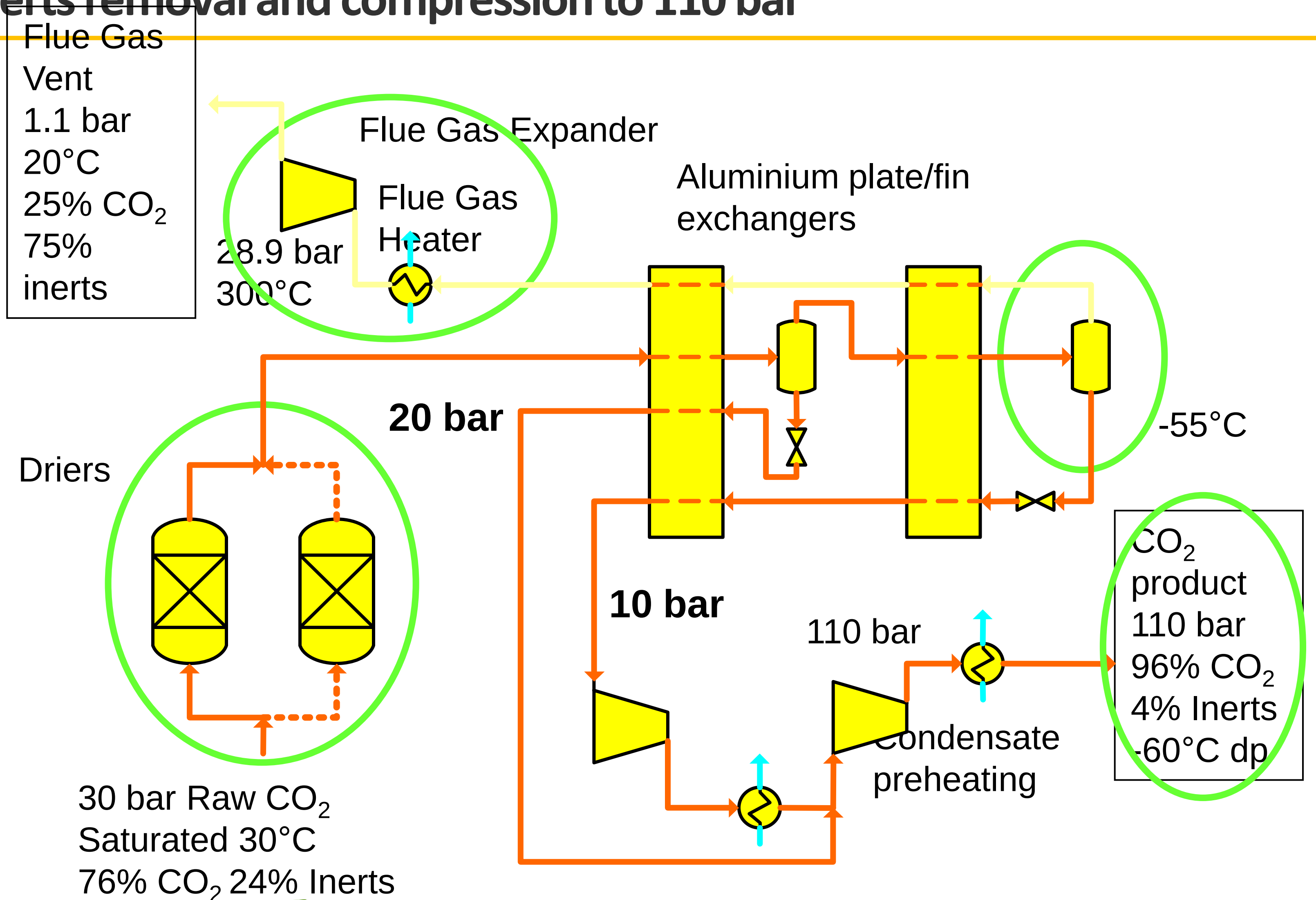
- only feasible at elevated pressure. Adiabatic CO_2 compression to 15bar with heat to BFW is economic.

No Nitric Acid is formed until all the SO_2 is converted

Pressure, reactor design, residence times, and NO concentration (>100ppm) are important

H2SO4 >25% concentration converted to gypsum

CO_2 Compression and Purification System – Inerts removal and compression to 110 bar



CONCLUSIONS

- Cost of electricity from the Allam cycle using natural gas fuel with 100% CO_2 capture is about the same as the best NGCC system with no CO_2 capture.

- CO_2 is produced as either a high pressure fluid for pipeline transportation or as a liquid for shipping in tankers.

- Cost of electricity using the coal based Allam cycle with 100% CO_2 capture is about 17% lower than a 600°C, 300bar steam cycle with no CO_2 capture.

- The demonstration Allam cycle plant at Laporte USA is currently nearing full power operation.

- Hydrogen can be produced at up to 90 bar pressure with 100% CO2 capture at an efficiency of over 75%, comparing the lower heating value of H2 product and natural gas feed.

- Hydrogen fuel for gas turbines and fuel cells for vehicles and decentralised power with 100% CO_2 capture.

- Hydrogen production can be integrated with large scale Allam cycle power production

- OXY-FUEL conversion of existing coal fired power stations offers low risk option for dealing with existing CO2 emission.