GTEN 2023 Symposium

October 16 - 18, 2023 I Banff, Alberta

25th Anniversary

Gas Turbine Systems for Cleaner Energy

- Air Pollution and GHG Emissions
- Emission Guidelines and Standards
- Balancing Emission Prevention & System Efficiency
- Clean Energy Considerations

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Presented at the Gas Turbines Energy Network (GTEN) 2023 Symposium
Banff, Alberta, Canada

Typical Industrial Gas Turbine Energy Systems

- Simple Cycle, Standby power
- New Gas Combined Cycle
- Combined Cycle Repowering
- Utility Coal Gasification
- Large Industrial Cogen
- Oilsands Gasification
- Pipeline Compression

- Small Industrial Cogeneration
- Municipal District Energy
- Micro-T Distributed Power/Heat
- Waste Heat Recovery
- Process Off-Gases, Biofuels









About 30 000 MWe installed in Canada
(~ 470 plants, 1200 units)

Air Emissions

(Smog, Acid Rain, Climate Change, Toxics)

Health & Ecosystems

Extreme, Unpredictable Weather

Air Pollution

- Sulphur Dioxide SO_2
- Nitrogen Oxides NO_2
- Volatile Organics VOC
- Carbon Monoxide CO

- Fine Particulate PM
- Mercury & Heavy Metals
- Ammonia

Greenhouse Gases

- Carbon Dioxide CO_2
- Methane CH_4
- Nitrous Oxide N_20
- SF_6 et al

Ozone Depletion

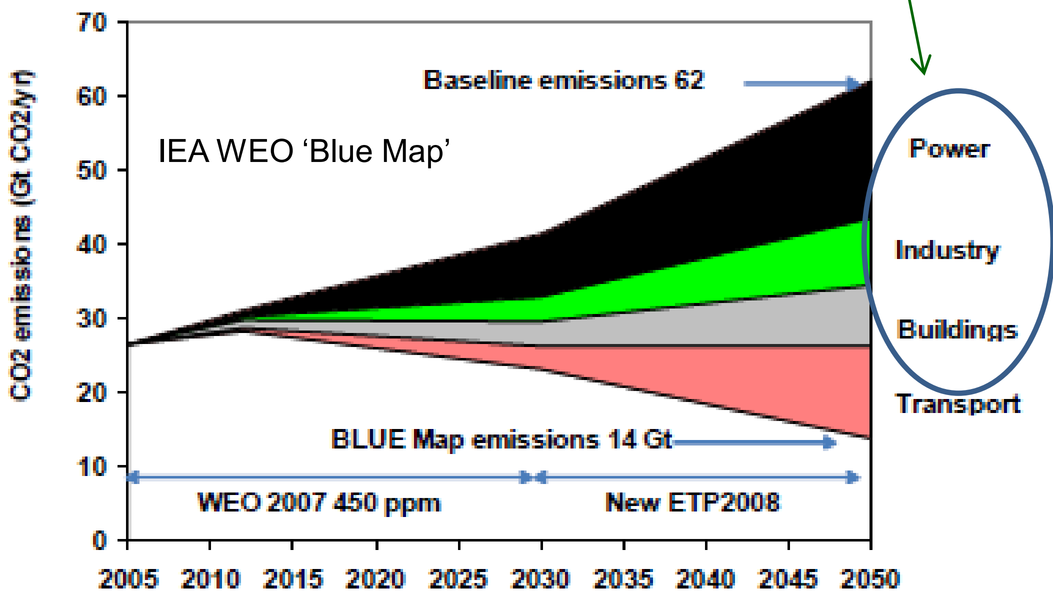
- CFCs

What are Cleaner Energy Choices ?

- Aggressive Energy Conservation and Efficiency
- Small Renewable Energies, Biomass Fuels
- High Efficiency Nat. Gas Systems (GTCC, GTCHP)
- Large Hydro & Nuclear Facilities
- Waste Energy Recovery, Hydrogen systems

GT systems can do 25-30% of these reductions

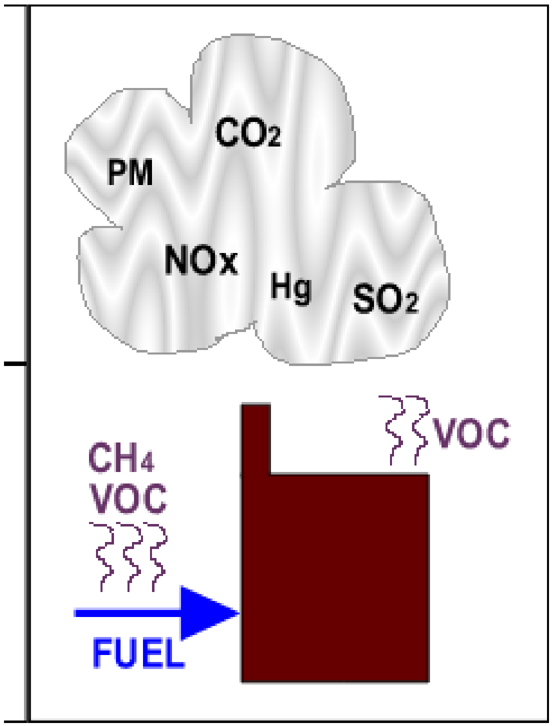
- *Air Pollution*
- *GHG Emissions*
- *Air Toxics*
- *Water Impacts*
- *Energy Security, Diversity*

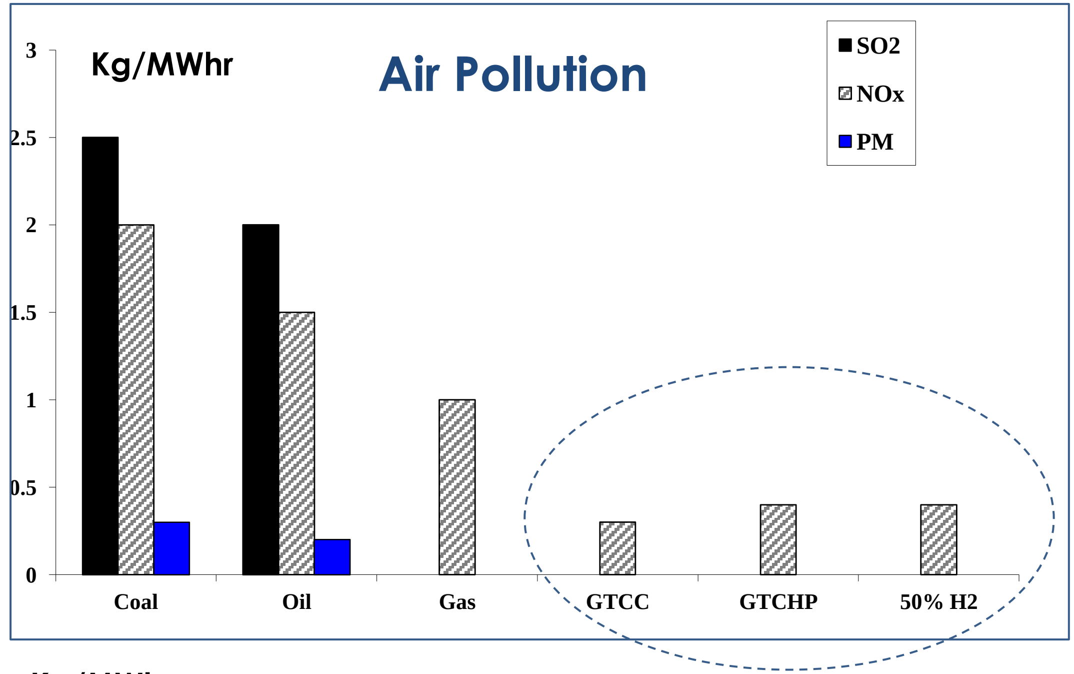


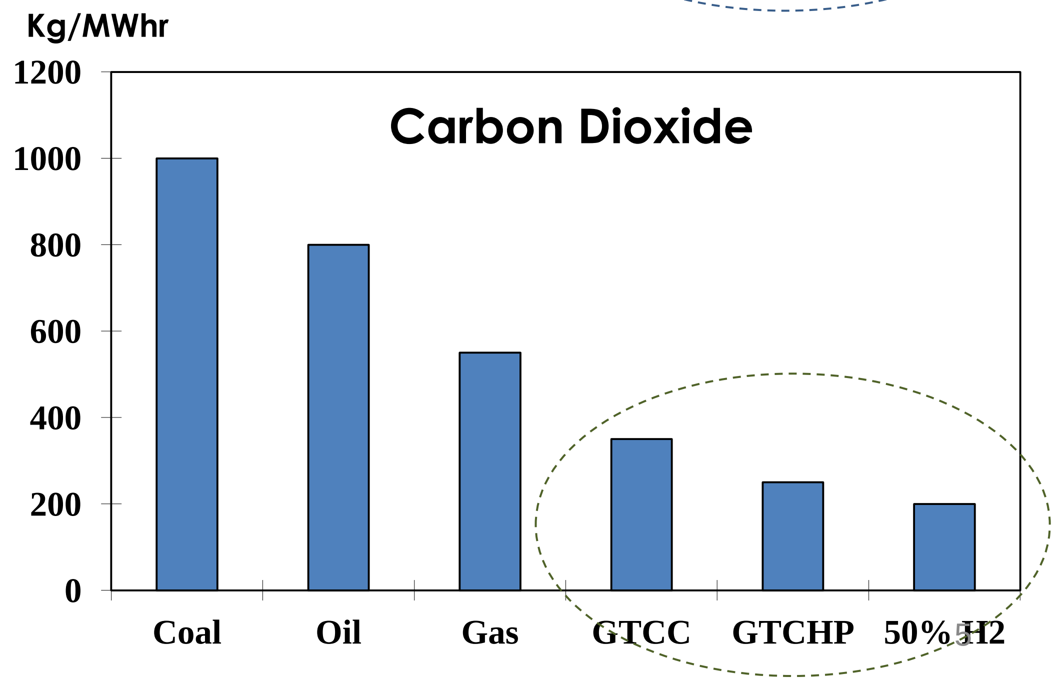
- Phaseout of Coal Steam Plants
- Support for Renewable Energy
- Hydrogen and CCS

Comparing Emissions;

“Cannot produce Air Pollution without making CO_2”

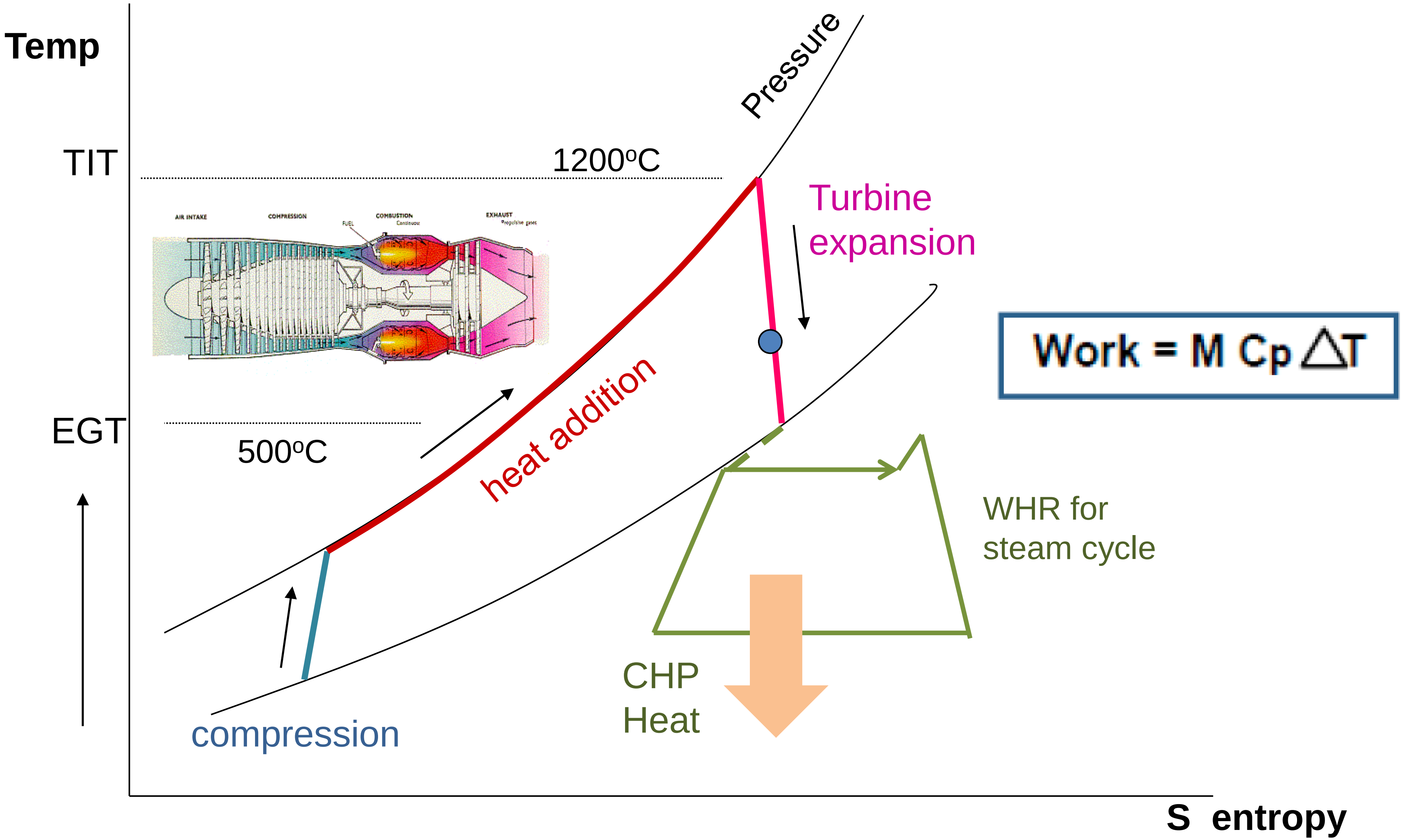






Gas Turbine systems on NG fuel have replaced/avoided many high emission systems, and have supported Renewable Energy

Brayton & Rankine Cycle for Gas Turbine Systems



Gas turbine based on airflow **(gas = air = N_2, CO_2, O_2, H_2O)**

Steam turbine based on steam flow

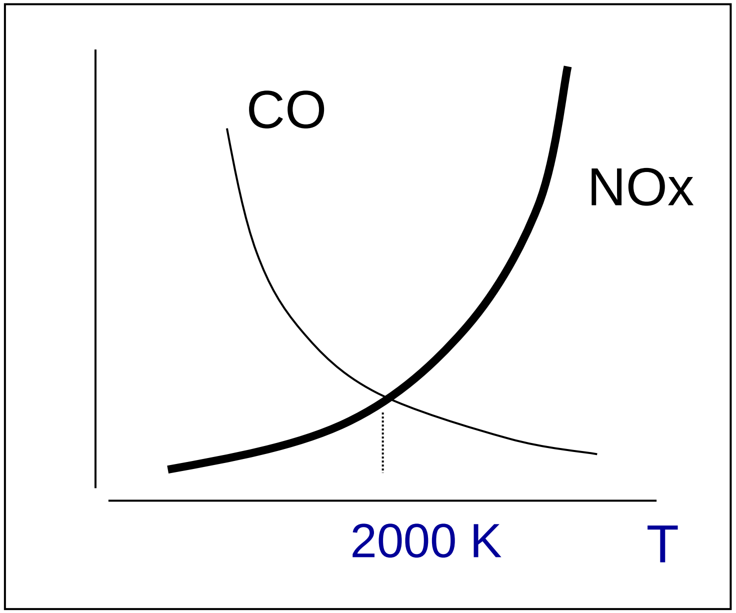
Air Pollution - *NOx Emissions*

$O + N_2 \longrightarrow NO + N$

$N + O_2 \longrightarrow NO + O$

3 Compounds of Concern:

NO, NO₂ smog , ***N₂O*** ghg



Thermal NOx:

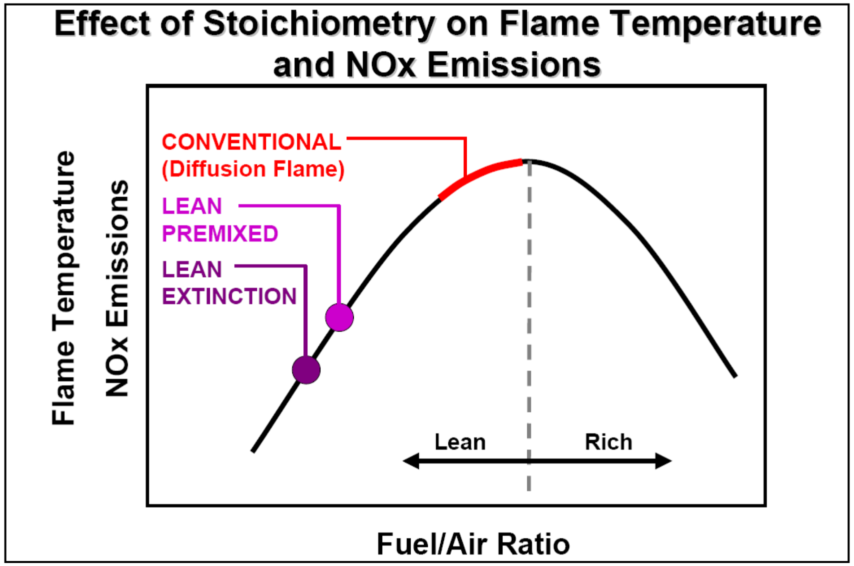
High Temperature Combustion

Fuel NOx:

From N_2 Content of Oil, Coal

Nitrous Oxide is N_2O, a GHG

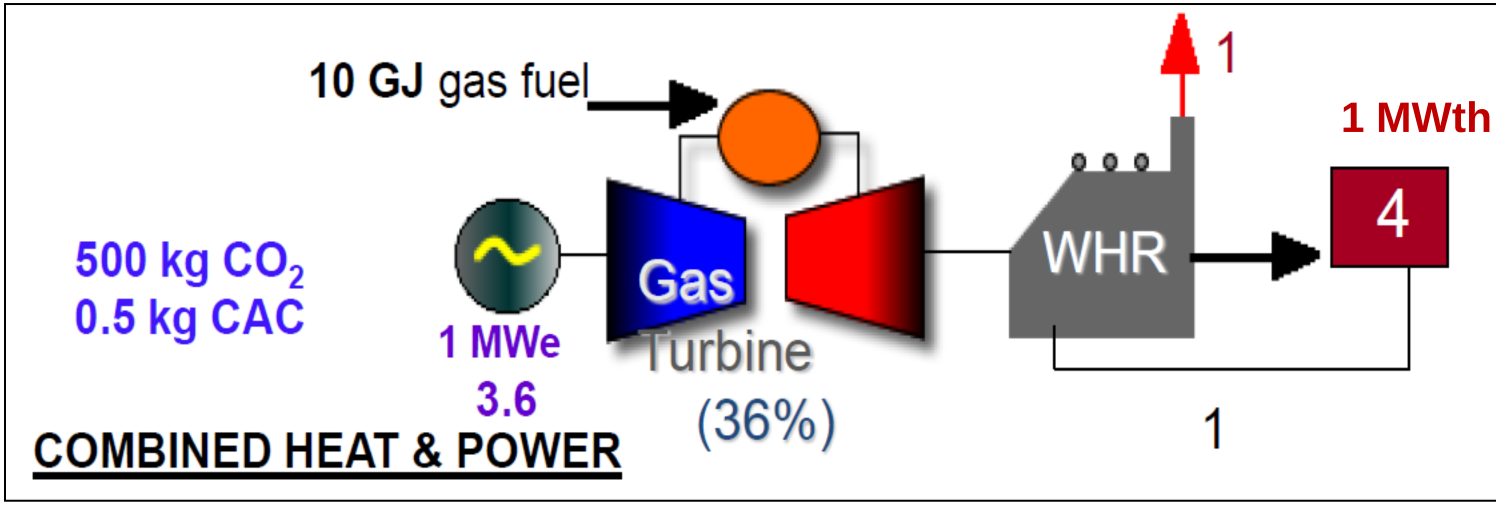
Balancing of NOx, CO and reliability



(Solar Turbines)

Cogeneration or Combined Heat & Power (CHP)

Producing 2-3 forms of energy from the same fuel, in same process

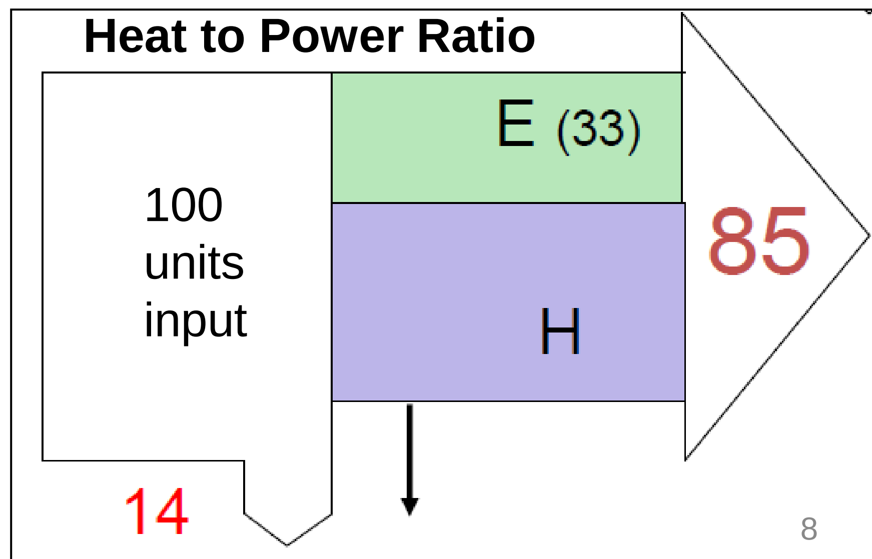


Quality of Energy

High

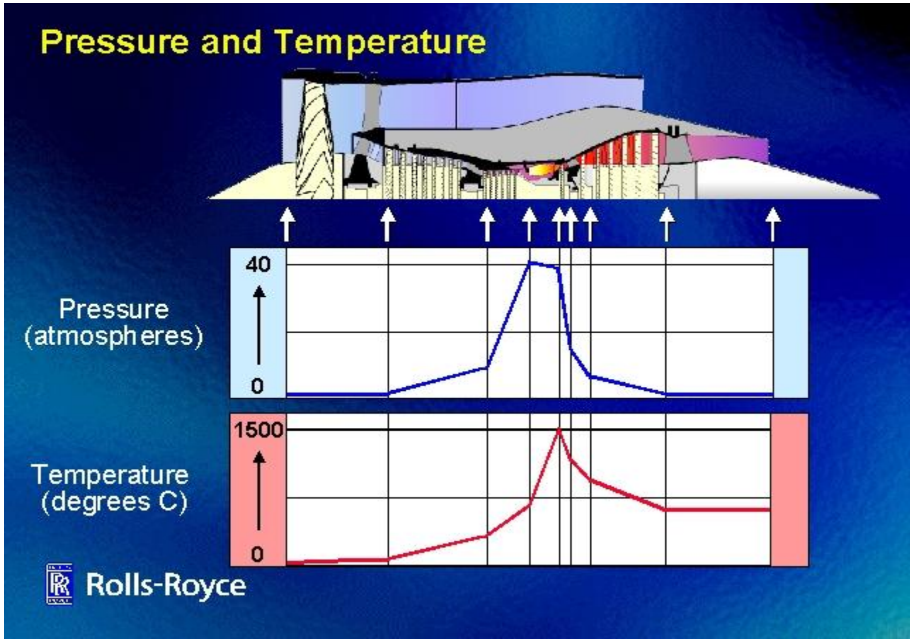
- Electricity & Shaft Power
- Industrial Process Heat
- Cooling
- High Pressure Steam
- Hot Water
- Space Heating

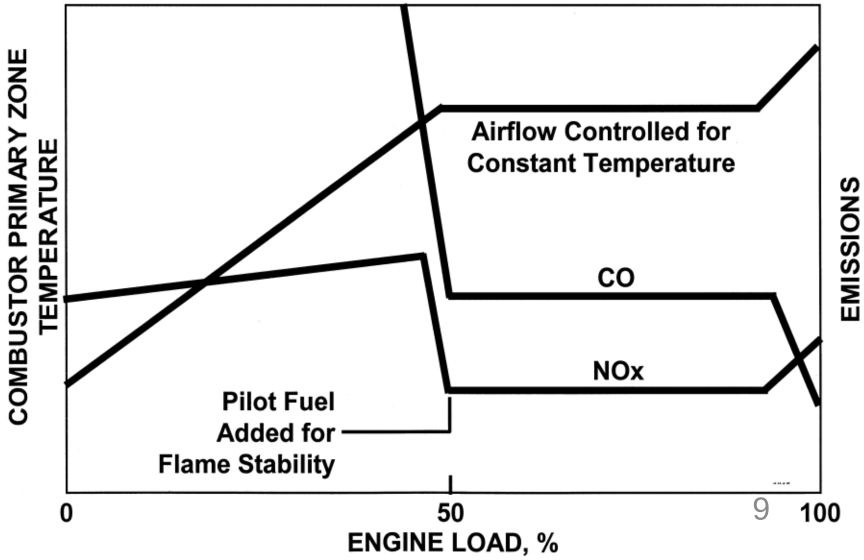
Low



Factors Affecting NOx and CO_2 Emissions in Gas Turbines

- Unit efficiency (***AIR*** mass flow, Pressure Ratio, Turbine Inlet Temp)
- Engine type (Aero or Frame)
- Fuels (CH_4, H_2 & syngas, liquids)
- Dry Low NOx combustor
- Part load, Operating Range, starts
- Cold and hot weather, humidity
- Compressor spools, N_1/N_2 speeds
- Specific Power (kW per lb/sec air)
- Waste heat recovery
- NOx Concentration vs Mass Flow
- Tradeoffs w/ other emission types





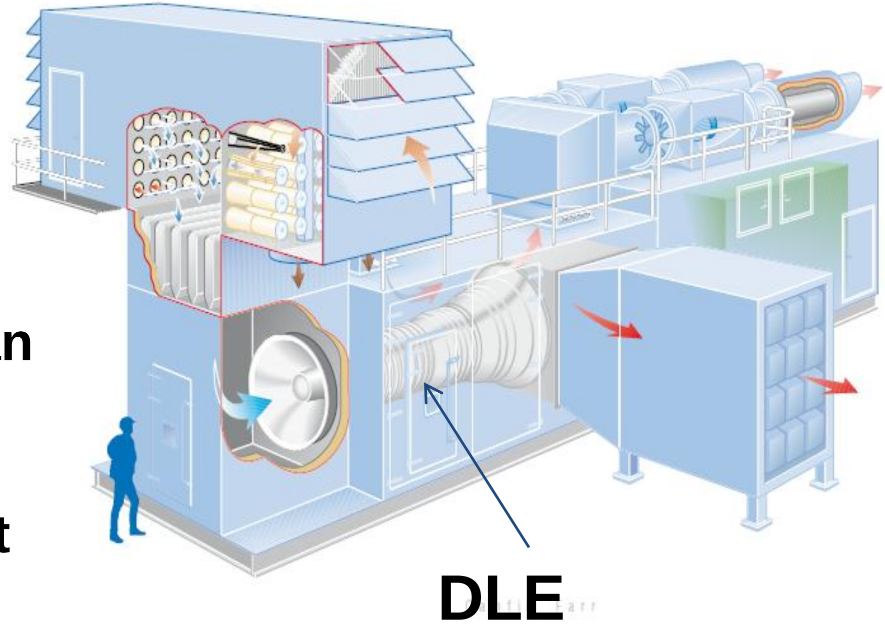
Clean Air for New Gas Turbine Systems

Are there $PM_{2.5}$ particulate emissions from gas-fired turbines?

(AP42 - 0.07 lb/MWhr ?)

Modern turbine air filter systems clean the incoming air with PM_2 by 99 %

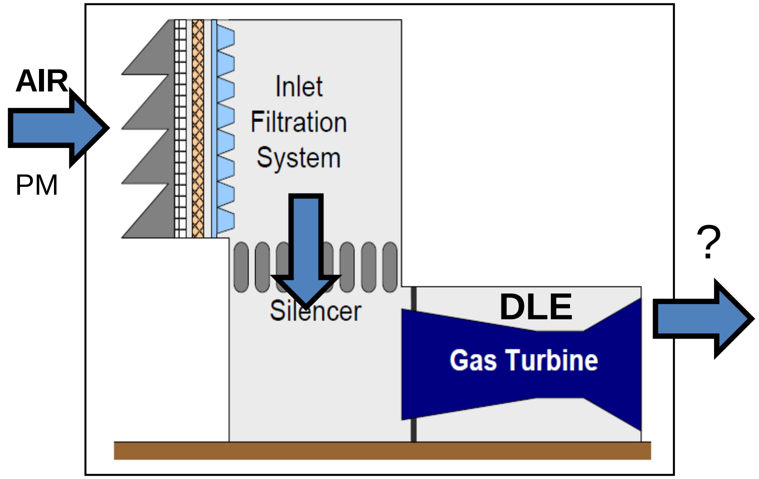
Small amounts of PM can escape, but must go through DLE combustor



Emissions of fine particulates?

Likely not – the incoming Airflow can be filtered down to $PM_{0.2}$ by 80%

GT system mass balance ?



Importance of Environmental Criteria, Units

A.

- **ppmv at Exhaust**
- **ppb at fence line**
- **mg/m^3**

- **kg per Fuel Input**

B.

- **mass per time (t/yr)**
- **kg per MW_e-hour output**
- **kg per MW_{th}-hour**

Concentration-based units, in ppmv and mg/m^3, require O_2 content (15%)

- some of these inherently include system efficiency

(CO_2 emissions at 35 000 ppmv ?)

'Clean Energy' and climate solutions may be better handled with 'B'

Examples of International Standards

(for GT Units Larger than ~ 10 MWe, gas fuel)

United States	**2 - 42 ppm**
United Kingdom	**60 mg/m^3**
Germany	**75 mg/m^3**
France	**50 mg/m^3 ***
Japan	**15 - 70 ppm**
Canada	**85 - 140 g/GJ_{out} ***
Australia	**70 mg/m^3**
EU LCPD	**50 - 75 mg/m^3 ***
World Bank	**125 mg/m^3**

- **Facility Cogeneration Incentives (Values Subject to Change)**
- **New US EPA rules, 2006**

Emissions Criteria

Traditional concentration (ppm, mg/m³) and fuel input (g/Gj_{in}, lb/MMBTU) criteria;

- **difficult to interpret**
- **do not give appropriate design signal**
- **do not encourage system efficiency**
- **do not encourage Pollution Prevention**

ICAO - *aircraft (kg_{NOx}/thrust)*

- **Aviation uses 'LTO' Operations Cycle**
- **Recip engines have kg/MWhr rules**

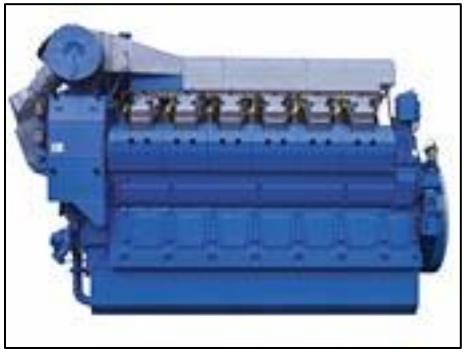
Output-based Rules;

Mass per Product Output; *kg/tonne, kg/MWhr, g/GJ_{out}*

tonnes/year

$/tonne

$/MWhr



Lbs / Hphr

Gas Turbine NOx Emissions (ppmv at 15% O_2)

$$ppmv_{15} = ppmv_{meas} \frac{(20.9 - O2_{15})}{(20.9 - O2_{meas})}$$

Uncontrolled; Older Units: 100-200 ppmv Newer Units 200-300 ppmv

F-factor (m^3 per GJ) exhaust flow to convert ppmv into grams per GJ heat
Natural gas; **240 m^3 per GJ** Hydrogen blends < 200

Mass Rate/Energy Output NOx Estimate; need mass airflow in kg/hr

$$\frac{ppmv \times MassFlow\,(kg/hr) \times m.wt.}{Power\,(MW)} = \_\_ \; Kg_{NOx} / MWhr$$

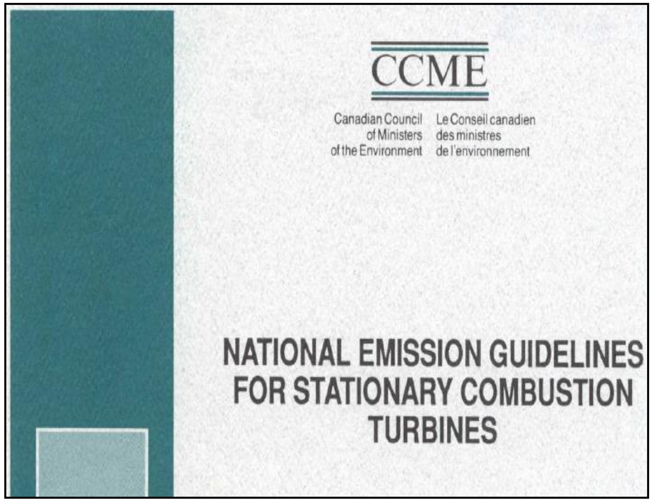
Example (30 MWe unit, air = 100 kg/sec)

$$\frac{25\,ppmv}{10^6} \times \frac{360\,000\,kg}{30\,MW\;\;hr} \times \frac{46}{29} = \mathbf{0.48\;\; kg/MWhr}$$

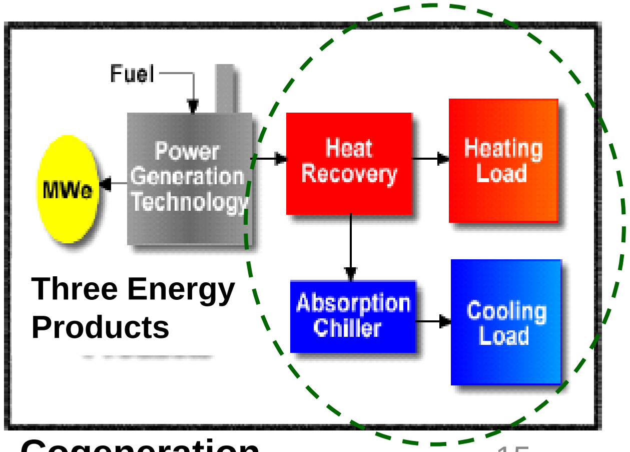
(for CHP, can include the 'MWth' for a lower emission factor)

Canadian Gas Turbine Emission Guidelines (1992)

- National Consensus, NOx Prevention
- Output-Based Standard for System Efficiency ($140\ g/GJ_{out}$ Power + 40 g/GJ Heat)
- Engine Sizing Considerations
- Balance Air Pollution with Greenhouse Gases
- Promotes Cogeneration, WHR and low CO_2
- Added NOx margin for GHG tradeoffs
- Operating Margin for Peaking Flexibility
- Flexible Emissions Monitoring
- Mass & Energy criteria for system efficiency, rather than volume & ppmv (for hydrogen)



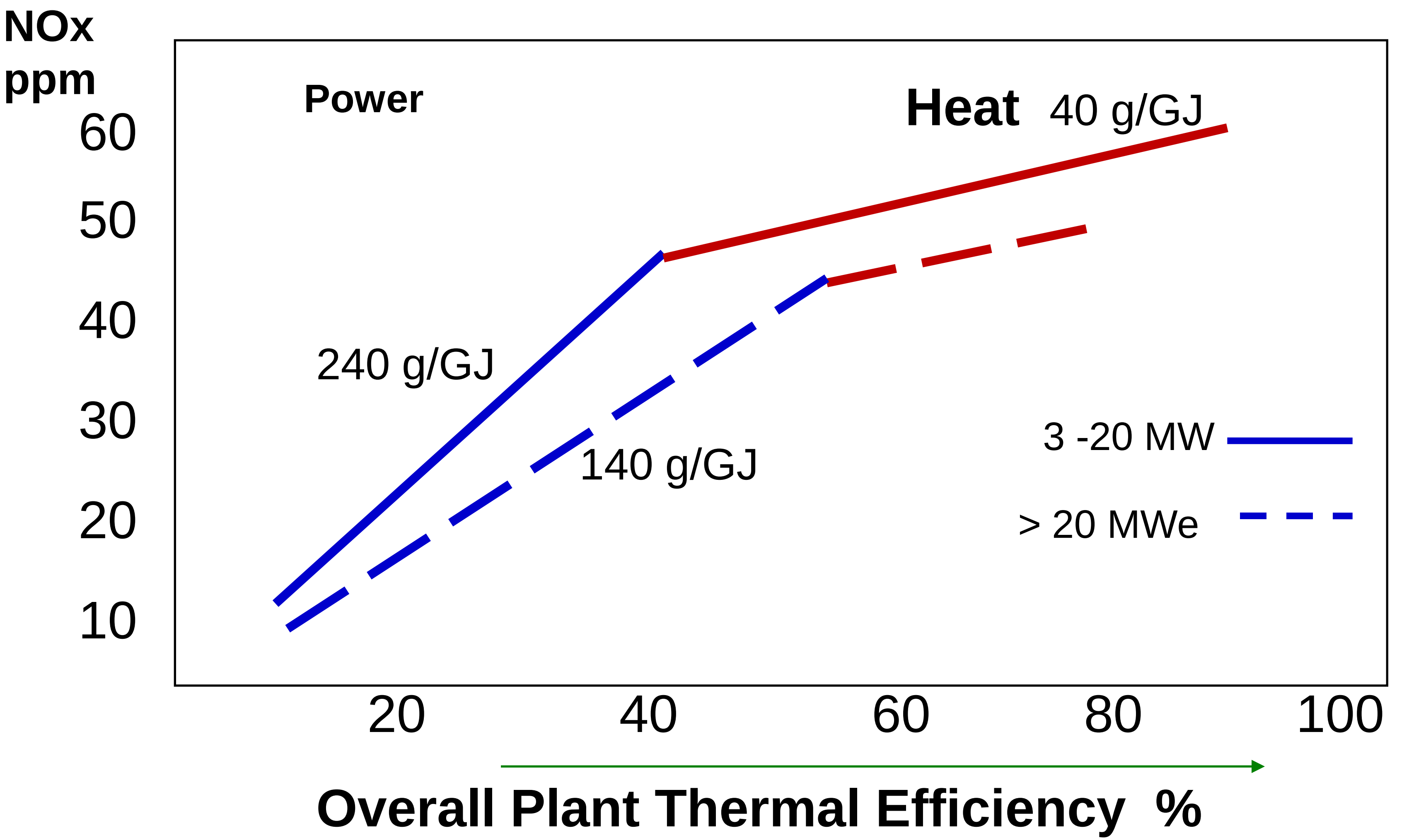
CCME - Canadian Council of Ministers of Environment, 1992



Cogeneration

<u>Canadian Gas Turbine Guideline</u> (1992)

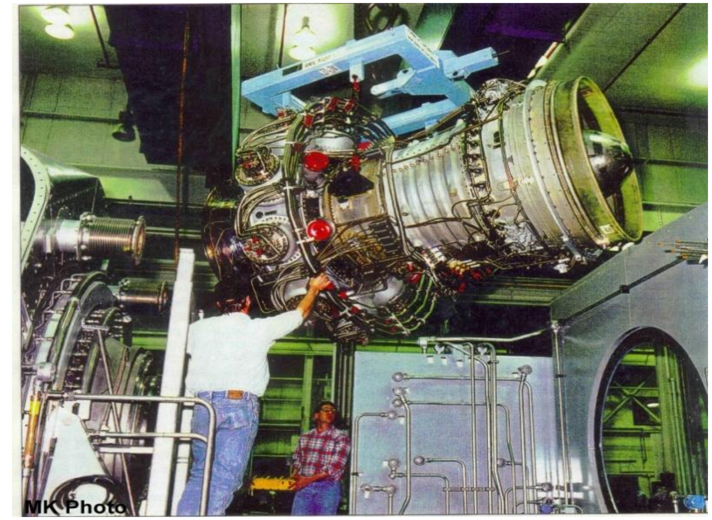
Energy Output-based Guideline allows higher NOx for smaller units, which tend to have higher system CHP efficiency



1992 Emission Guideline based on;

ASME and IAGT events (1989/91), industry consultation, and …..

TCPL Nipigon Waste Heat Recovery, 1991



Rolls Royce RB211 DLE

TransAlta Ottawa Hospital Cogen, 1991

GE LM6000 steam injection

New US EPA Rules for Gas Turbines (2006)

Can choose Output-based, or Concentration-Based Rules *(EPA OAR-2004-0490)*

Size, Heat Input (MMBTU/hr)		ppmv	lb/MWhr
(New Units, Natural Gas Fuel)			
< 50	(electricity, 3.5 MWe)	42	2.3
	(mechanical, 3.5 MW)	100	5.5
50 to 850	(3 – 110 MW)	25	1.2
Over 850	(> 110 MW)	15	0.43
Units in Arctic, Offshore			
	< 30 MW	150	8.7
	> 30 MW	96	4.7

- MW could include MWth for waste heat in CHP
- Efficiency based, SCR likely not required
- Flexible Emissions Monitoring

Part III

Environmental Protection Agency

40 CFR Part 60

Standards of Performance for Stationary Combustion Turbines; Final Rule

Revised Federal Rules for Canada

Guidelines for the Reduction of Nitrogen Oxide Emissions from Natural Gas-Fuelled Stationary Combustion Turbines

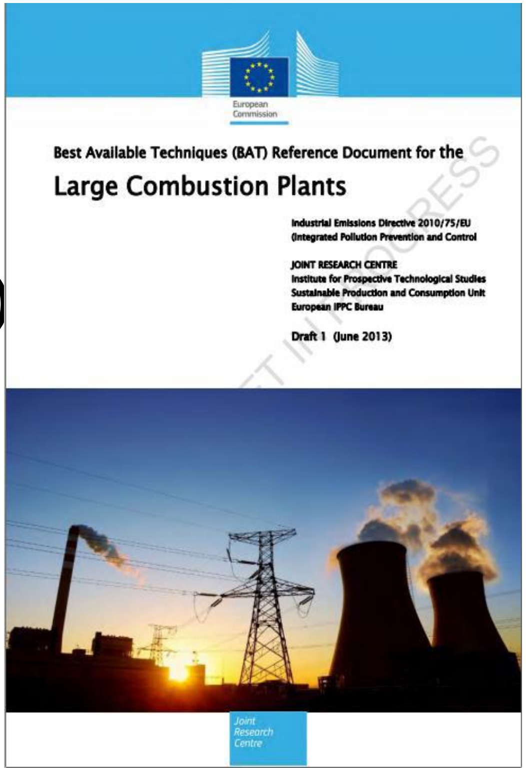
?

Application	Turbine Power Rating (MW)	NO_x Emission Limits ($g/GJ_{(power\ output)}$)	NO_x Emission limits (ppmv)@ 15% O_2
Non-peaking combustion turbines - Mechanical Drive	≥ 1 and < 4	500	75
Non-peaking combustion turbines - Electricity Generation	≥ 1 and < 4	290	42
Peaking combustion turbines – all	≥ 1 and < 4	exempt	exempt
Non-peaking combustion turbines and Peaking combustion turbines – all	4 - 70	140	25
Non-peaking combustion turbines – all	> 70	85	15
Peaking combustion turbines – all	> 70	140	25

Environment and Climate Change Canada (Nov 2017)

EU Large Plant Combustion Directive (LCPD)

- Emission Limit Values for SO_2, NO_x, PM for most industrial plants with over 50 MWth Heat Input
- Combines plant permits with trading allowances for existing and new facilities (now under review with EU ETS)
- Refers to GHG trading for plants > 20 MWth
- EU BAT Reference Guide (BREFs) July 2017 Decision ↘



NOx Emission Limits for GTs (2001 - Natural gas)

- **50 mg/m^3 (simple) or 75 mg/m^3 (cogen w/ 75% eff'y)**
- **Combined Cycle: 50 x eff'y / 35**
- **Mechanical drives: 75 mg/m^3**

Liquid and other gaseous fuels: 120 mg/m^3

US EPA CLEAN AIR ACT REGULATION OF GHG EMISSIONS (May 2023)

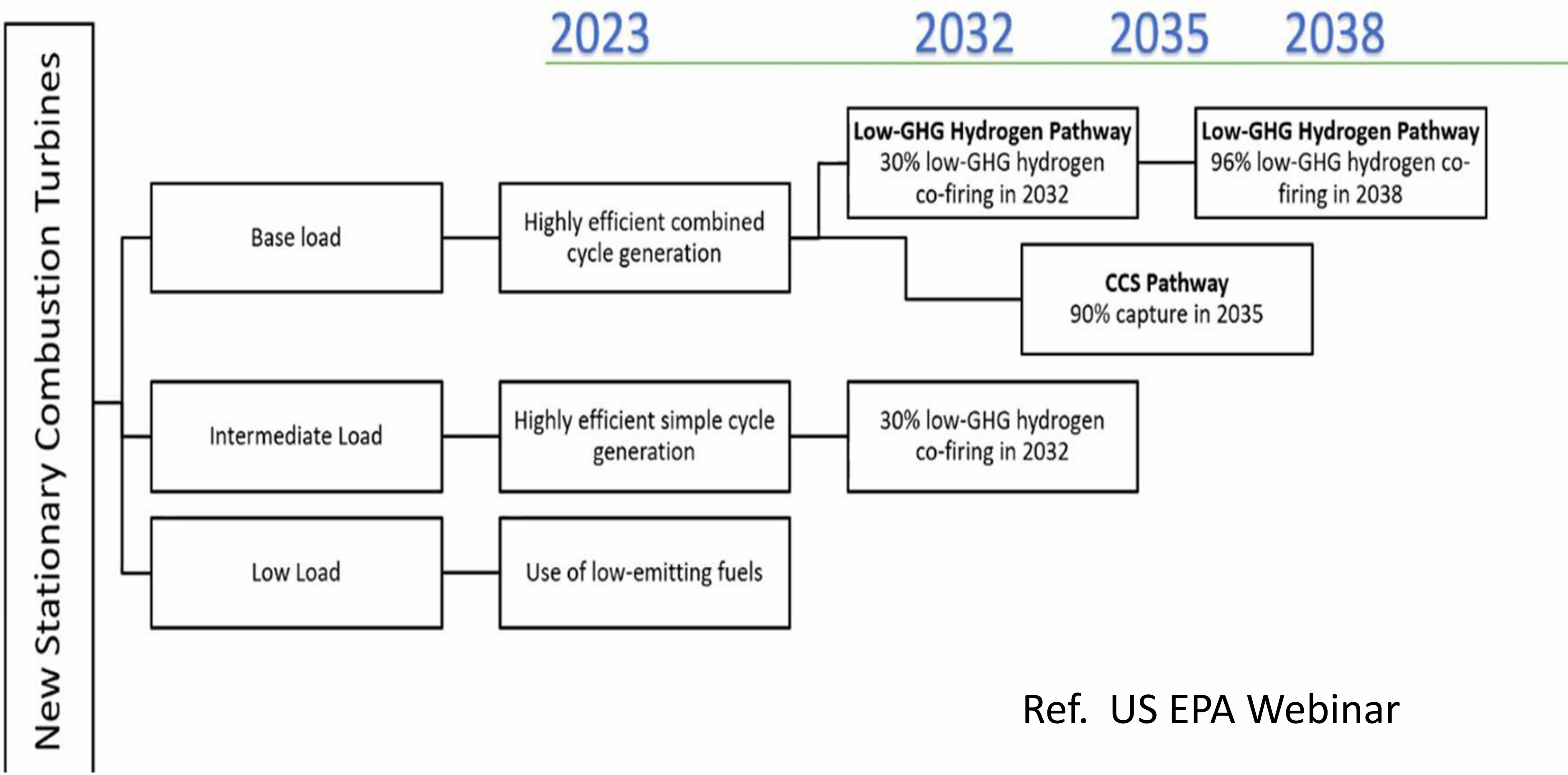
PROPOSED EMISSION LEVELS FOR NEW COMBUSTION TURBINES

Best system of emission reduction (BSER) standards

	Phase 1	**Phase 2 2032-2035**
Intermediate Load (Capacity Factor 20% - 50%)		
Efficient Simple cycle Generation	**1150 lb CO_2/MWhr**	With 30% low-GHG hydrogen co-firing; **1000 lb CO_2/MWh**
Base Load Subcategory (Capacity Factor >50%)		
Efficient Combined cycle Generation	**770 lb CO_2/MWhr** for > 2000 MMBtu/h	GTCC with 30% low-GHG hydrogen co-firing: **680 lb CO_2/MWh**
Efficient Combined cycle	**770 – 900 lb CO_2/MWhr** for < 2,000 MMBtu/h	with 90% CCS, begin 2035 **90 lbCO_2/MWh**

Proposal for New Stationary Combustion Turbines

- Standards effective from date of publication (May 23, 2023)
- Three subcategories: base load, intermediate load, low load
- Base load units have two pathways: 90% CCS in 2035 or 96% low-GHG hydrogen in 2038

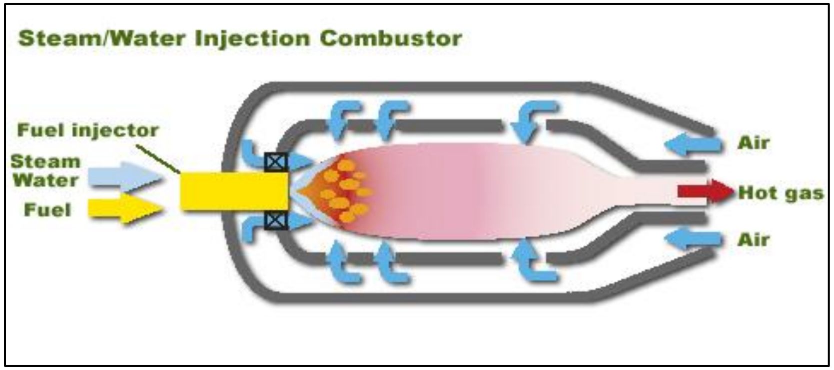


Ref. US EPA Webinar

NOx Reduction Methods

Steam/Water Injection

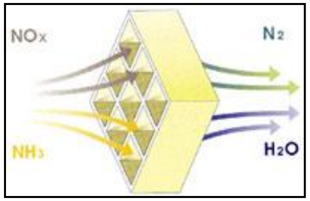
- Prevention, 2/3 red'n to 1 kg/MWhr
- Some Combustion Component Wear
- Plant Efficiency Penalty
- Depends upon value of plant steam

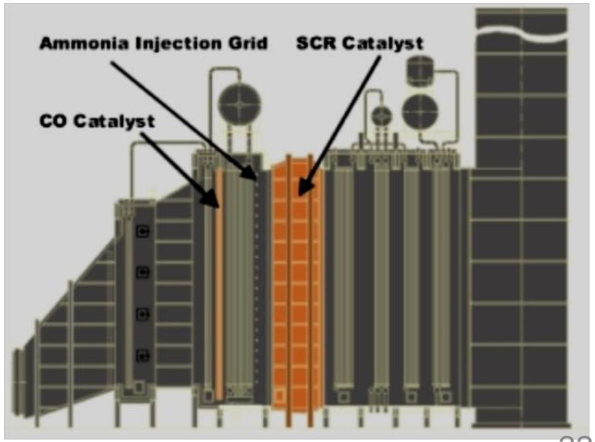


(Kawasaki)

Selective Catalytic Reduction (SCR)

- NH3 injection into catalyst in HRSG
- ~ 80% NOx Reduction
- **Backend Control**
  - **- Ammonia emissions & handling (toxic)**
  - **- fine PM emissions, N_2O ?**
  - **- Cycling duty - ammonia slip**
  - **- Efficiency loss in HRSG**
- **Marginal, low $/tonne benefit after DLN**

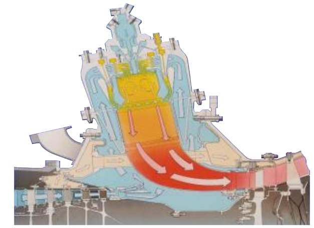




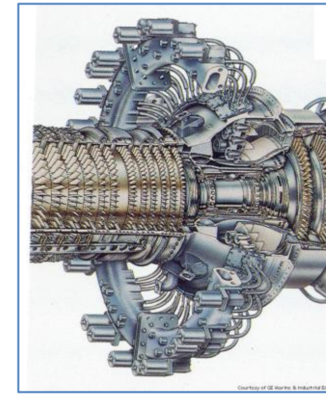
IST Aecon

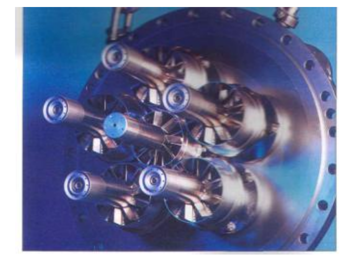
Gas Turbine Dry Low Emissions (DLE) Combustion

- <u>Preventative</u> reduction by 60-90%
- Fuel mixes with air before flame zone
- High Temperatures and Pressures
- Too Low Values may lead to inoperability and combustor problems
- Mech. drives need wide operating range
- Effects of Plant Cycling, Transients



RR Siemens

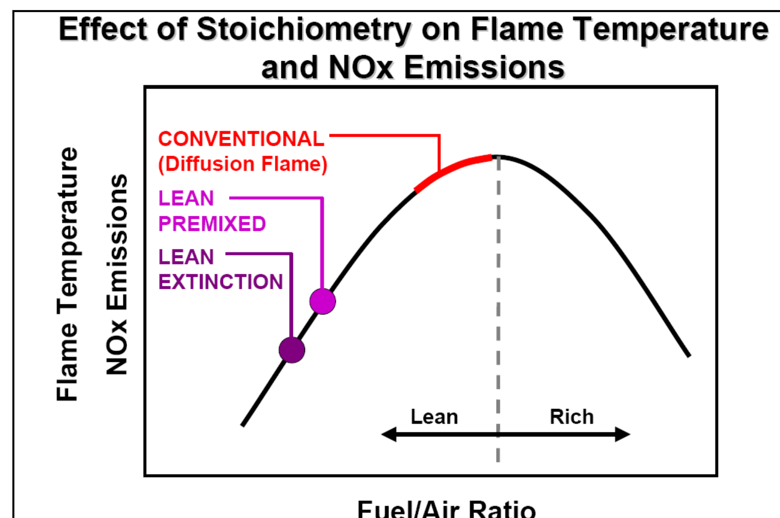




General Electric

H_2 fuel blends have different properties
- need flexibility on NOx emission rules,
- plus care for safety

Volume-based emission criteria ?

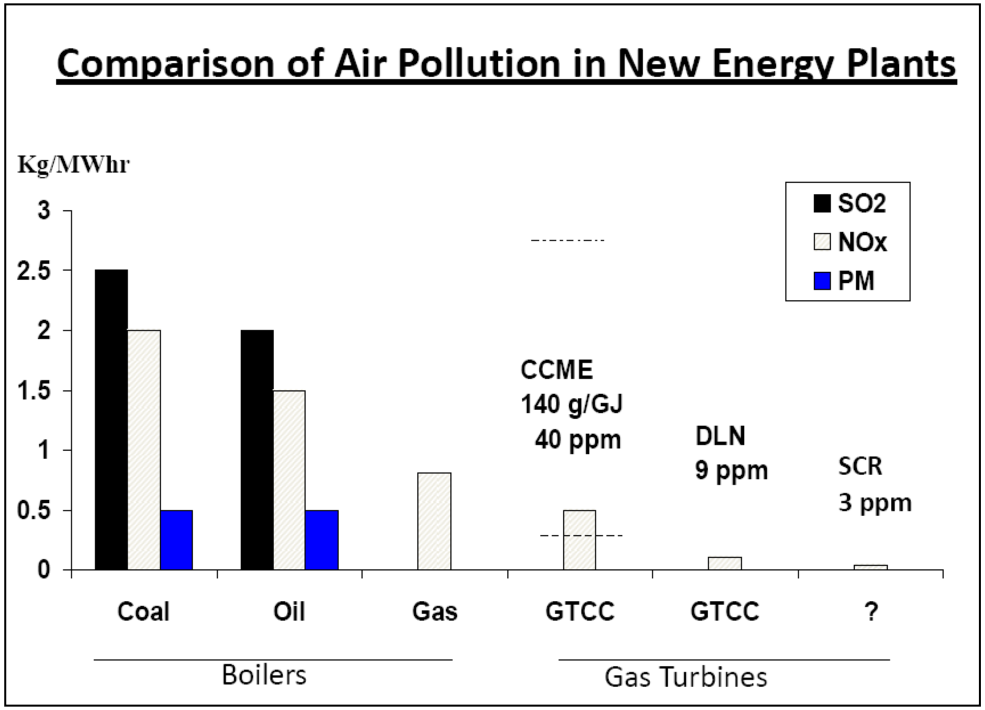


Solar Turbines

EA Assessments of Gas Turbine Plants

(2002 Study, for *TransCanada P/L and Environment Canada)*

- **Companies may be required to install added ammonia-based SCR controls after DLN**
- **Ammonia transportation & handling is a serious local health and safety issue**
- **Given the capital & operating costs and collateral impacts associated with SCR systems, the environmental benefits do not justify the economic expense.**



Marginal, low $/tonne benefit after DLN

(T. McCann, B. Howard, M. Klein, 2003)

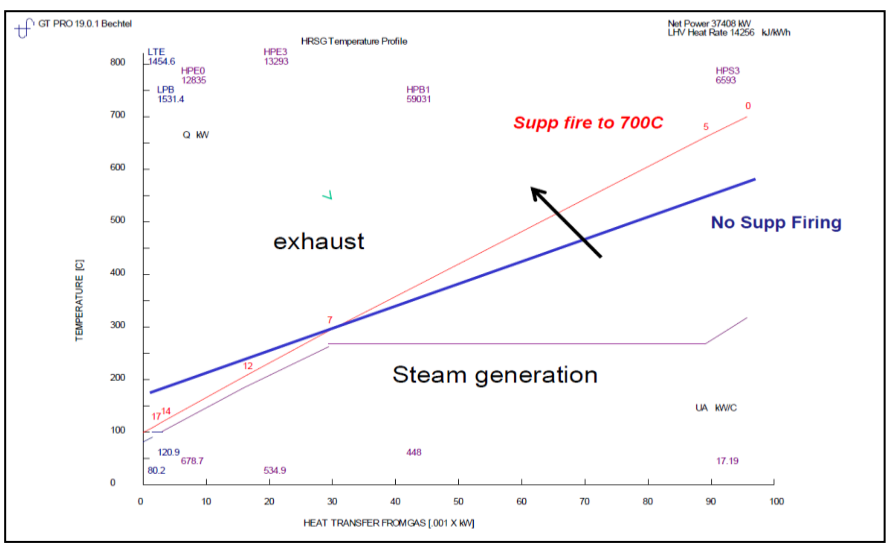
Emissions Valuation; 300 MWe GTCC Plant

2 TWhrs	With SCR System		DLN Without SCR	
	tpy	$000/yr	tpy	$000/yr
NOx	100	200	400	800
Ammonia (5 ppm)	50	250	0	0
PM 2.5	50	250	0	0
N_2O x 310	10 000	200	0	0
CO_2	727000	14540	720000	14400
GHG (from NH_3)	600	12	0	0
		$15450 K		$15200 K

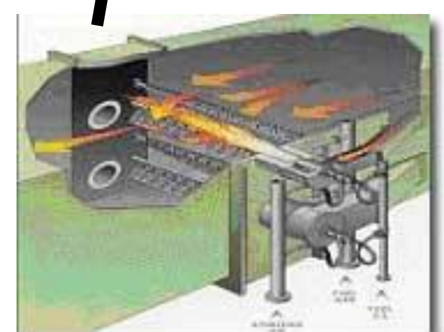
Air Pollution @ $2000 & $5000/tonne **GHGs @ 20/tonne**

Waste Heat and Duct Burners in CHP

- **Duct Burners for auxiliary firing can double/triple steam output from HRSG ~100 % efficiency for heat)**
- **Duct burners can add a bit of combustion NOx, … but they allow a smaller size of GT engine for given heat load (reduces annual fuel & emissions)**
- **Also increases heat transfer, lowers stack temp**
- **Allows for greater fuel flexibility, using waste fuels**



C. Meyer-Homji, Bechtel Corp.

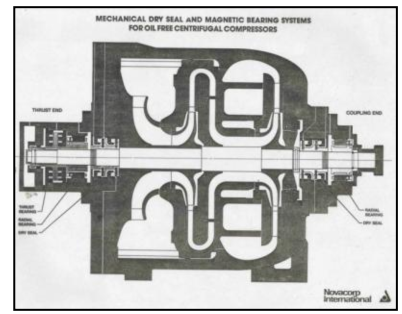


(Coen)

Env'tl Solutions for Gas Pipeline Compression

- High Operating Pressure (low ΔP)
- Efficient and Reliable DLN Gas Turbine
- Minimizing Stops and Starts
- Waste Heat Recovery
- Gas-to-Gas Exchange, Aerial Coolers
- Dry Gas Seals to reduce Methane Venting
- Leak Monitoring, Better Valves & Regulators
- Air or Hydraulic Engine Starters
- Hot-Tapping Procedures, Gas Transfer Units
- System Optimization, Reliability


TCPL/Atlantic, Nipigon, ON



Gas Compressor Dry Gas Seals


Crowsnest ORC


Aerial coolers, Crowsnest BC

Hydrogen - a 'manufactured' form of energy carrier;
@ 0.14 GJ per kg, regardless of source, H_2 is expensive ($ per GJ)

<u>**High Value Energy Applications**</u>

Industrial cogeneration
- Small systems for onsite use,
- or larger systems for power exports

District energy w/ CHP systems
- Hot and cold water piping, LP steam
- electricity for public transit

Utility peak power
- Support power outages
- follow intermittent renewables

High Temperature Furnaces
- Cement, steel & ethylene processes
- process feedstocks

Cogeneration Whitby ON

District Energy, CHP

GT Peaking Meadow L. SK

Cement Kiln Burner

Considerations for Hydrogen-Blend Combustion

H_2-NG blends; an important env'tl topic

Non-linear performance, difficult to generalize on combustion, performance and safe operation

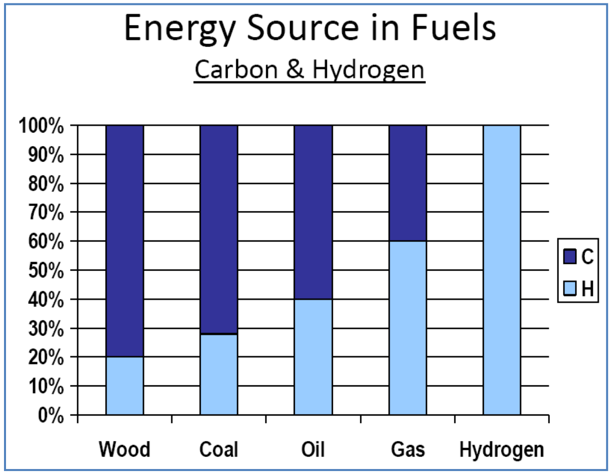
- Higher volume flows, small fuel injection points
- Instabilities, Auto-Ignition, Blow-off, Flashback
- NOx emissions can be a barrier to H_2

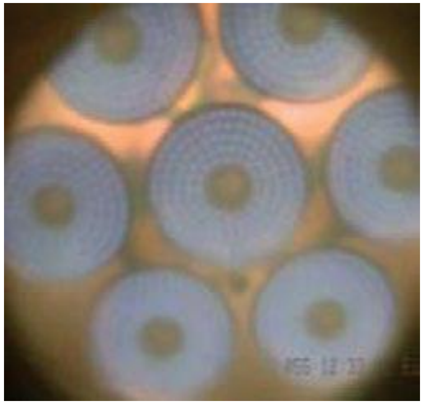
NG fuel for startup, and designs needed for operation on various H_2 blend ranges

Mass & Energy criteria for system efficiency rather than volume and ppmv

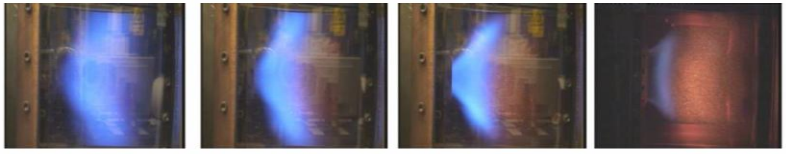
H_2 applications need flexibility on NOx emission rules, plus care for safety

Add a NOx margin for GHG tradeoffs ?





GE DLN 2.6e



Hydrogen Blending (K.Bohan, RR/Siemens)

Recent Study on Pollutant Emissions Reporting (2021)

Comparison of H_2 blends for NOx emissions based on;

- ppmv dry @ 15% O_2, and
- mass per energy & output

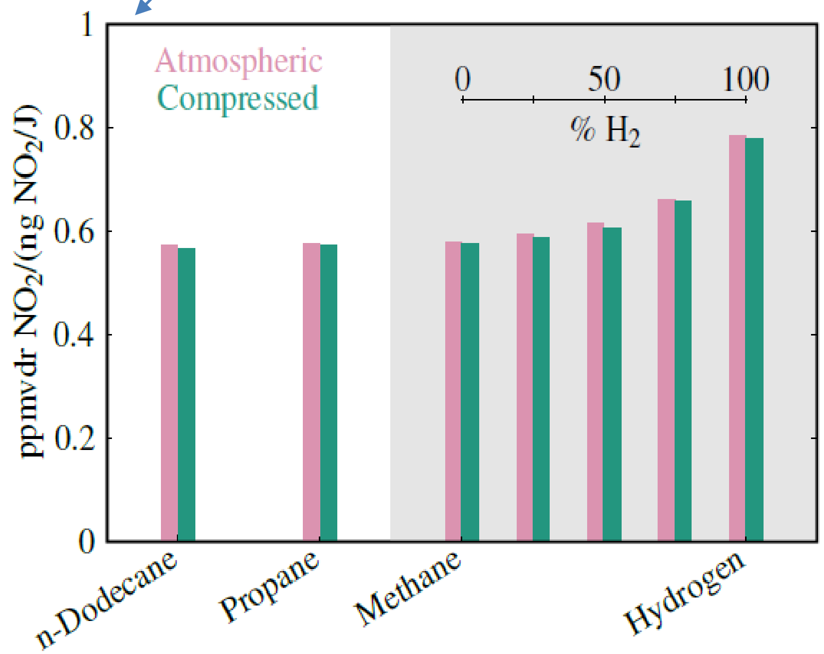
Hydrogen has more exhaust moisture, spec.heat, and different use of oxygen

On a ppmv basis, H_2 emissions of NOx can be 20-40 % higher than on NG

On a gr/GJ or lb/MWhr basis, they may be in the same range as NG DLE

Would mass/output-based emission stds make a difference in developing reliable low GHG combustors for H_2 blends (op range, flex %, transients?

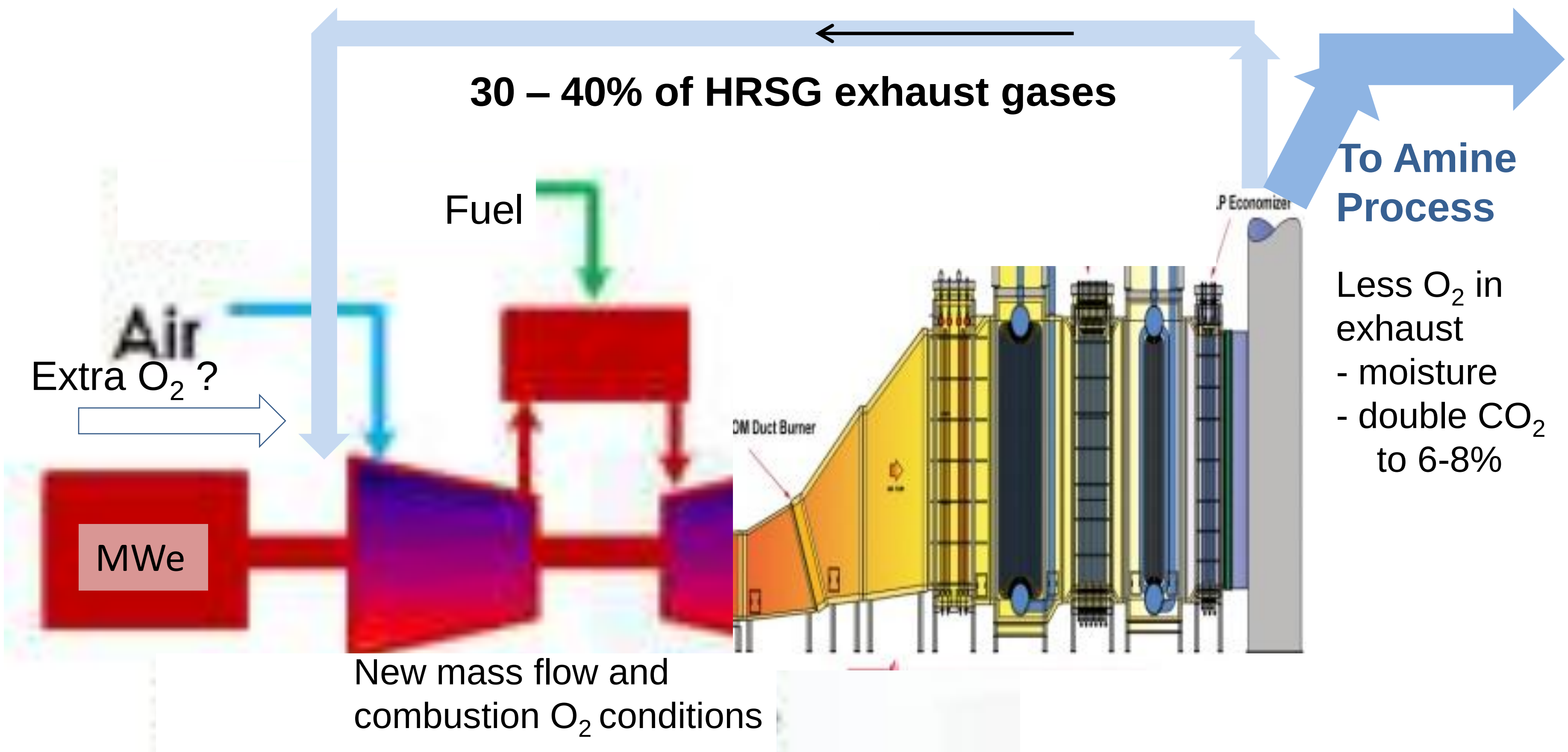
ppmv NOx vs gr/GJ



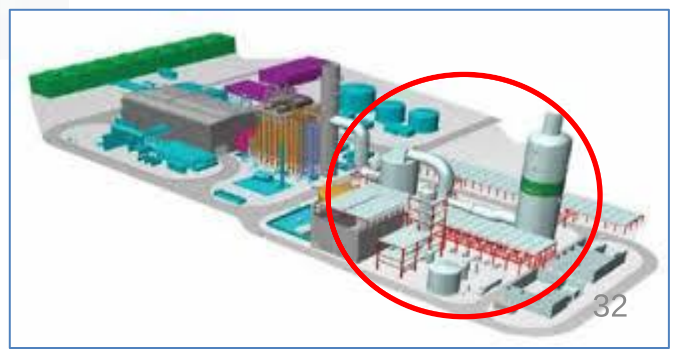
GT2022-80971

Electric Power Research Institute, Georgia Tech. and Ecole Polytechnic

Carbon Capture and Exhaust Gas Recirculation

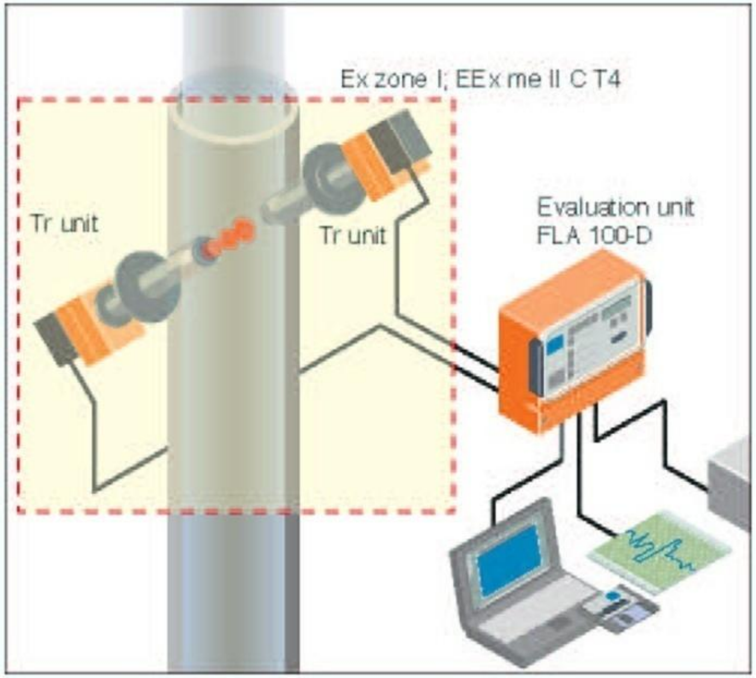


- EGR to reduce the cost of CO_2 capture
- Reduces system efficiency
- Reduced NOx emissions, higher CO
- Duct burning may be difficult
- Practical capture; 90 % ?   or __ kg/MWhr



Emissions Measurement

- Continuous Emissions Measurement
- Process Estimation Methods
- Surrogate & parametric methods
- Predictive Emissions Monitoring



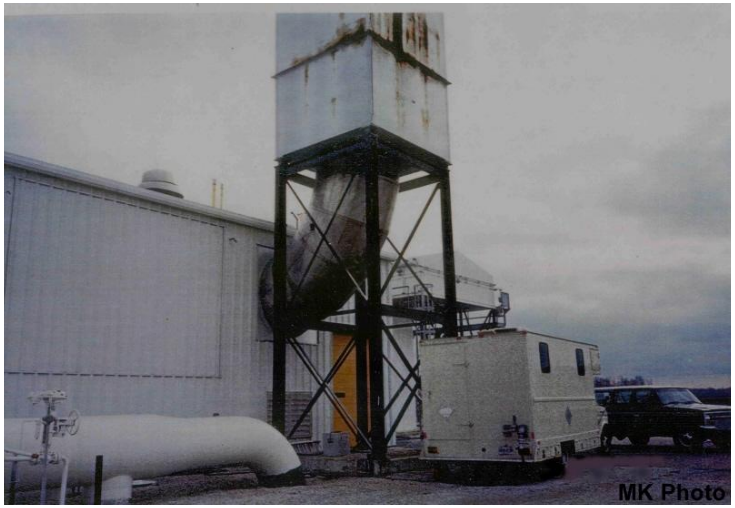
(CEM Specialties)

PEMs;

- *good predictability of GT operation*
- *cost-effective emissions reporting*
- *use of F-factors for mass emissions*
- *process efficiency optimization, GHGs*

Measurement sampling;

- *Consider longer averaging times*



EnvCan CEM van (Ont 1994)

LNG System Environmental Performance

Process and Fuel Efficiency

- Liquefaction design choices
- Feed conditions, Precooling methods
- Compressor drivers,   Aero vs Frame GTs
- WHR and Cogeneration, Low methane loss
- Variable Speed Electric Drives
- TurboExpanders, Absorption Chillers
- Flaring reduction, use BOG fuel

LNG Exports to Asia or Europe

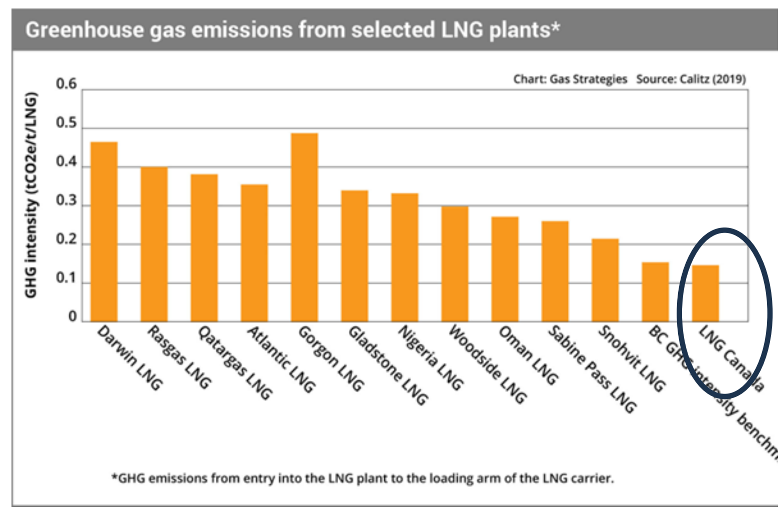
1 bcf/day = 7 mtpa

For mix of GTCHP & GTCC,

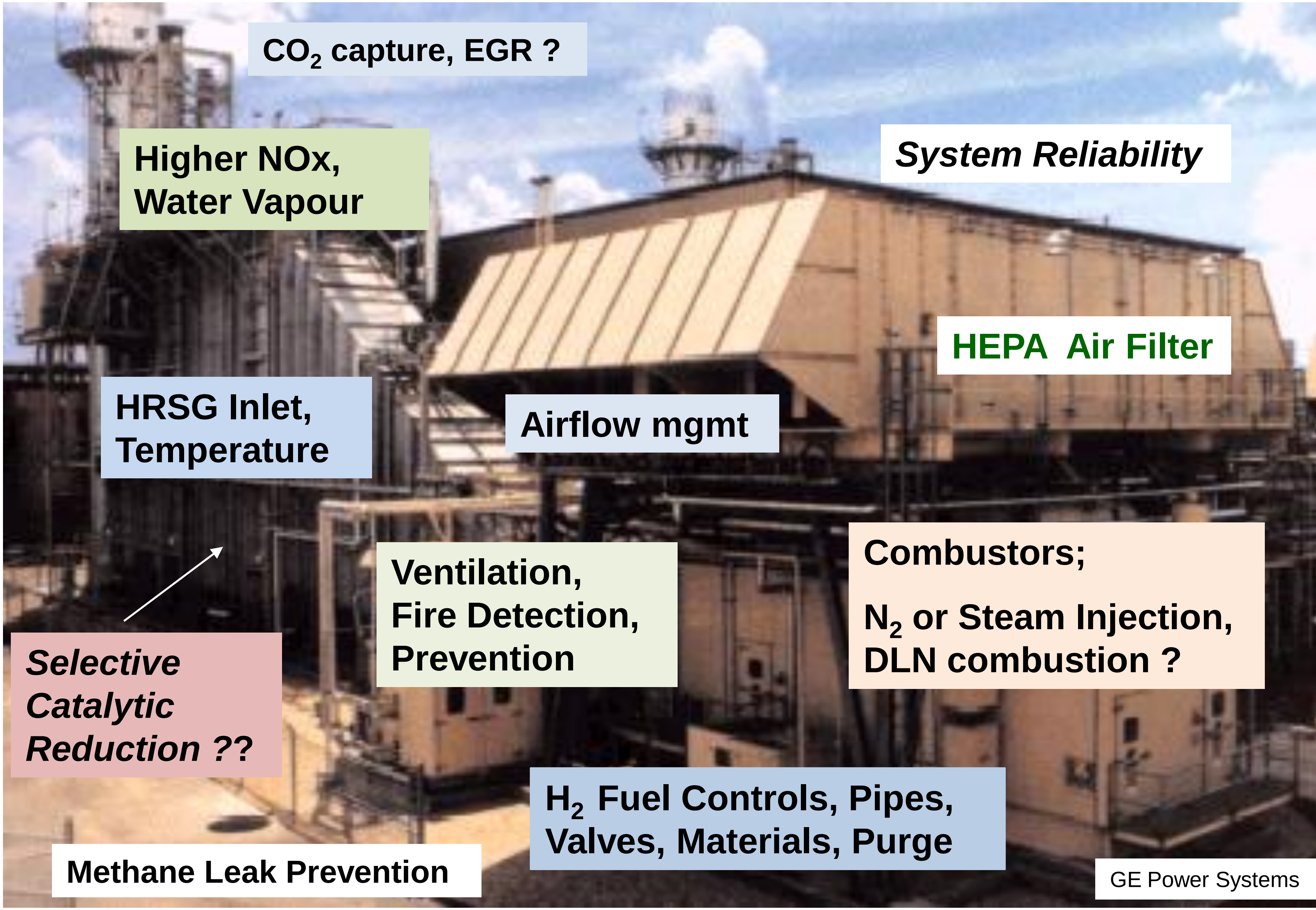
1 bcf/day ➔ 6000 MWe ➔ 40 million MWhr

Lifecycle GHG red'n from coal can be about

0.6 t/MWhr = 24 MT/yr red'n per bcf/d LNG



Hydrogen Fuels in Gas Turbine Systems



Maximizing System Reliability and Safety **(H_2/NG readiness certificates ?)**

Potential for GT Distributed & Integrated Energy Systems

Electrification/Hybridization ***Flexibility & Resilience*** ***Support v-RE***

GTCC, CHP (MWe + MW_{th})

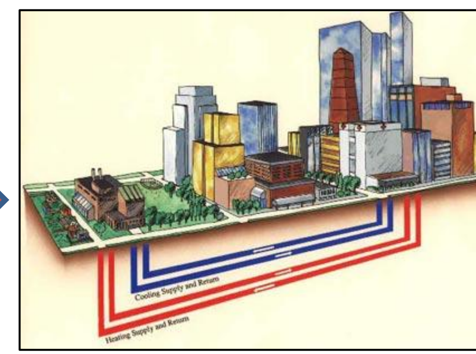
Public Transit

Heating & Cooling Services

Combined Cycle

EV Charging, Hybrid cars

District Energy



plus; Renewable Natural Gas, Off-peak Hydrogen, Synthetic Hydrocarbons

Electricity Storage & Batteries, Thermal Hot/Cold Water Storage

Organizations for Gas Turbine Energy Systems

(Training, Networking, Research, Policy)

Gas Turbines for Energy Network (GTEN)

ASME TurboExpo
Int'l Gas Turbine Institute (IGTI)

European Turbine Network (ETN Global)

Global Power and Propulsion Society (GPPS)

Related Groups

- **National Research Council Canada (NRCC)**
- **Electric Power Research Institute (EPRI)**
- **US DOE Nat'l Energy Technology Lab (NETL)**

Considerations for a Clean Energy Transition

GTEN

Gas turbine systems powered by air mass flow have contributed a lot to clean energy systems in many applications

- **Energy Diversity, Security and Reliability are very important**
- **All potential solutions will be necessary**
- **Expensive H_2-based fuels can contribute in high value applications**
- **Improved standards must be developed to ensure Hydrogen systems are designed for safe and reliable operation**
- **Air emissions reg'ns should use energy output-based rules**
- **Need focused education & training (GTEN committee can help)**