Environmental Issues and Standards for Hydrogen

- **Air Pollution and GHG Emissions**
- **Balancing Emission Prevention & System Efficiency**
- **High Value Energy Applications for Hydrogen**
- **Environmental Issues and Standards for H_2 combustion**

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Typical Industrial Gas Turbine Energy Systems

GTEN

- Simple Cycle, Standby power
- New Gas Combined Cycle
- Combined Cycle Repowering
- Large Industrial Cogen
- Oil Sands Gasification
- Gas Pipeline Compression
- Offshore Platforms
- Small Industrial Cogeneration
- Municipal District Energy

About 1200 units in Canada
(470 plants, ~ 29 000 MW)

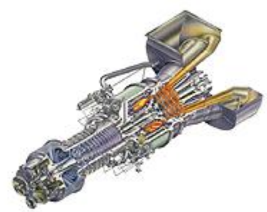
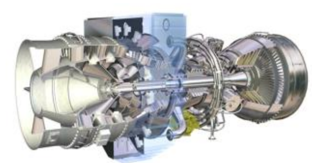
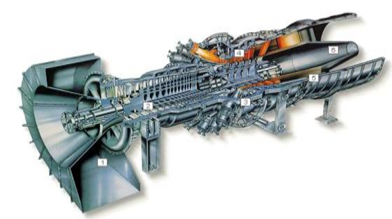
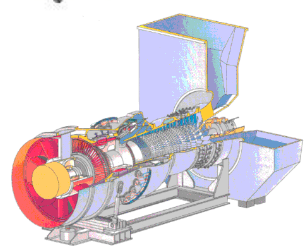
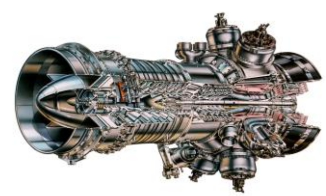
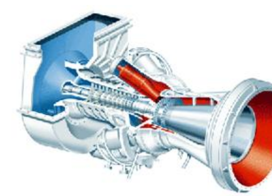
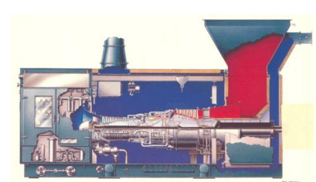
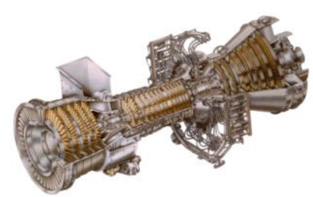
Many different types;

- Aeroderivatives
- Small industrials
- Large Frame Industrials
  + Steam turbines & HRSGs








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

Effects can diminish over time
Involves detailed design

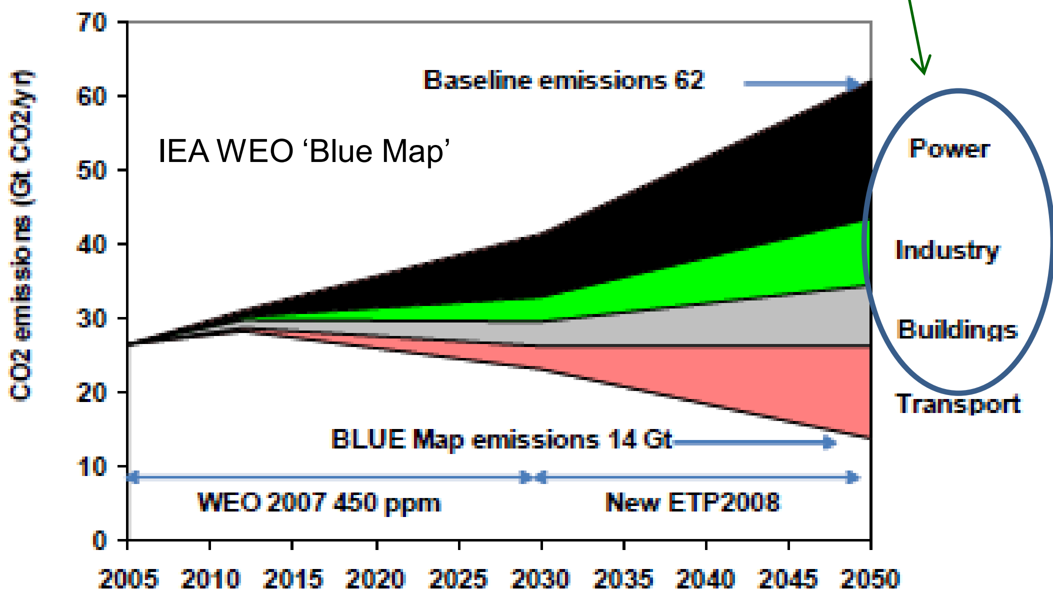
Effects not reversible
Requires a 'big picture' approach

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

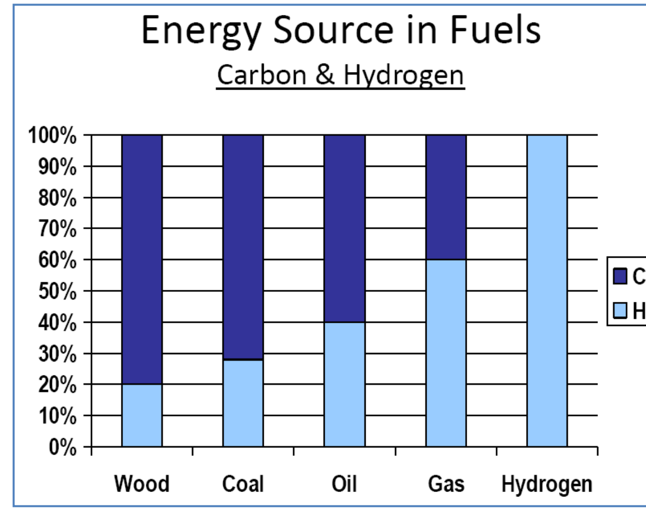
- *Air Pollution*
- *GHG Emissions*
- *Air Toxics*
- *Water Impacts*
- *Energy Security, Diversity*



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

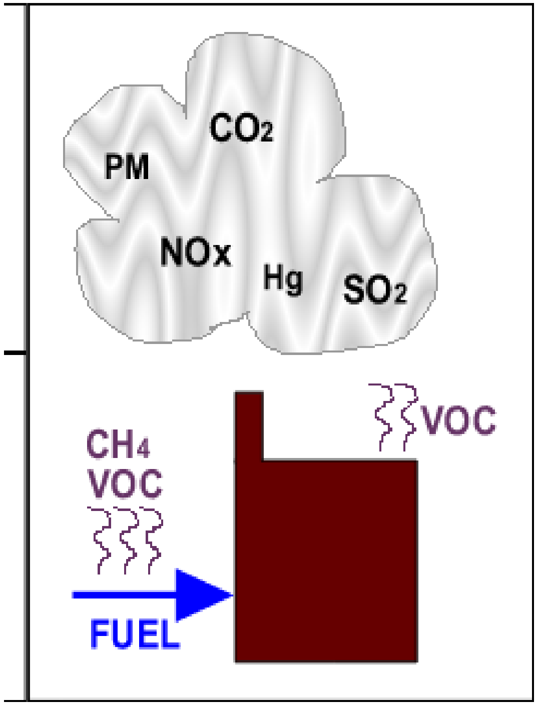
Natural Gas Systems and Renewable Energy

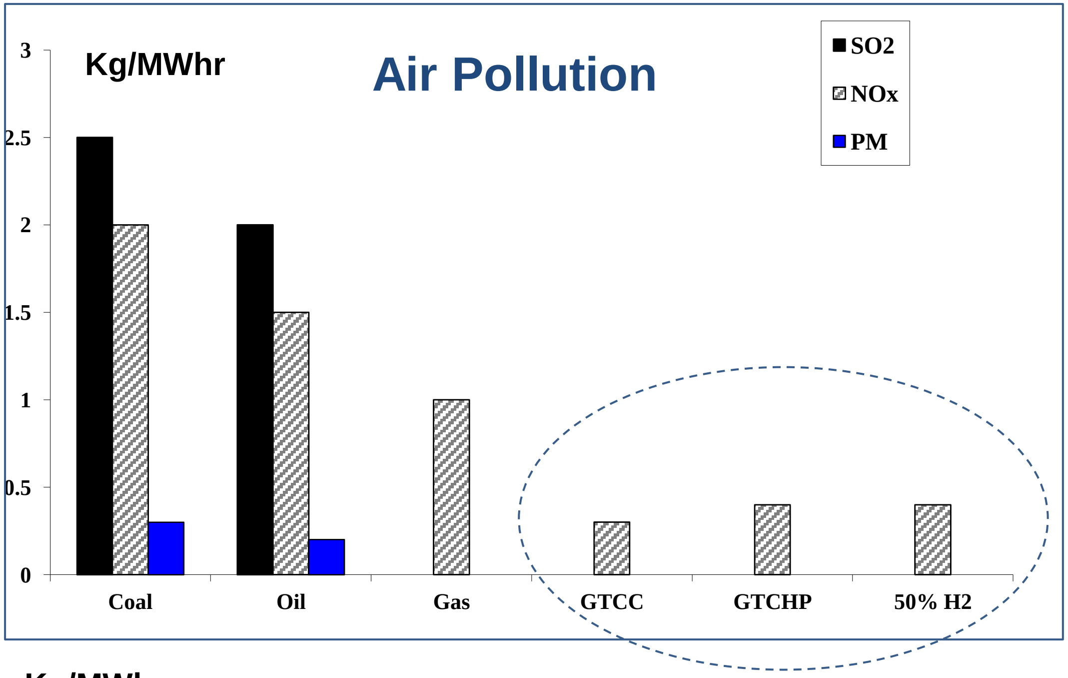
- Distributed Energy Systems
- Diversity in Unit Size, Applications
- Waste Heat Recovery, Efficiency
- Cogen and District Energy
- System Reliability, Islanding
- Fast Starts and Ramp Rates
- Cycle Innovations & Hydrogen

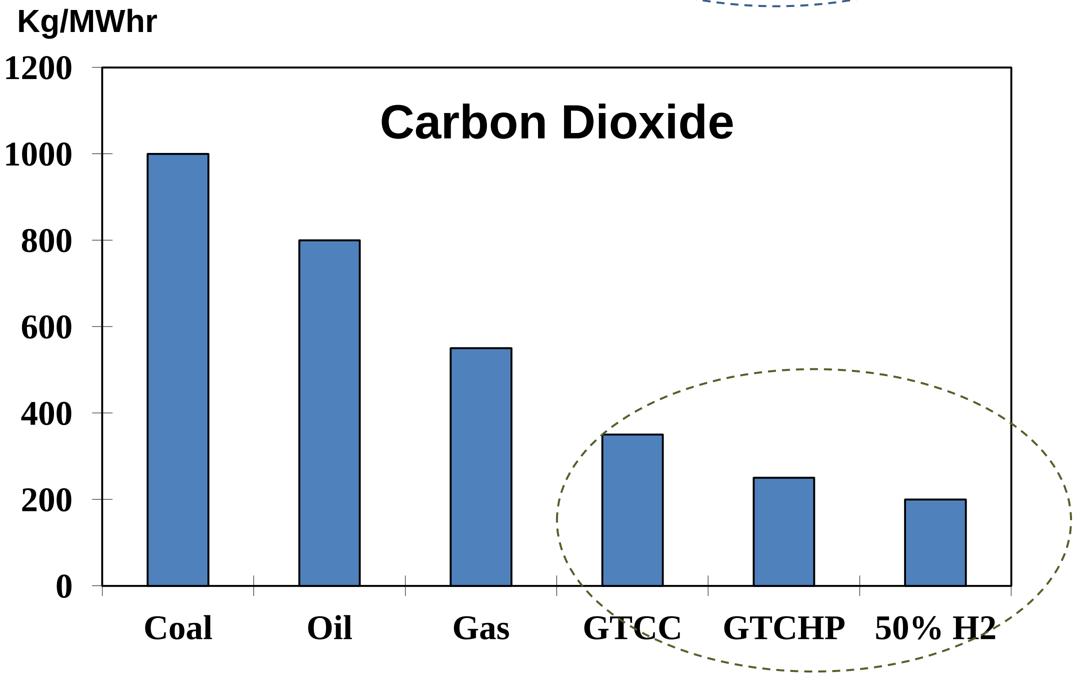


Comparing Emissions;

“Cannot produce Air Pollution without making CO_2”







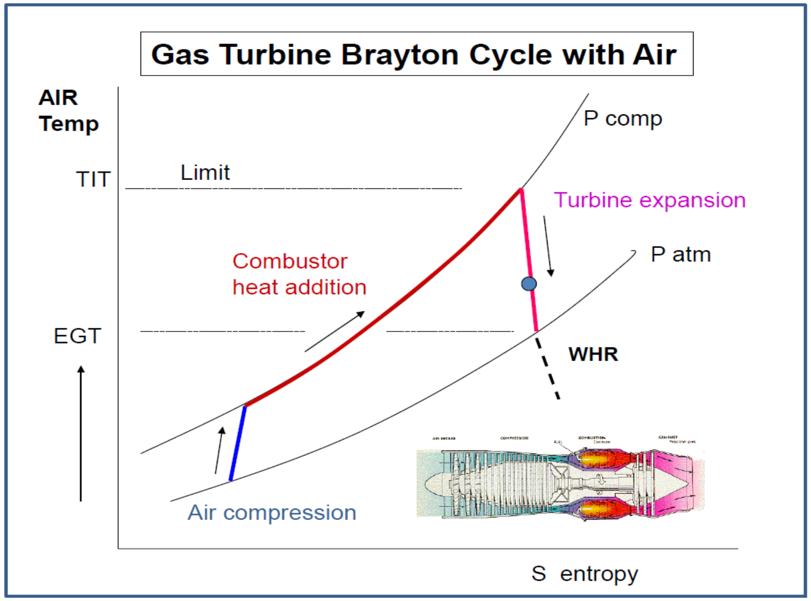
Gas Turbine systems on NG fuel have replaced/avoided many high emission systems, and have supported Renewable Energy

Considerations in Fuel Combustion & Energy Quality

Fuels do not burn;
- **as solid or liquid**
- **to produce electricity**

Fuel always burns as vapour (gas)
- **always produces heat**

Gas turbines are based on air mass flow for power (‘Gas’ = Air)



Electricity and Thermal Heat

MWe are not equal to MWth
PJe is not equal to PJ th

High Value applications ‘produce’ several energy forms at once

Quality of Energy

• Electricity & Shaft Power	High
• Industrial Process Heat	↓
• Cooling	
• High Pressure Steam	
• Hot Water	
• Space Heating	Low

70% CHP eff’y >> than 90% for heat

High Value Energy Applications; Combined Heat & Power

All types of H_2-based fuels will be needed

For high fuel costs, CHP & DES systems can provide multiple benefits

Natural Gas is mostly Hydrogen Energy

- very clean; CHP used close to demand

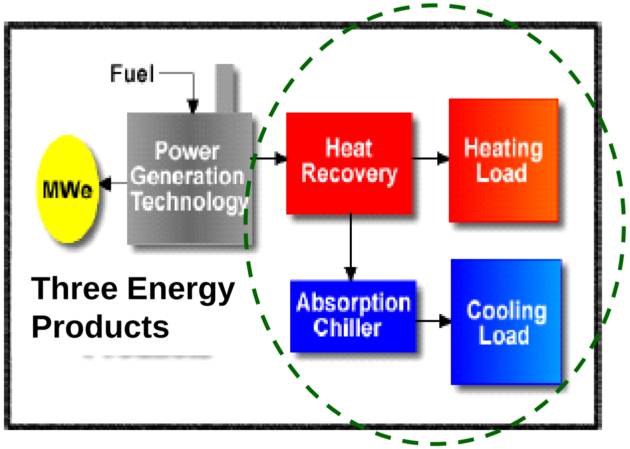
200-250 kg_{CO2}/MWhr   0.5 kg_{NOx}/MWhr

Waste Heat use is 'Zero emission' energy, similar to Renewable energy

Power Disruptions are Important;

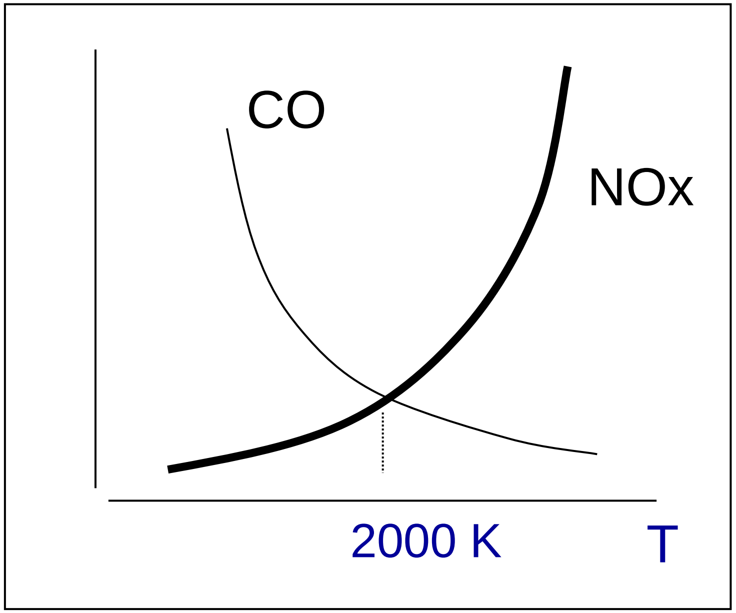
- Onsite CHP can function through outages

Can use all exhaust heat from small GT units



Onsite CHP: Adaptation

Air Pollution - *NOx Emissions*



$$O + N_2 \longrightarrow NO + N$$
$$N + O_2 \longrightarrow NO + O$$

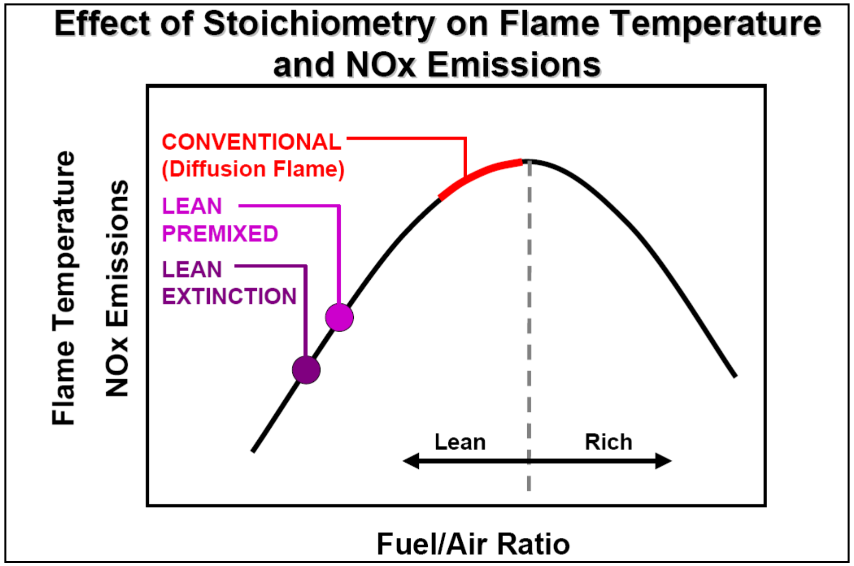
3 Compounds of Concern:

NO, NO_2 smog , ***N_2O*** ghg

Thermal NOx:
High Temperature Combustion

Fuel NOx:
From N_2 Content of Oil, Coal

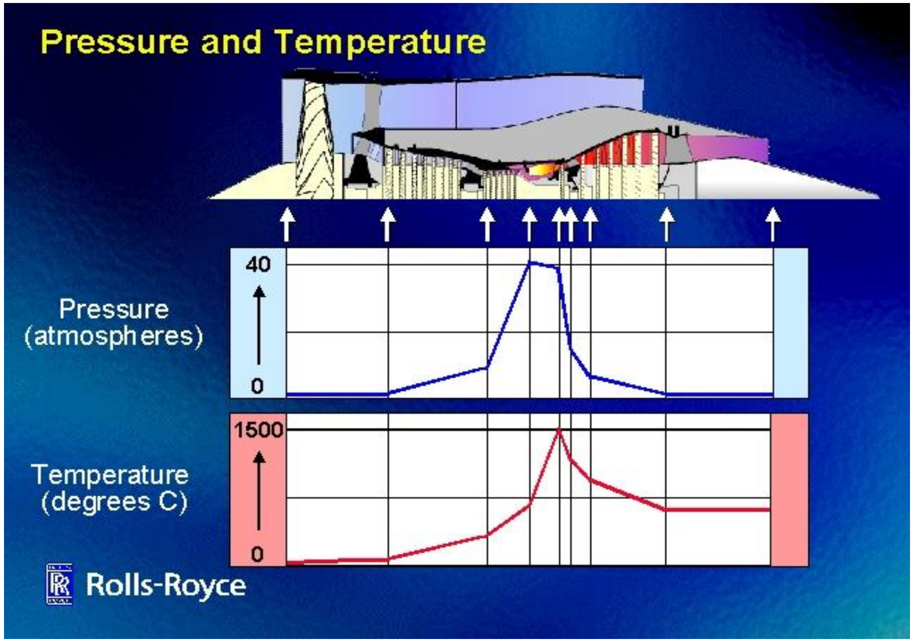
- ***Nitrous Oxide is N_2O, a GHG***

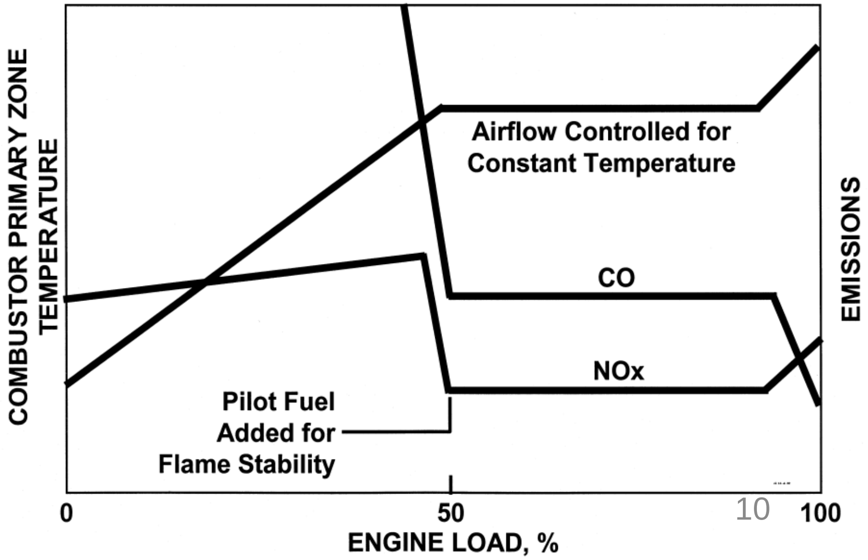


(Solar Turbines)

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)**
- **Dry Low NOx combustor**
- **Part load, Operating Range, starts**
- **Cold and hot weather, humidity**
- **Type of air compressor (spools)**
- **N_1/N_2, Output Speeds**
- **Specific Power (kW per lb/sec air)**
- **Waste heat recovery**
- **NOx Concentration vs Mass Flow**
- **Tradeoffs w/ other emission types**





Importance of Environmental Units

A.

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

- **kg per GJ fuel Input**

B.

- **mass per time (t/yr)**
- **kg per MWe output**
- **kg per MWth**

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

- ppmv and kg/MWhr are linked by 'F-factor' (fuel ratio of exh. gas to GJ)

- CO_2 emissions at 35 000 ppmv ?

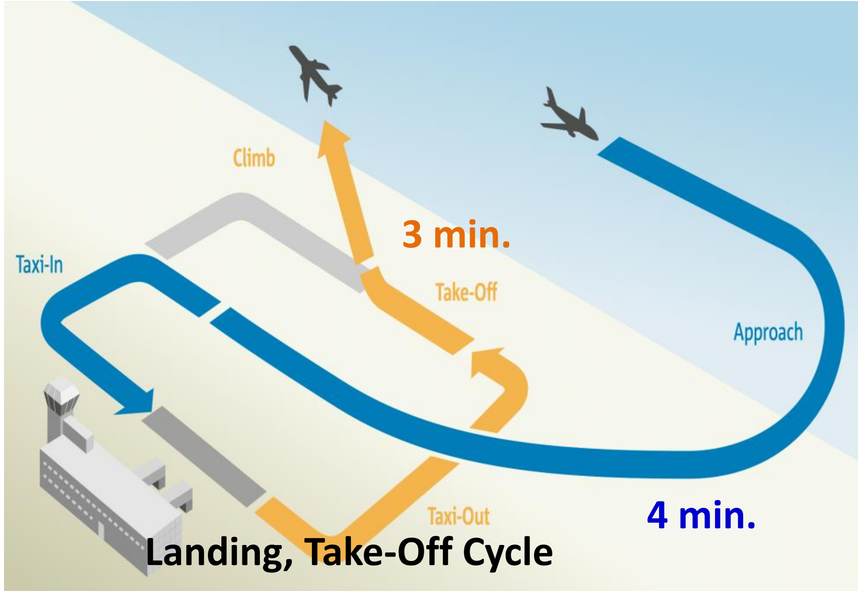
- mass/energy criteria inherently include system efficiency

Emissions Criteria

Traditional concentration (ppm, mg/m^3) 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**

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



ICAO - *aircraft (kg$_{NOx}$/thrust)*

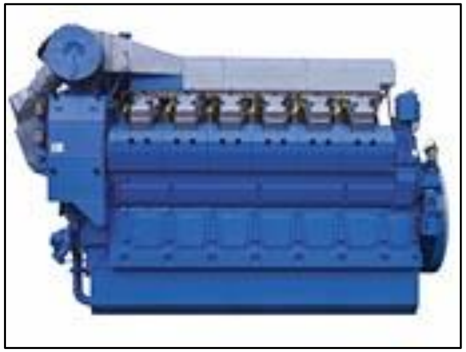
Output-based Rules;

Mass per Product Output; *kg/tonne, kg/MWhr, g/GJ$_{out}$*

tonnes/year

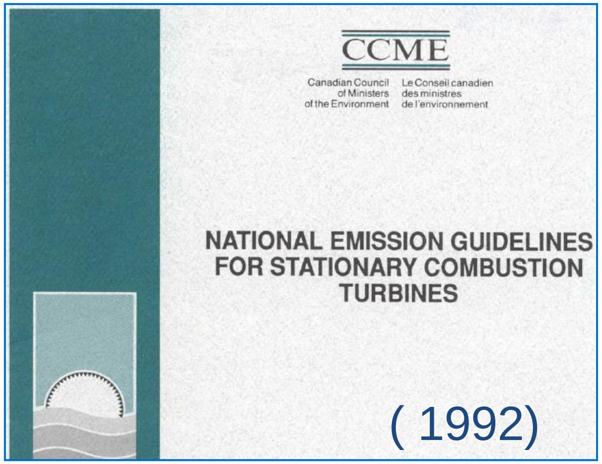
$/tonne

$/MWhr



Lbs/HpHr

Canadian Gas Turbine Emission Guidelines   (1992)

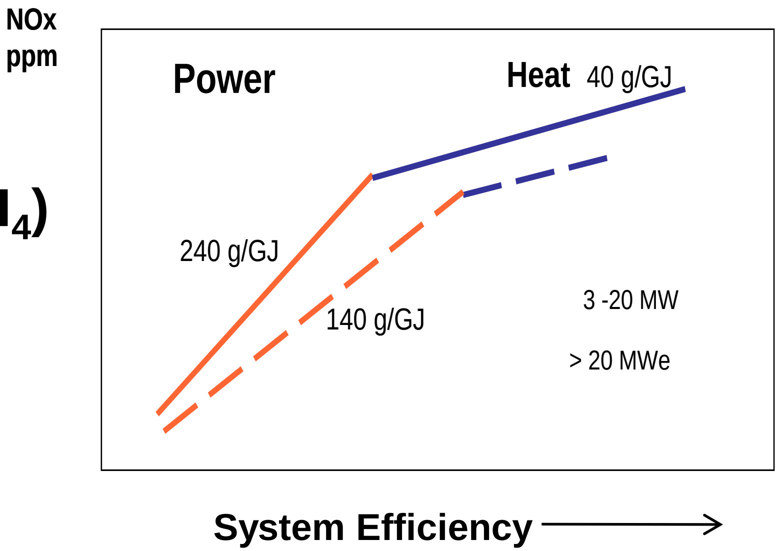

CCME
Canadian Council of Ministers of the Environment
Le Conseil canadien des ministres de l'environnement
NATIONAL EMISSION GUIDELINES FOR STATIONARY COMBUSTION TURBINES
(1992)

- NOx Prevention & Clean Energy Objectives
- Output-Based Standard for Efficiency

  (140 g/GJ_{out} Power + 40 g/GJ Heat)

  0.5 kg/MWhr 1 lb/MWhr

- Promotes Cogeneration and low CO_2
- Higher NOx for smaller units, which have higher system CHP efficiency
- Syngas & Reliability considerations (ie CH_4)
- Added NOx margin for GHG tradeoffs
- Mass & Energy criteria for system efficiency, rather than volume & ppmv

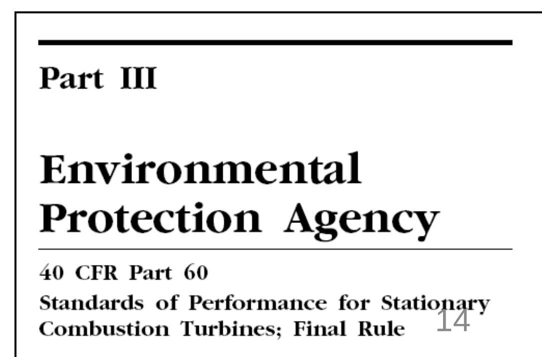


New US EPA Rules for Gas Turbines (2006)

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

- **original 2005 draft used only lb/MWhr**
- **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

Draft 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	$\geq$ 1 and < 4	500	75
Non-peaking combustion turbines - Electricity Generation	$\geq$ 1 and < 4	290	42
Peaking combustion turbines – all	$\geq$ 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 CEPA, Nov 2017

Gas Turbines - *NOx Emissions* (ppmv at 15% O_2)

Uncontrolled; 200-300 ppmv Dry Low Emissions; 15-25 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

$$\frac{\text{ppmv} \times \text{Mass Flow (kg/hr)} \times \text{m.wt.}}{\text{Power (MW)}} = \_\_ \ \text{Kg}_{NOx} / \text{MWhr}$$

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

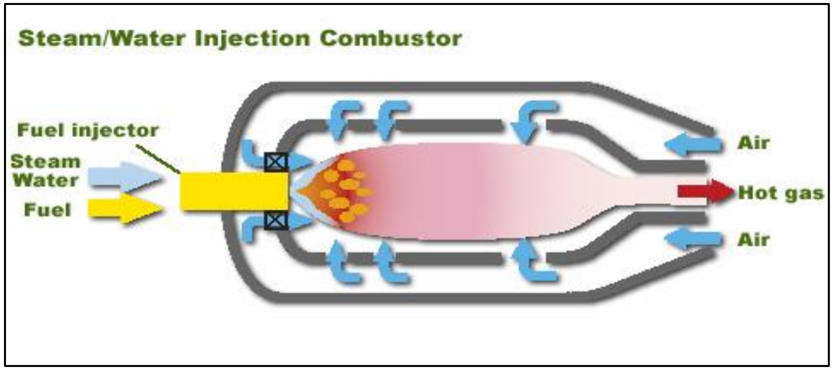
$$\frac{25 \text{ ppm}}{10^6} \times \frac{360\,000 \text{ kg}}{30 \text{ MW hr}} \times \frac{46}{29} = \mathbf{0.48 \ kg/MWhr}$$

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

NOx Reduction Methods

Steam/Water Injection

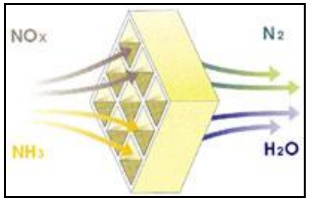
- Prevention, 2/3 red'n to 1 kg/MWhr
- Some Combustion Component Wear
- Plant Efficiency Penalty
- Depends upon value of plant steam



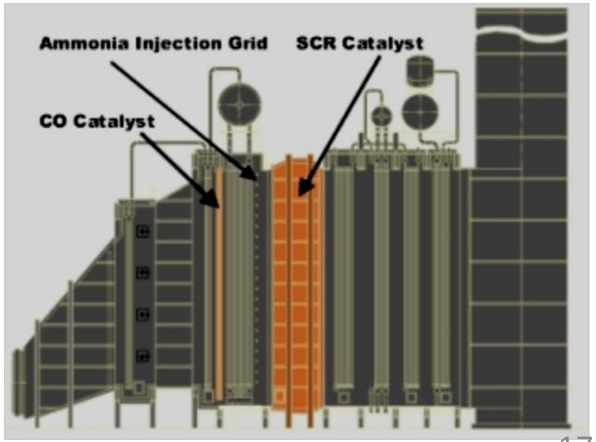
(Kawasaki)

Selective Catalytic Reduction (SCR)

- NH_3 injection into catalyst in HRSG
- ~ 80% NOx volume reduction



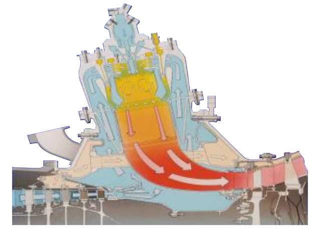
- **Backend Control**
  - Ammonia emissions & handling (toxic)
  - fine PM emissions, N_2O ?
  - Cycling duty for V-RE - ammonia slip
  - Efficiency loss in HRSG
- **Marginal, low $/tonne benefit after DLN**



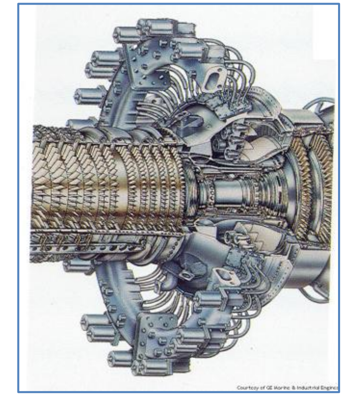
IST Aecon

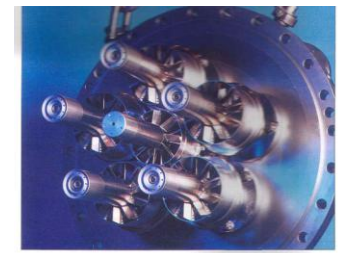
Gas Turbine Dry Low Emissions (DLE) Combustion

- **Preventative 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**
  - (emissions of formaldehyde ?)
- **Mech. drives need wide operating range**
- **Effects of Plant Cycling, Transients**



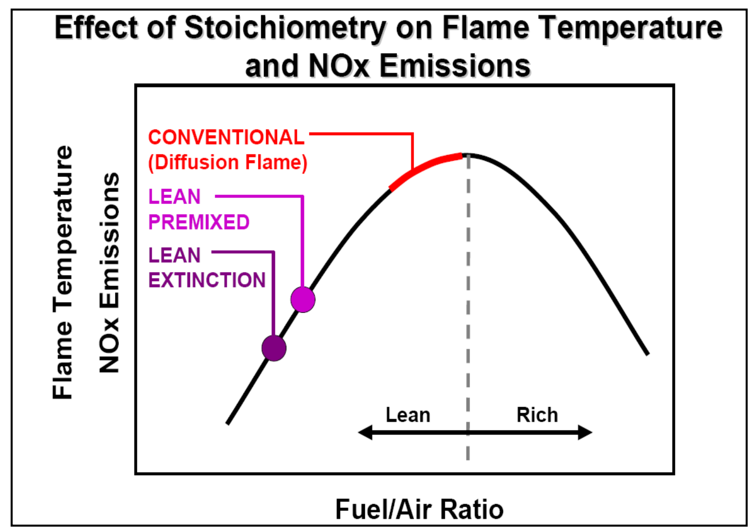
RR Siemens





General Electric

H_2 'fuel' blends have different properties
- need flexibility on NOx emission rules
- very lean combustion
- plus care for safety



Solar Turbines

Hydrogen Production Spectrum sourced from;

Renewable Energy
- and sub-surface conversion

NG Reforming w/ CO_2 Capture

Methane Pyrolysis

Nuclear Energy

NG Reforming (SMR)

Coal-MSW Gasification w/CCS

Hydrogen is a 'manufactured' form of energy; At 0.14 GJ per kg, and regardless of source, H_2 will be expensive as '$ per GJ' of energy

High Value Energy Applications for Hydrogen

… with Reliability, Diversity & Resilience

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

Cogeneration
Whitby ON

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

District
Energy, CHP

Utility peak power
- Support power outages
- Energy storage
- follow intermittent renewables

GT Peaking
Meadow L. SK

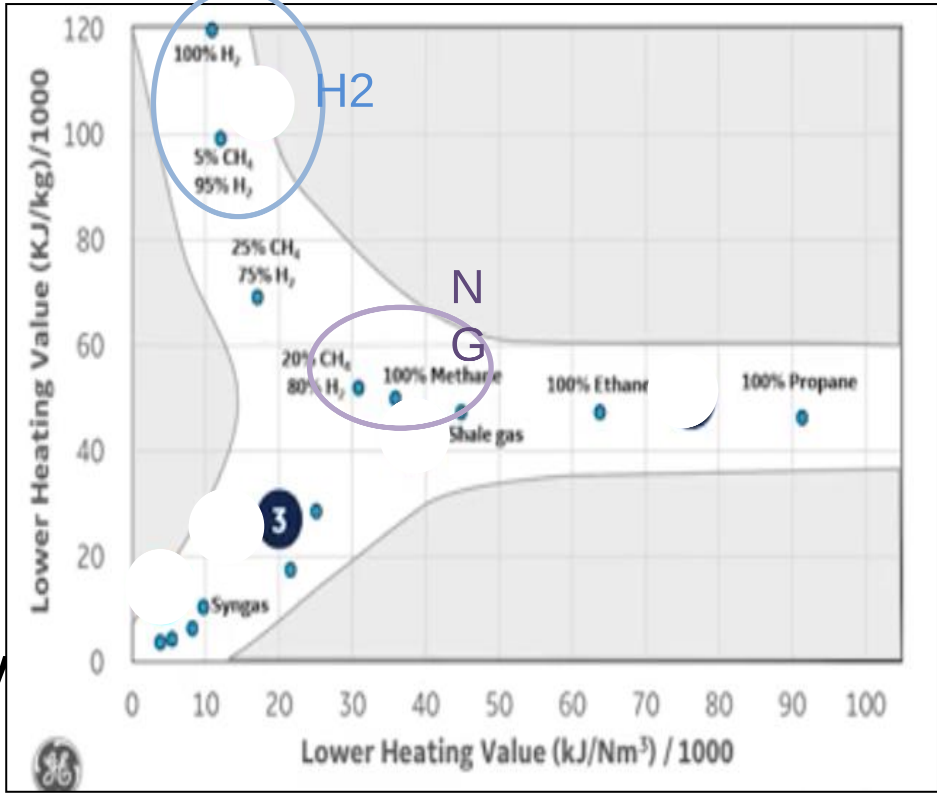
High Temperature Furnaces
- Cement, steel & ethylene processes
- process feedstocks

Cement Kiln
Burner

Hydrogen 'Fuel' Combustion

- Non-linear Volume & Heat Values
- High Flame Temp, Flame speed
- Flashback, auto-ignition, safety
- unstable flame when cycling ?
- more NOx ppmv *(not in kg/MWh ?)*
- need range-ability for NG blends
- often need NG to start & stop
- more moisture in exhaust

LHV by mass



LHV by volume (J.Goldmeer, GE)

- Balancing NOx vs GHG emissions ?

LHV and 'ppmv' emissions criteria for NOx are not compatible with GHG policy

(use HHV and kg/MWhr)

30% vol H_2 60% vol H_2 100% vol H_2

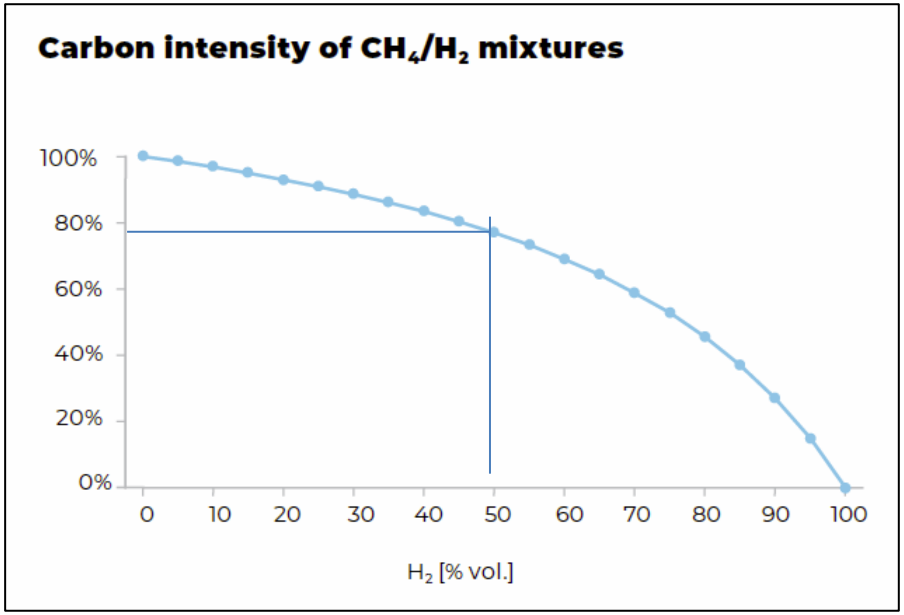
H_2 blended flames (K.Bohan, Siemens)

Properties of Blended Hydrogen / Methane Gases

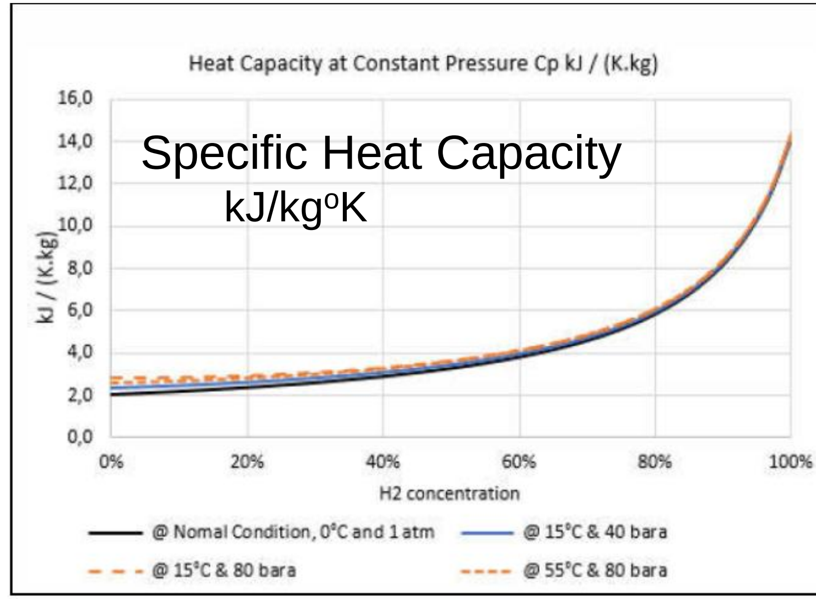
$H_2 : CH_4$ (vol. %)		0 : 100 (methane)	20 : 80	50 : 50	80 : 20	100 : 0 (hydrogen)	
Mole Weight		16	13	9	5	2	
Lower Heating Value (LHV)	kBTU/lb	21.5	22.4	24.9	31.6	51.6	Mass
	GJ/tonne	50	52	57.8	73.3	120	
	BTU/ft³	909	782	592	400	274	Volume
Fuel Flow Mass Ratio	$\frac{LHV_{CH4}}{LHV}$	1.0	0.96	0.86	0.68	0.42	
Stoich. Ratio Air/Fuel mass	Kg/kg	17	18	19	23	34	
Wobbe Index LHV/SG$^{.5}$	BTU/ft³	1220	1157	1060	983	1040	
Flammability % Range	Lower / Higher	5 / 15	4.8 / 18	4.4 / 25	4.2 / 42	4 / 75	

Adapted from Solar Turbines Technology Seminar, 1984

Combustion Characteristics



50/50 blend reduces CO_2 by ~ 20% (ETN)



Specific Heat capacity of blended gases at various conditions (T & P)

Solar Turbines

Non-linear performance, difficult to generalize on combustion and GHG impacts;

- **Specific Gravity, Wobbe index, Heating Values (HHV vs LHV) Air/fuel ratios;**

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_20$$

$$H_2 + 1/2O_2 \rightarrow H_20$$

less air required
more exhaust moisture
more specific heat

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

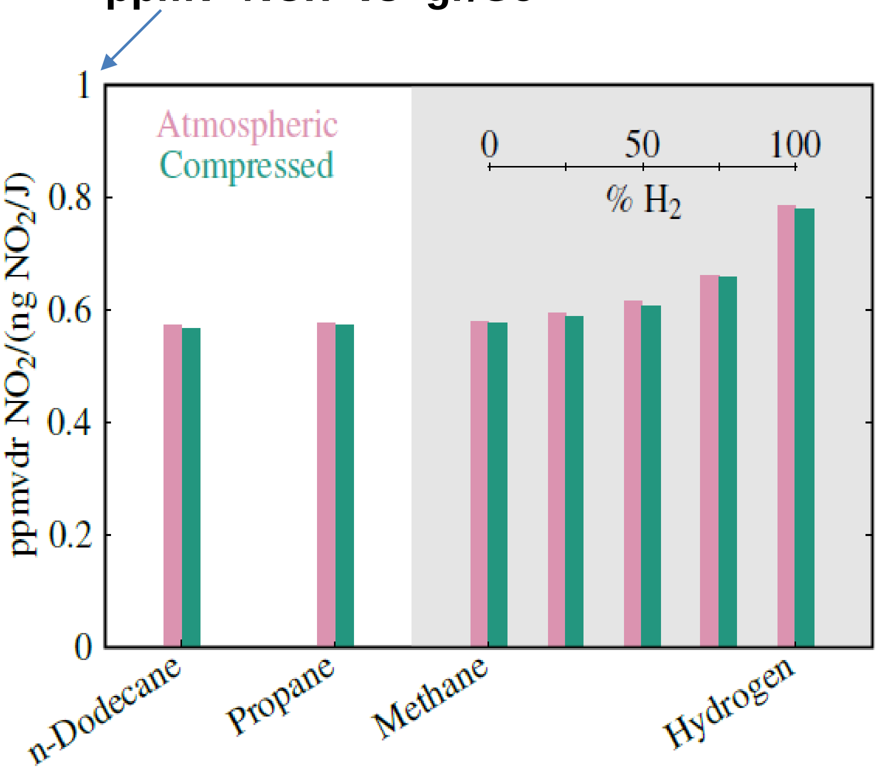
Hydrogen has more exhaust moisture, spec.heat, and different use of oxygen

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?

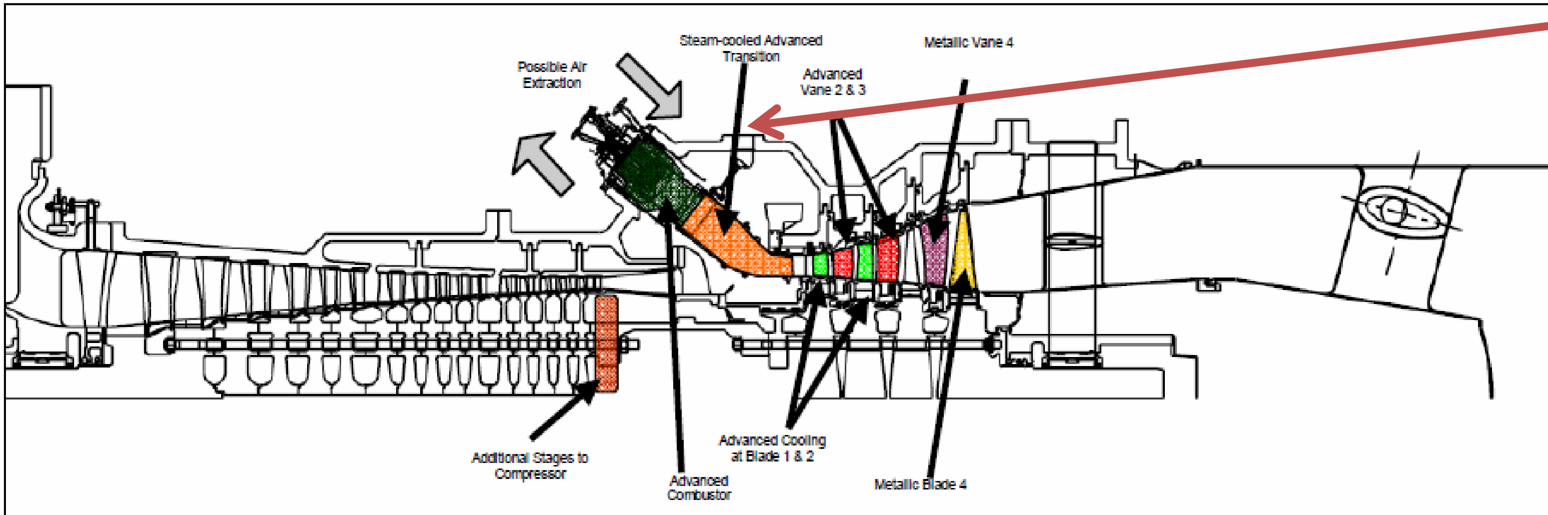
ppmv NOx vs gr/GJ



GT2022-80971

Electric Power Research Institute, Georgia Tech. and Ecole Polytechnic

Special Considerations for Hydrogen-Blend Combustion



. Identification of Technology Needs for the Advanced Hydrogen Gas Turbine

(US NETL, Siemens)

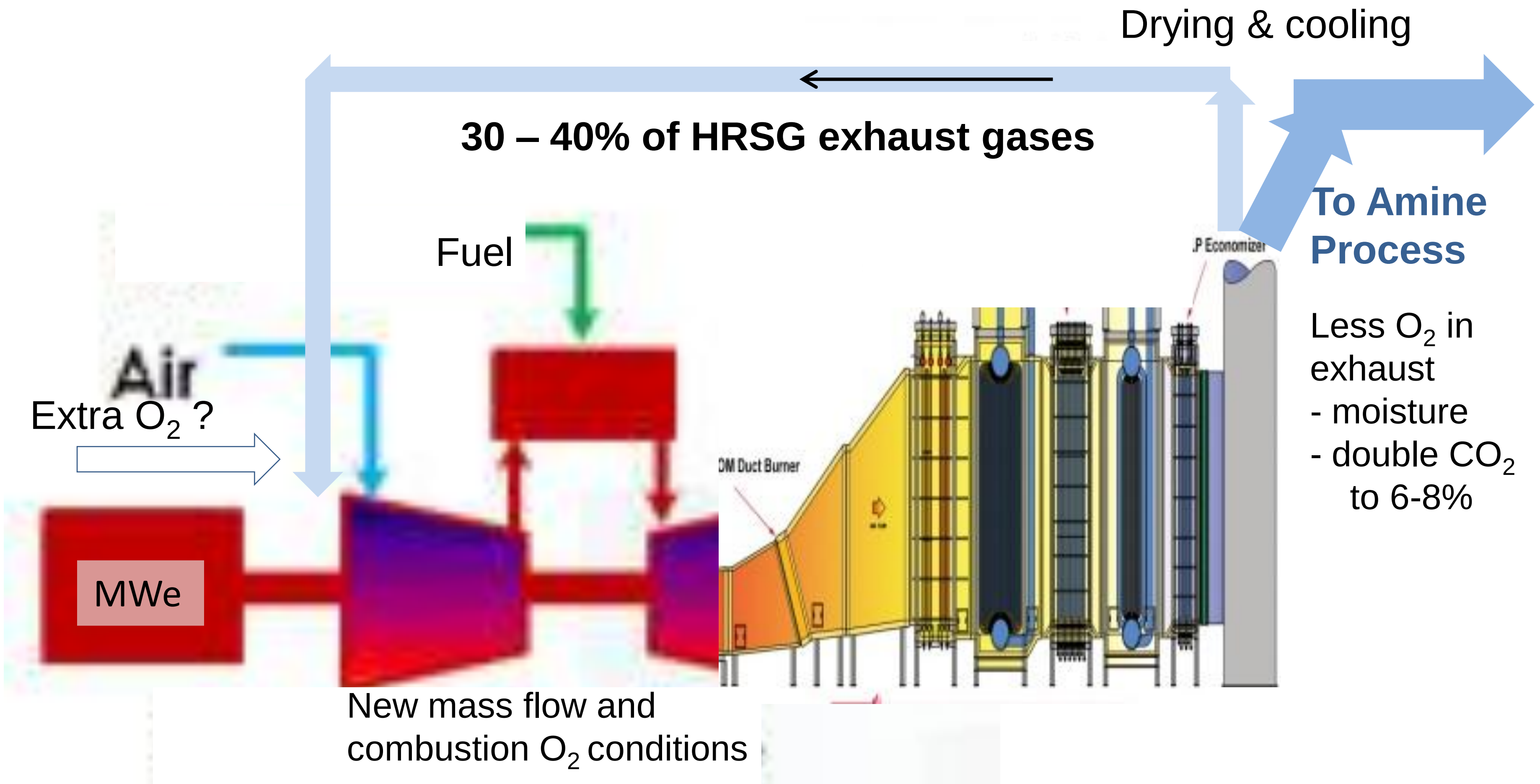
- **Varying H_2 Blends (20-60%) depending on GT unit, Airflow management**
- **Fuel/Air Dilution, Flame sensors, Dynamic Instabilities, Auto-Ignition**
- **Part-Load Operation, Safety and Ventilation**

<u>Research and Development;</u>

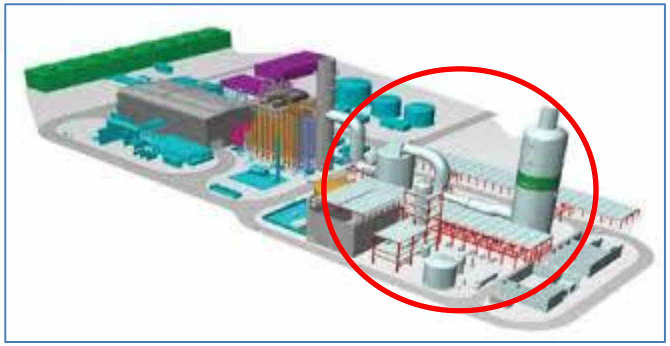
US DOE Nat'l Energy Tech. Lab (NETL) **Electric Power Research Inst. (EPRI)**

National Research Council Canada **European Turbine Network (ETN)**

Carbon Capture and Exhaust Gas Recirculation



- EGR to reduce the cost of CO_2 capture
- Reduces system efficiency
- Reduced NOx emissions, higher CO
- H2–NG fuel blends ?
- Duct burning will be difficult

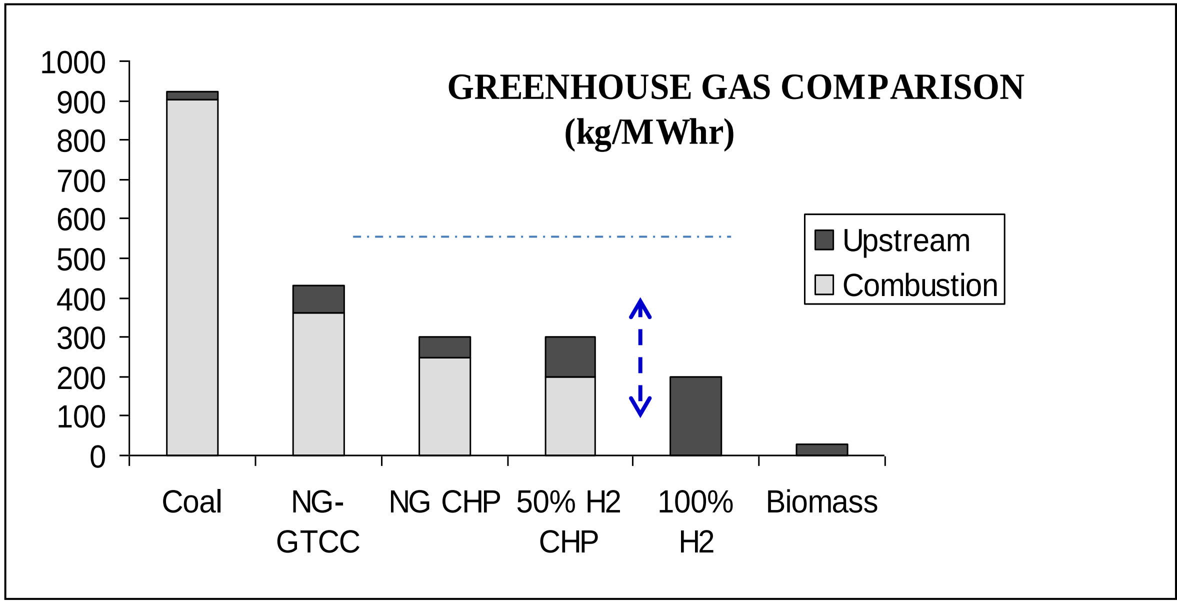


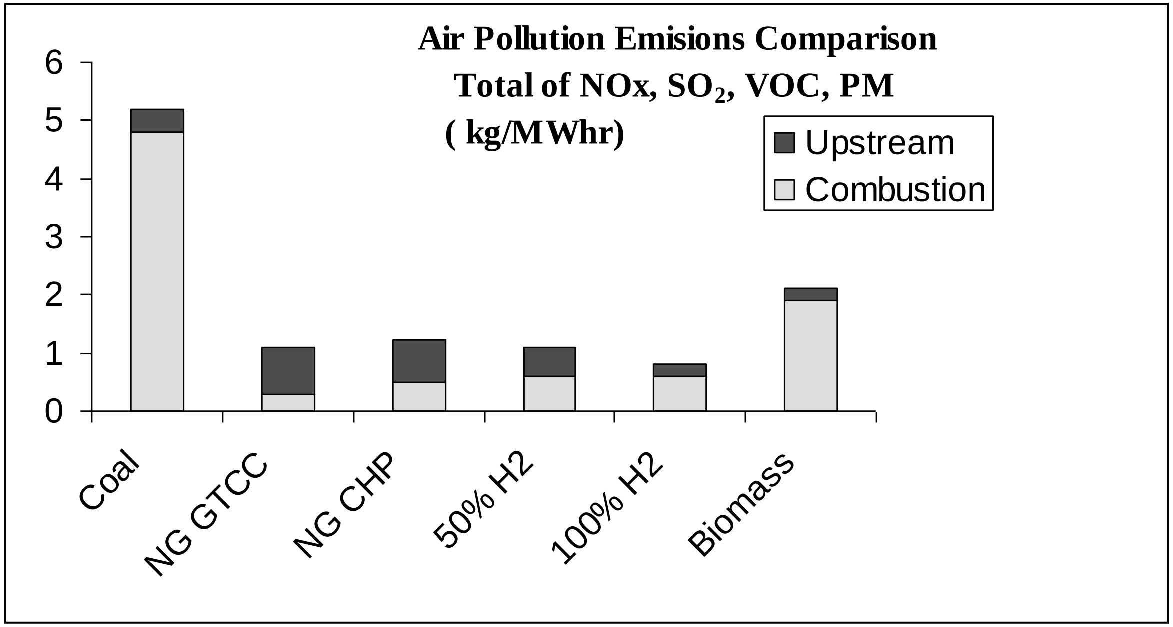
An Example of Full Fuel Cycle Emissions

Cogen/CHP and District energy have lower GHG impacts with increasing system efficiency

H_2 blend impacts are very dependent on type of source (SMR, or zero C)

+ assumptions on CCS and methane





NOx; with increasing H_2;
- **volume ppmv may rise**

- **kg_{NOx}/MWhr may fall, or be equal (?) in DLE combustion**

Hydrogen Operational Impacts

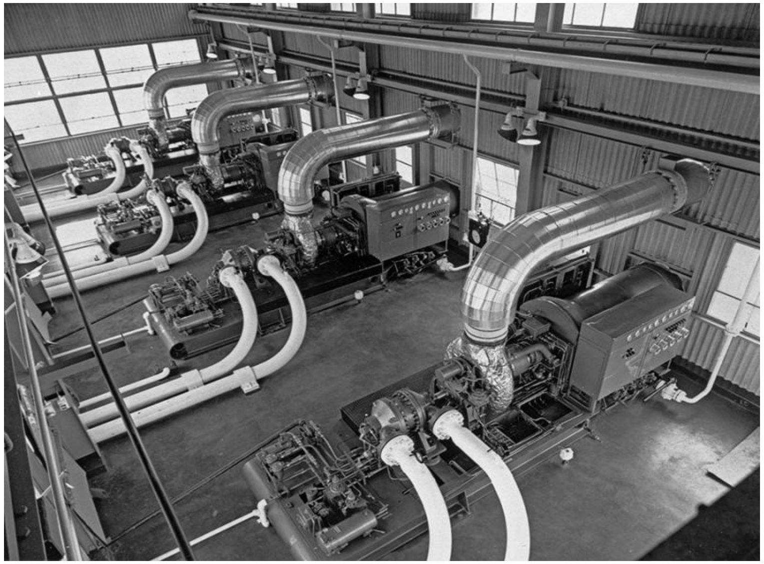
Gas Turbine Package System

- Existing Upgrades, or New Units
- Operating range, stop/starts
- Pressures and Temperatures
- GT Safety, ISO 21789
- % blend ranges, rates of change
- Electrical system protection

Compressor Building

- Possible Leak locations, HAZOP
- Welded vs Bolted flanges
- Unit Purge and Bldg Ventilation
- Leak & Flame Detection   (not IR)
- Training,   Supply chain, Parts

Hydrogen testing, Siemens SGT 800 turbine



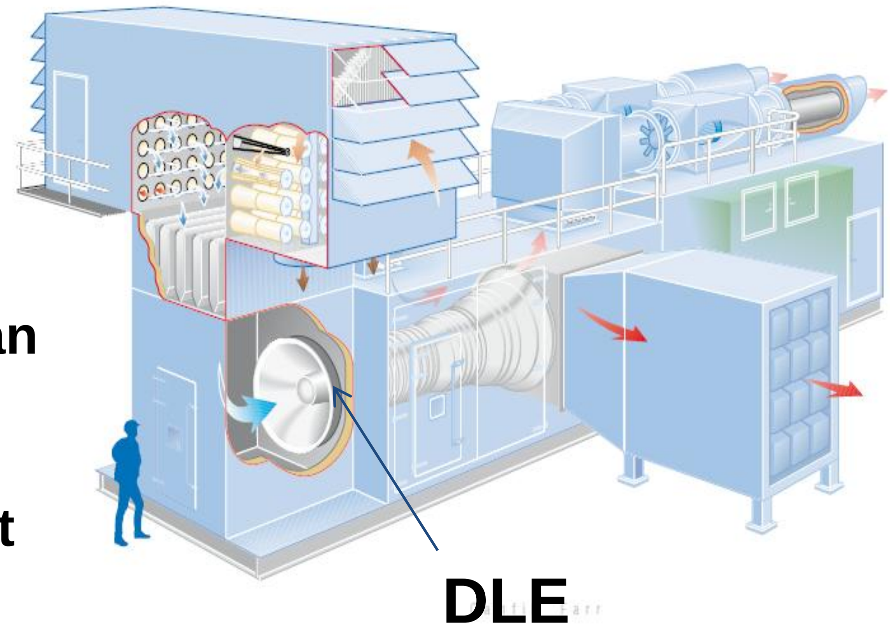
Solar Turbines

Clean Air for New Gas Turbine Systems

New pre-mix DLE combustors have most incoming air going through direct combustion

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

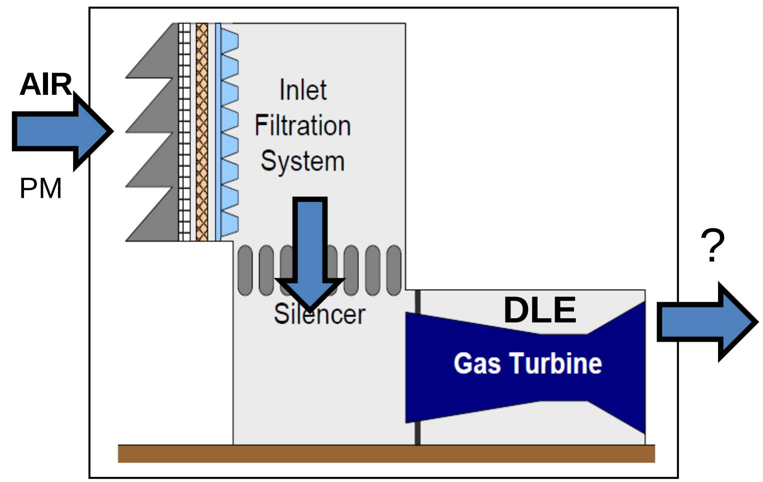
Small amounts of PM can escape, but must go through DLE combustor



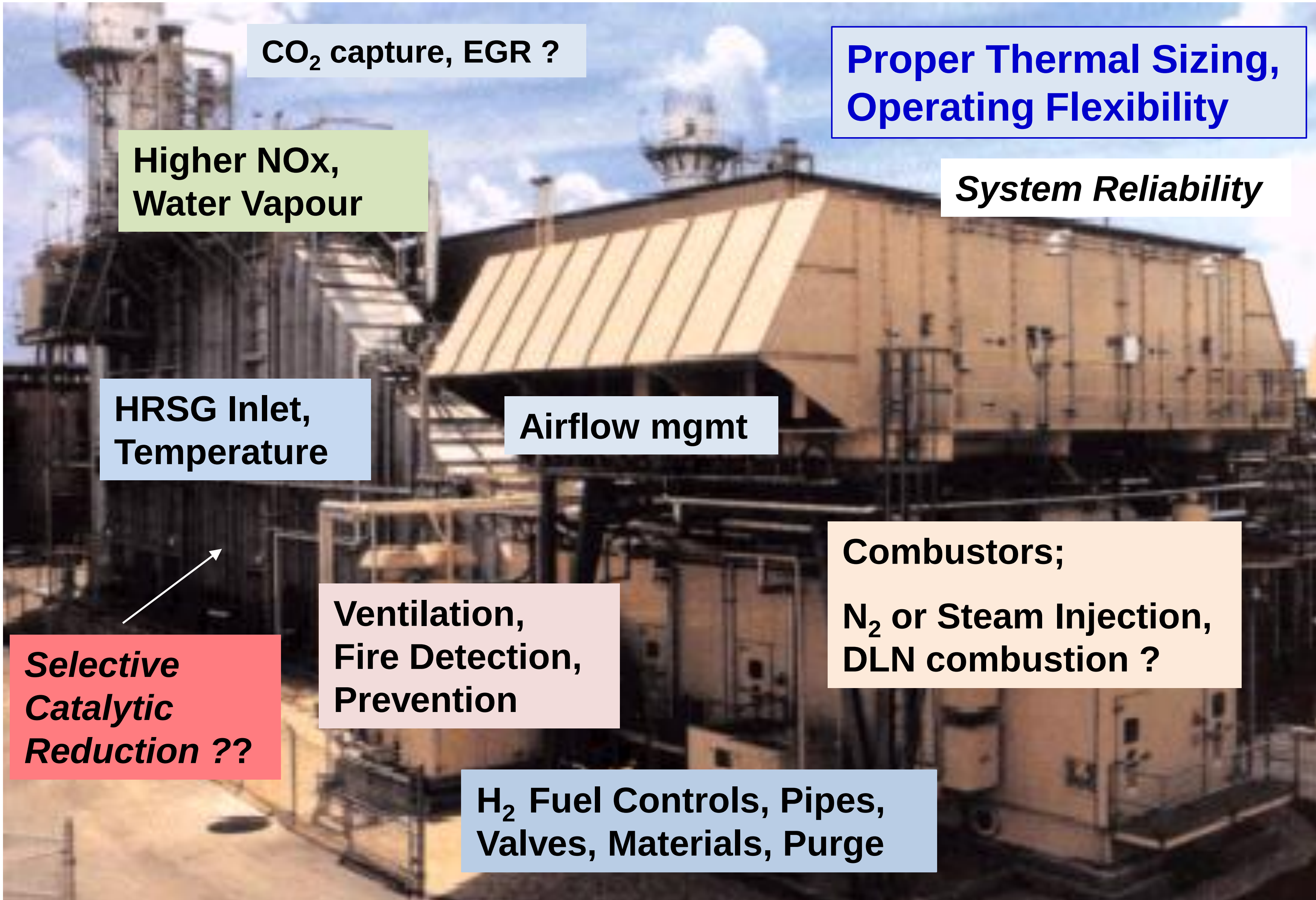
Emissions of fine particulates?

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

GT system mass balance ?



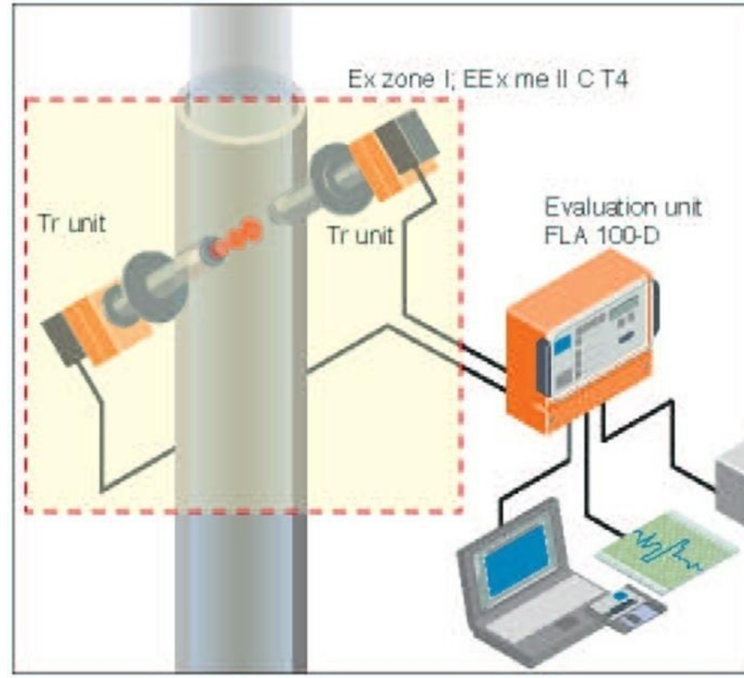
Hydrogen Fuels in Gas Turbine Systems



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

Emissions Measurement

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



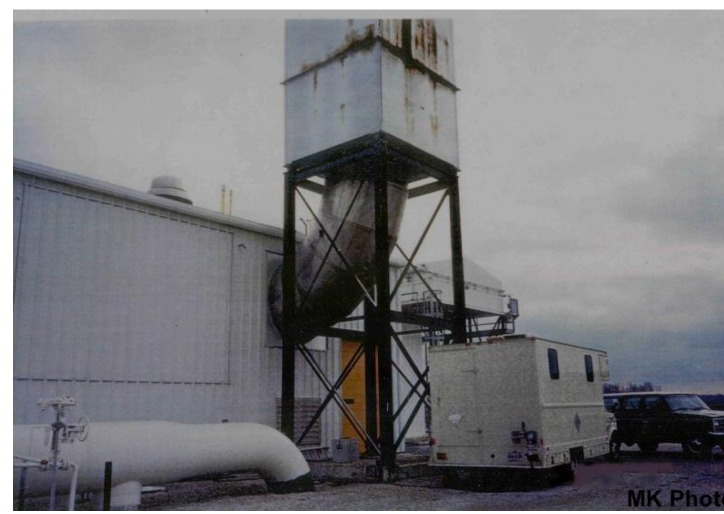
(CEM Specialties)

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)

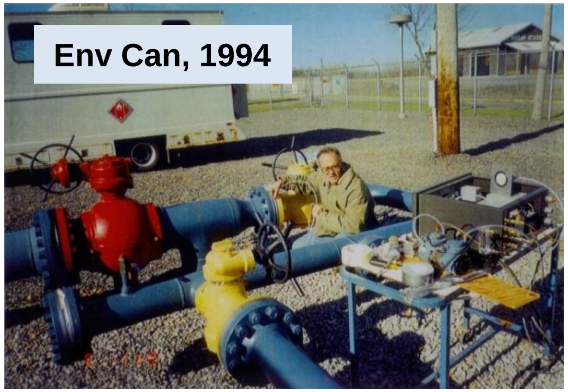
NG Lifecycle - Gas Compression Innovations for CO_2 and Methane Improvements (1980-90s)

- Aerial gas discharge coolers
- Waste Heat Recovery (Steam, ORCs)
- Higher pipeline pressures (less ΔP)
- Axial Inlet compressor piping retrofits
- Replace recips with high efficiency GTs
- Efficient and Reliable DLN Gas Turbines
- Reduced station blowdowns
- Dry Gas Seals to reduce venting
- Minimizing Stops and Starts
- Fugitive methane monitoring

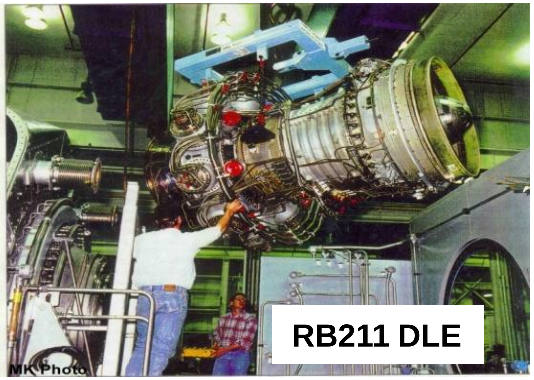
Waste heat CC, Ontario, 1991

DGS

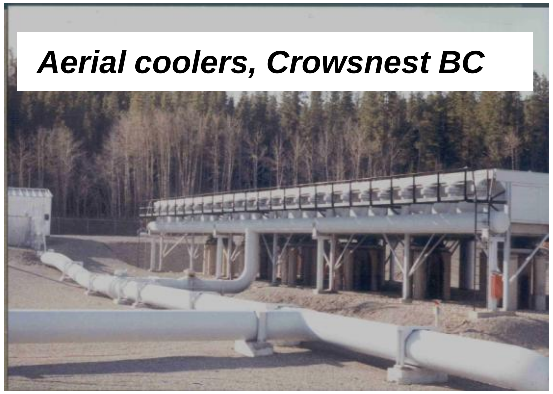
Norwalk Gas transfer compressor



Env Can, 1994



RB211 DLE



Aerial coolers, Crowsnest BC

Potential for Distributed & Integrated Energy Systems

Electrification ***Hybridization & H_2*** ***Flexibility & Resilience***

GTCC, CHP (MWe + MW_{th})

Univ of Calgary CHP Plant

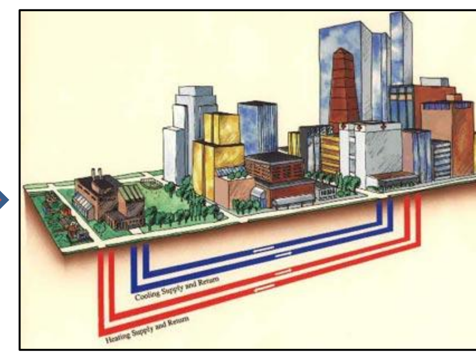
Public Transit

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

LNG System Environmental Performance

Process Efficiency

- Liquefaction design choices
- Feed conditions, Precooling methods
- Compressor speeds, pressure levels
- Variable Speed Electric Drives
- TurboExpanders, Absorption Chillers
- Flaring reduction, use BOG fuel

Fuel Efficiency

- Compressor drivers, Inlet Conditioning
- WHR and Cogeneration, Minimize losses
- Industrial vs Aeroderivative GT units
- Upstream fugitive methane, pipeline & comp stns
- Onsite vs GTCC/Hydro Imports, transmission
- Transient and Ambient Conditions
- High System Reliability

"Cleanest LNG" ?

< 0.2 t_{CO2} per t_{LNG}

- other impacts

- End use benefits

International Collaboration on GT Energy Issues

Establish common objectives on a clean energy transition

(Policy, R&D, Applications, Standards, Training, Reliability)

ASME International Gas Turbine Institute

GTEN

ETN Global

Some other groups;

- US DOE National Energy Technology Labs (NETL)
- Electric Power Research Institute (EPRI)
- Natural Gas Associations (CGA, AGA, GTI, Eurogas)
- Global Propulsion and Power Society (GPPS)
- Gas Turbine Society of Japan (GTSJ)

Considerations for a Clean H_2 Energy Transition

- **Energy Diversity, Security and Reliability are very important**
- **All potential solutions will be necessary, including GT systems**
- **Expensive H_2-based fuels can contribute in high value applications**
  - **gas turbines in cogeneration, district energy, distributed energy**
- **Air emissions regulations should use energy output-based rules**
- **Improved standards must be developed to ensure Hydrogen systems are designed for safe and reliable operation**
- **Need focused education & training, International Collaboration**



GTEN