GTEN 2019 Symposium

October 21-23, 2019 | Banff, Alberta

Gas Turbine Systems for Cleaner Energy

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

Manfred Klein

MA Klein & Associates
maklein@rogers.com

Presented at the Gas Turbines Energy Network (GTEN) 2019 Symposium
Banff, Alberta, Canada - October 2019

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 28 000 MWe installed in Canada
(~ 470 plants, 1150 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

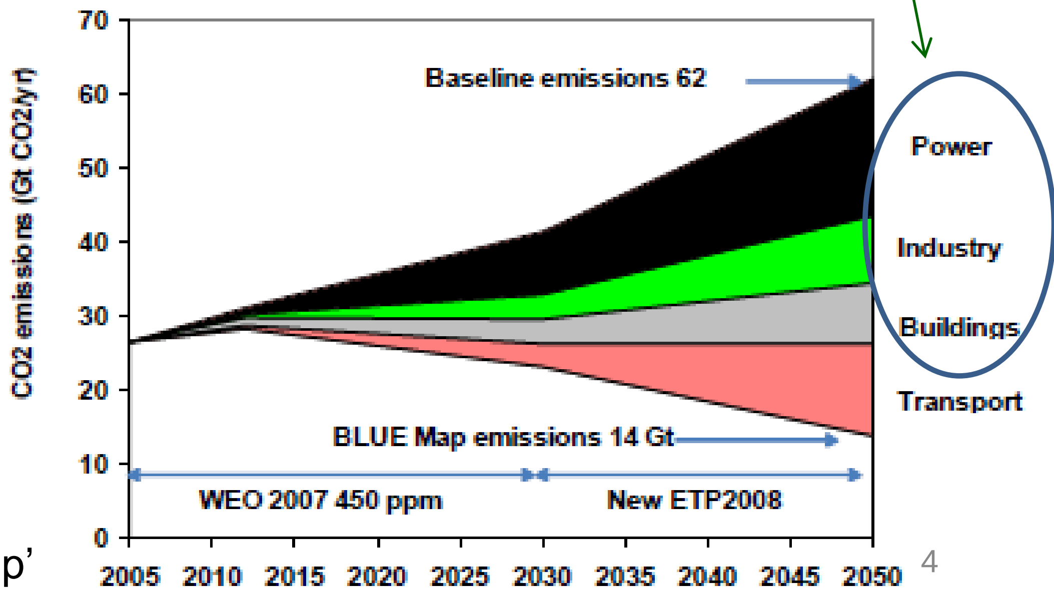
- CFCs

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**
- **Coal & Bitumen Gasification, Polygen w/CCS**
- **Waste Energy Recovery**

GT systems can do 25-30% of these reductions

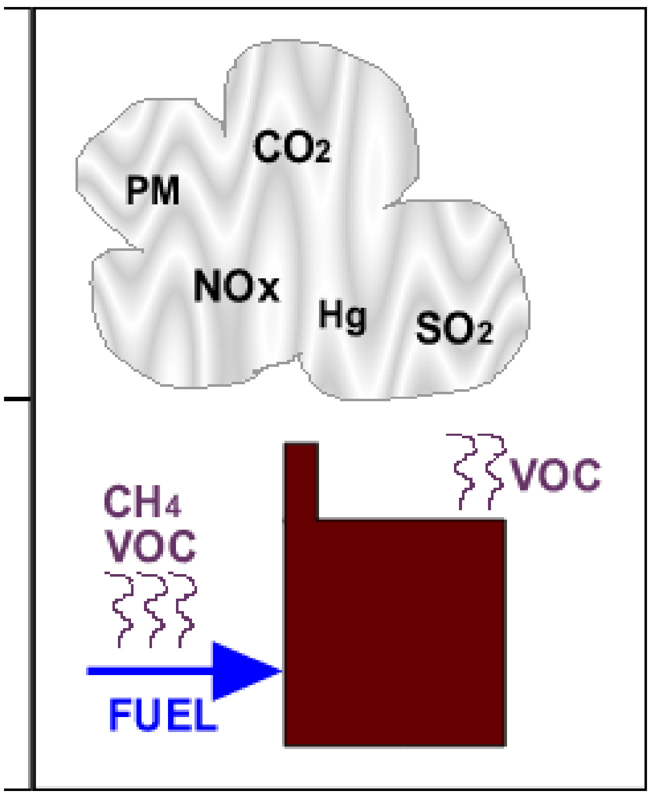
- ***Air Pollution***
- ***GHG Emissions***
- ***Air Toxics***
- ***Water Impacts***
- ***Energy Security***



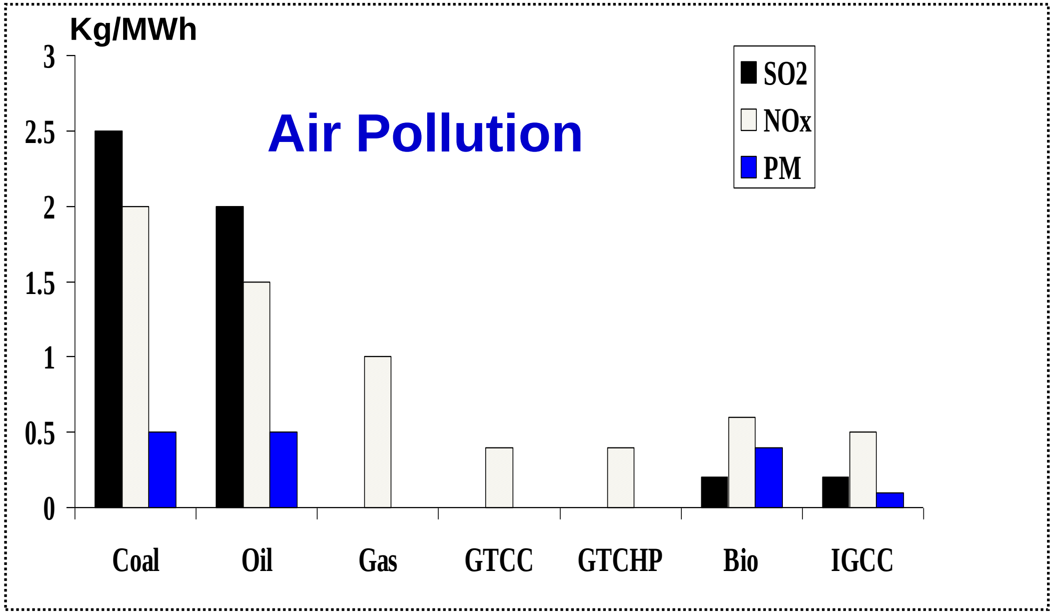
IEA WEO 'Blue Map'

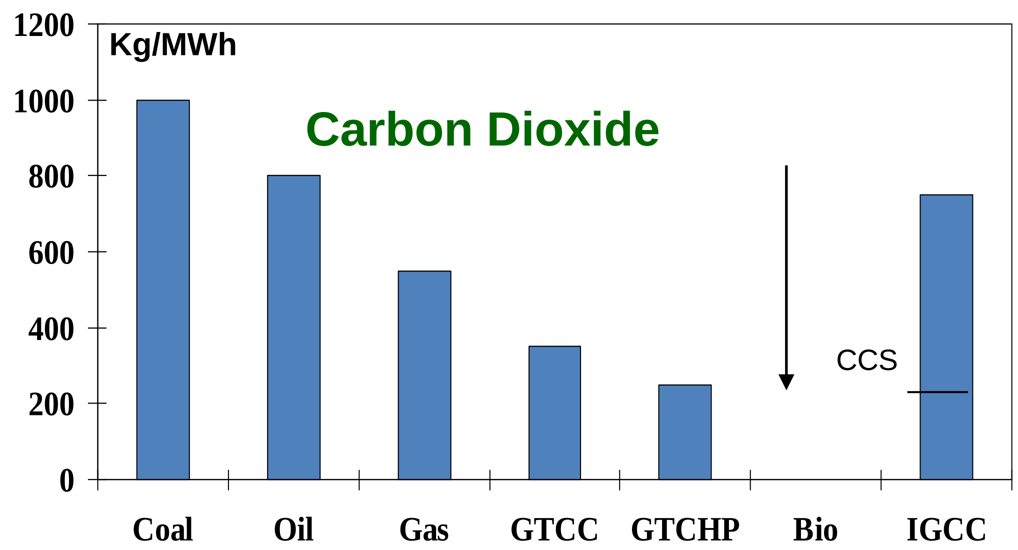
Environmental Issues

Air Emissions



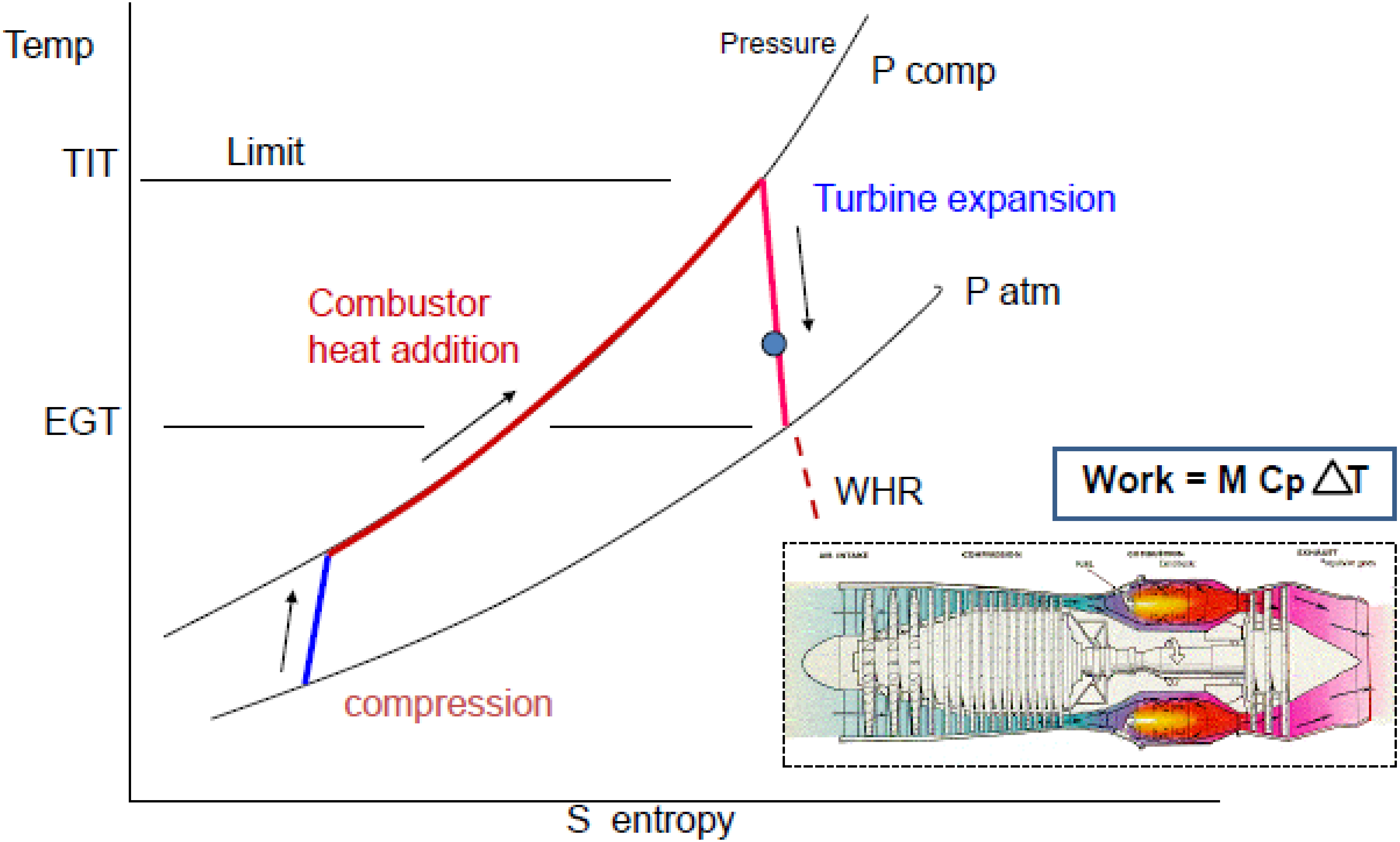
"Cannot produce Air Pollution without making CO_2"





Comparing Emissions from Thermal Energy

Brayton Cycle; Cycle diagram for Gas Turbine

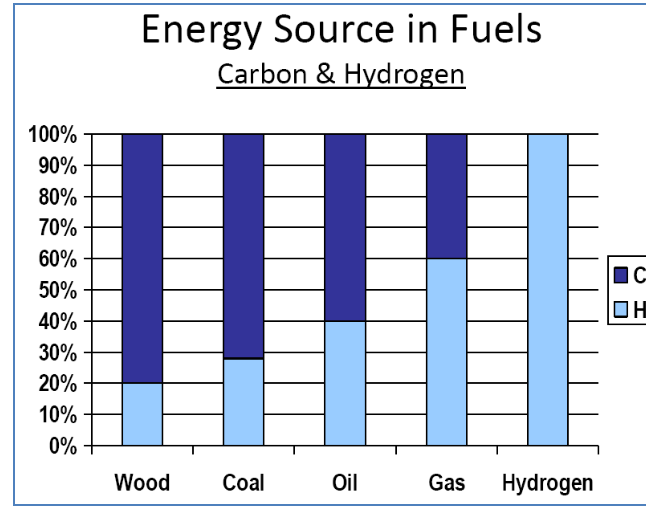


Gas Turbine defined by high pressure hot air, as a gas, powering the blades

(not because of gas fuel)

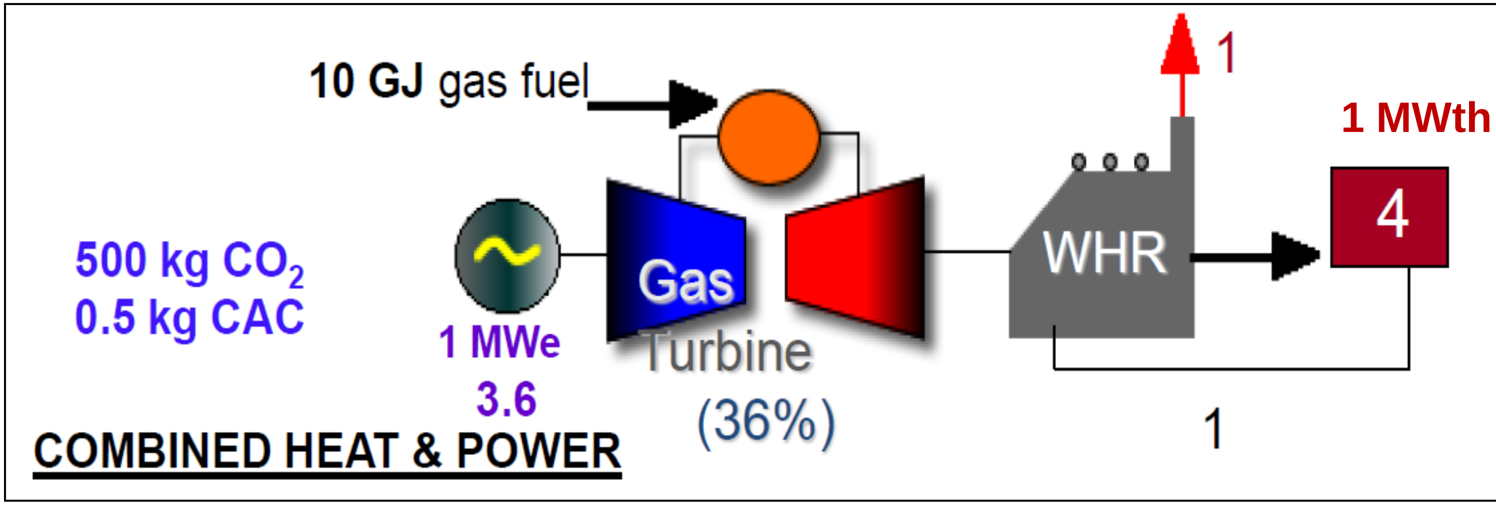
Natural Gas Systems and Renewable Energy

- 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



Cogeneration or Combined Heat & Power (CHP)

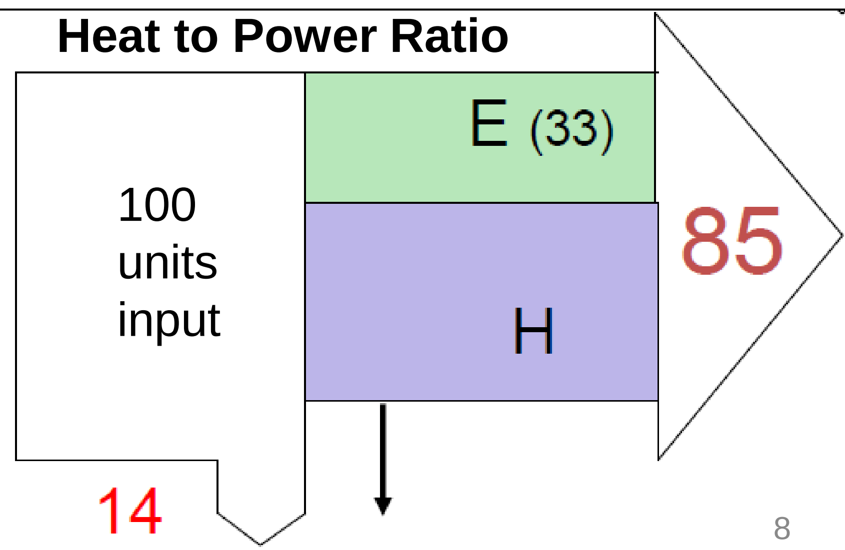
Producing 2-3 forms of energy from the same fuel, in same process



Quality of Energy

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

Heat to Power Ratio



Combined Heat & Power - Some Basic CHP Considerations

Fuel burning does not make Power, always makes Heat first (C-H-P byproduct power)

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

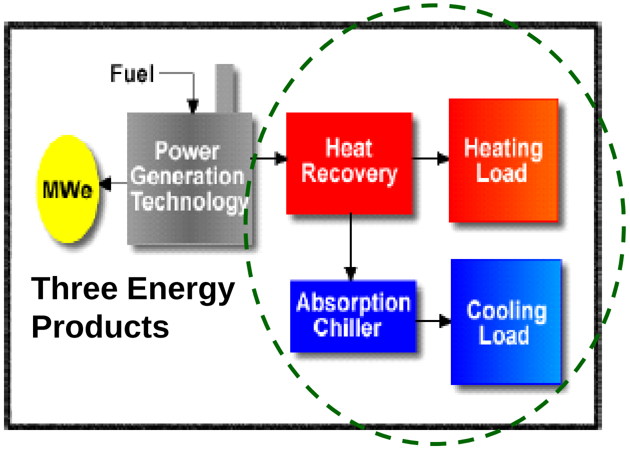
Distributed CHP, WHR & DES systems are not 'business-as-usual'

Natural Gas is mostly Hydrogen Energy
- very clean; used close to demand

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

Power Disruptions are Important;
- Onsite CHP can function through outages

Can use all exhaust heat from small GT units



Onsite CHP: Adaptation

Potential for Distributed & Integrated Energy Systems

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

GTCC, CHP (MWe + MW_{th})

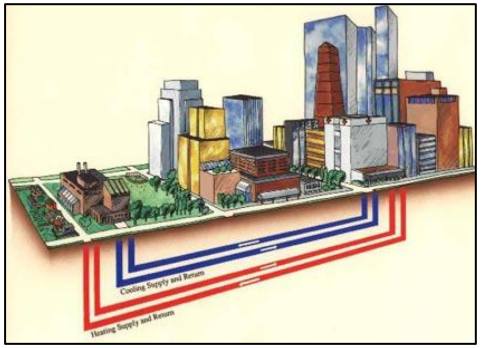
Public Transit

Heating & Cooling Services

Combined Cycle

EV Charging, Hybrid cars

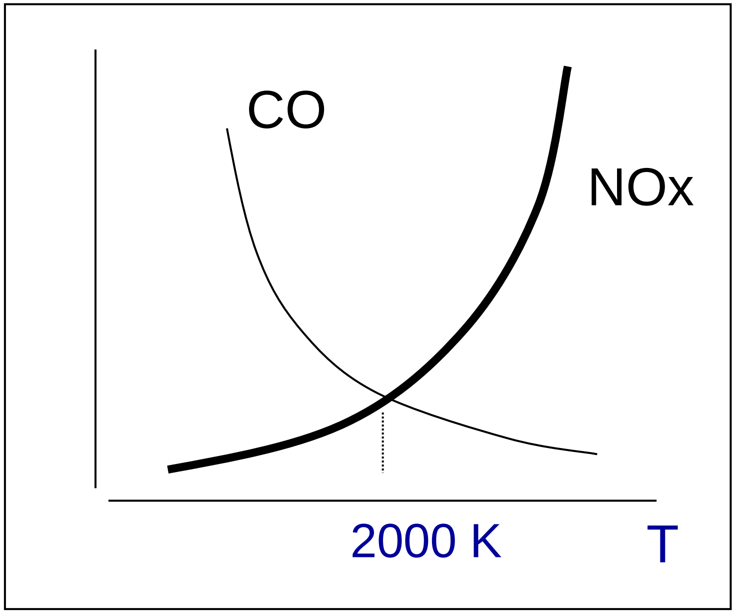
District Energy



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

Electricity Storage & Batteries, Thermal Hot/Cold Water Storage

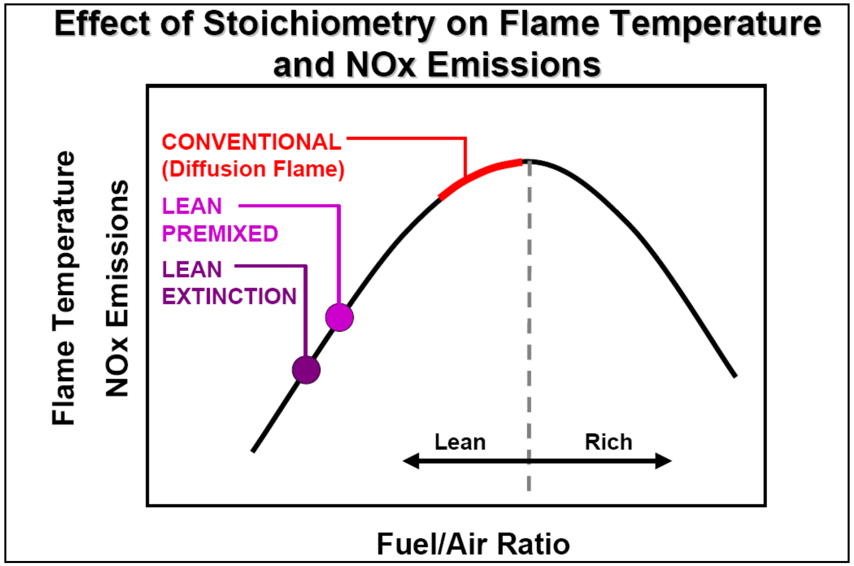
Air Pollution - *NOx Emissions*



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

3 Compounds of Concern:

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



Thermal NOx:
High Temperature Combustion

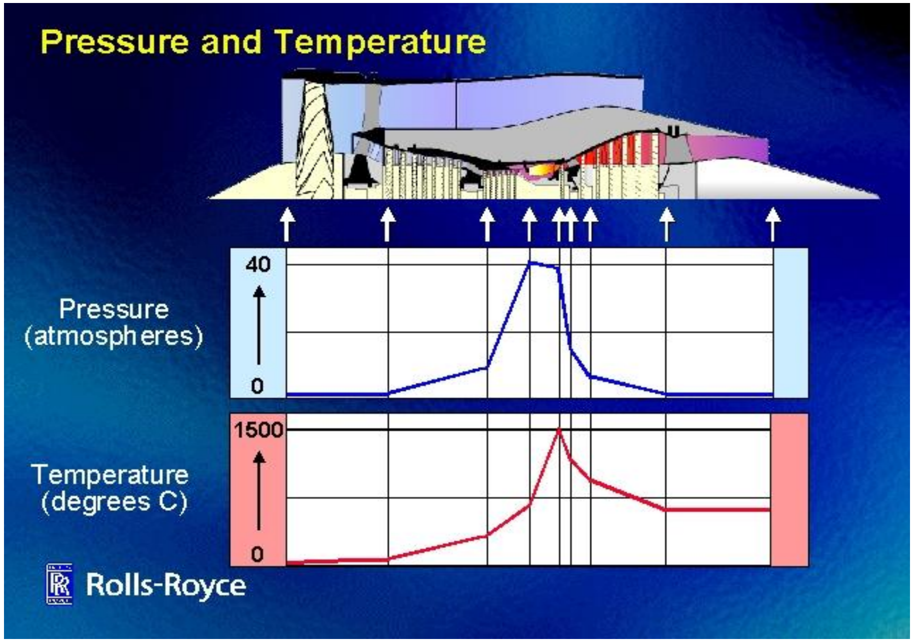
Fuel NOx:
From N_2 Content of Oil, Coal

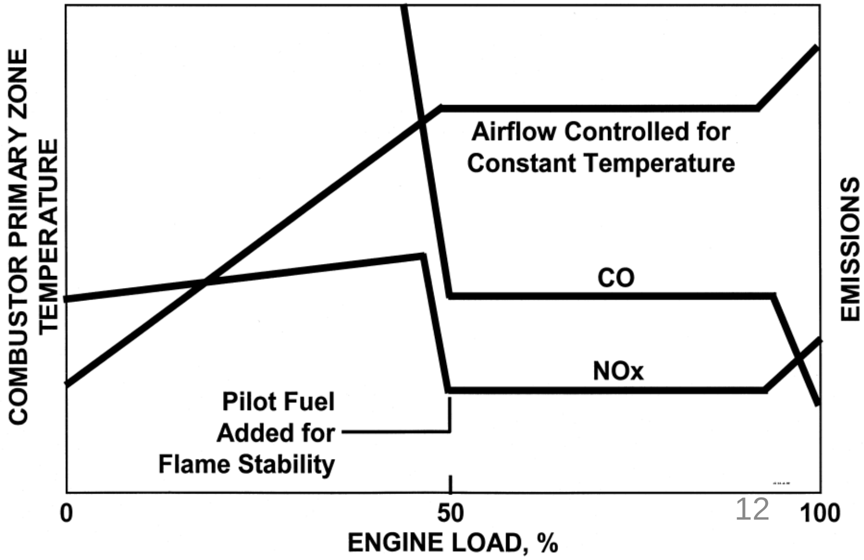
- ***Nitrous Oxide is N_2O, a GHG***

(Solar Turbines)

Factors Affecting NOx 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)
- NOx Concentration vs Mass Flow
- Tradeoffs w/ other emission types





Importance of Environmental Units

A.

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

- **kg per Fuel Input**

B.

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

Concentration based units, in ppm and mg/m3, require O_2 content (15%)

- some of these inherently include system efficiency

(CO_2 emissions at 35 000 ppm ?)

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**

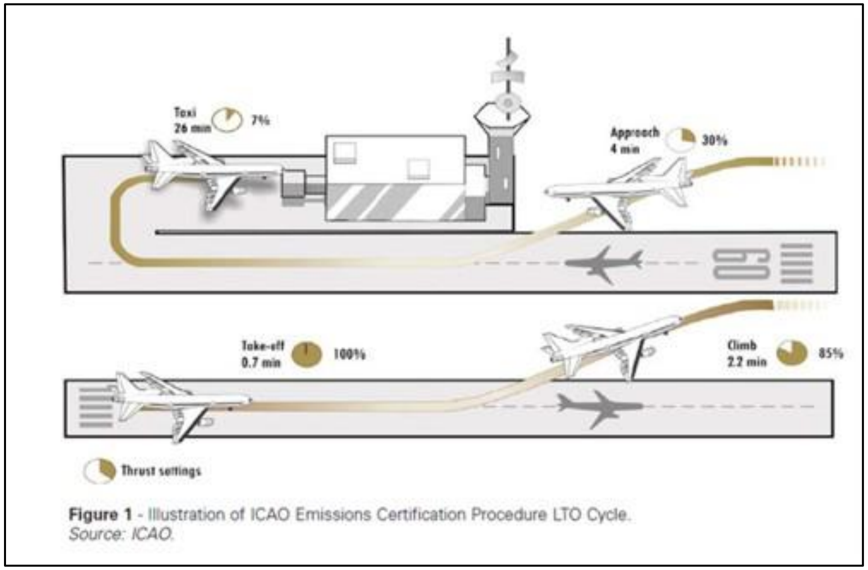


Figure 1 - Illustration of ICAO Emissions Certification Procedure LTO Cycle.
Source: ICAO.

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

Output-based Rules;

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

tonnes/yr

$/tonne

$/MWhr

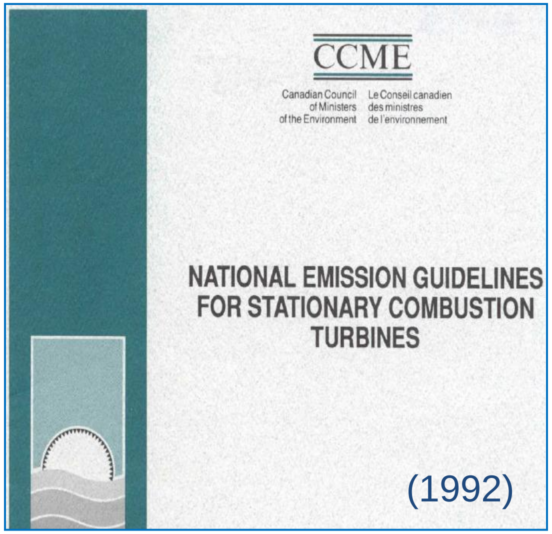
Lbs/HpHr

Canadian CCME Gas Turbine Emission Guidelines, 1992

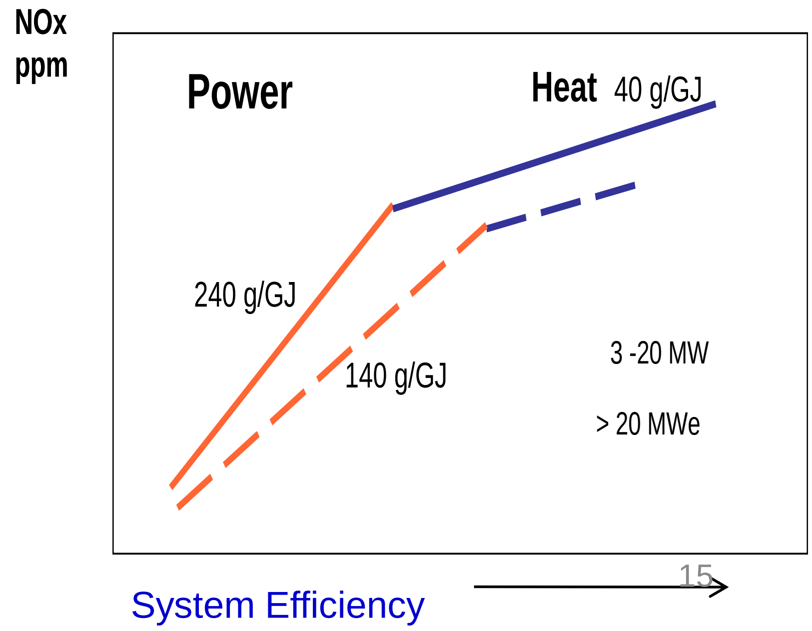
- **Reasonable NOx & GHG Prevention**
- **Clean Energy Objectives, EA Policy Clarity**

- **Output-Based Standard for Efficiency**
  (140 g/GJ$_{out}$ Power + 40 g/GJ Heat)

0.5 kg/MWhr (~ 1 lb/MWhr)

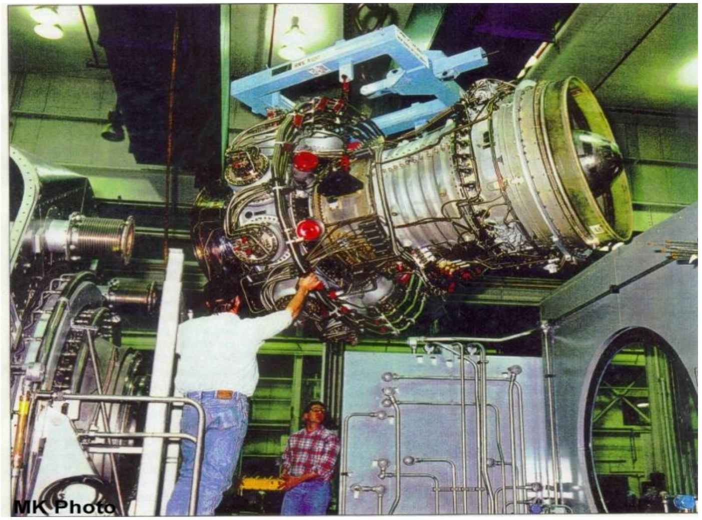


- Engine Sizing Considerations
- Promotes WHR, Cogeneration & low CO_2
- Keep Reliability, Minimize CH_4 losses
- Flexible Emissions Monitoring
- Cold Climate and Off-Design conditions
- Approach adopted by USEPA (2006)



Emission Guideline based on industry consultation, and …..

TCPL Nipigon Waste Heat Recovery, 1991



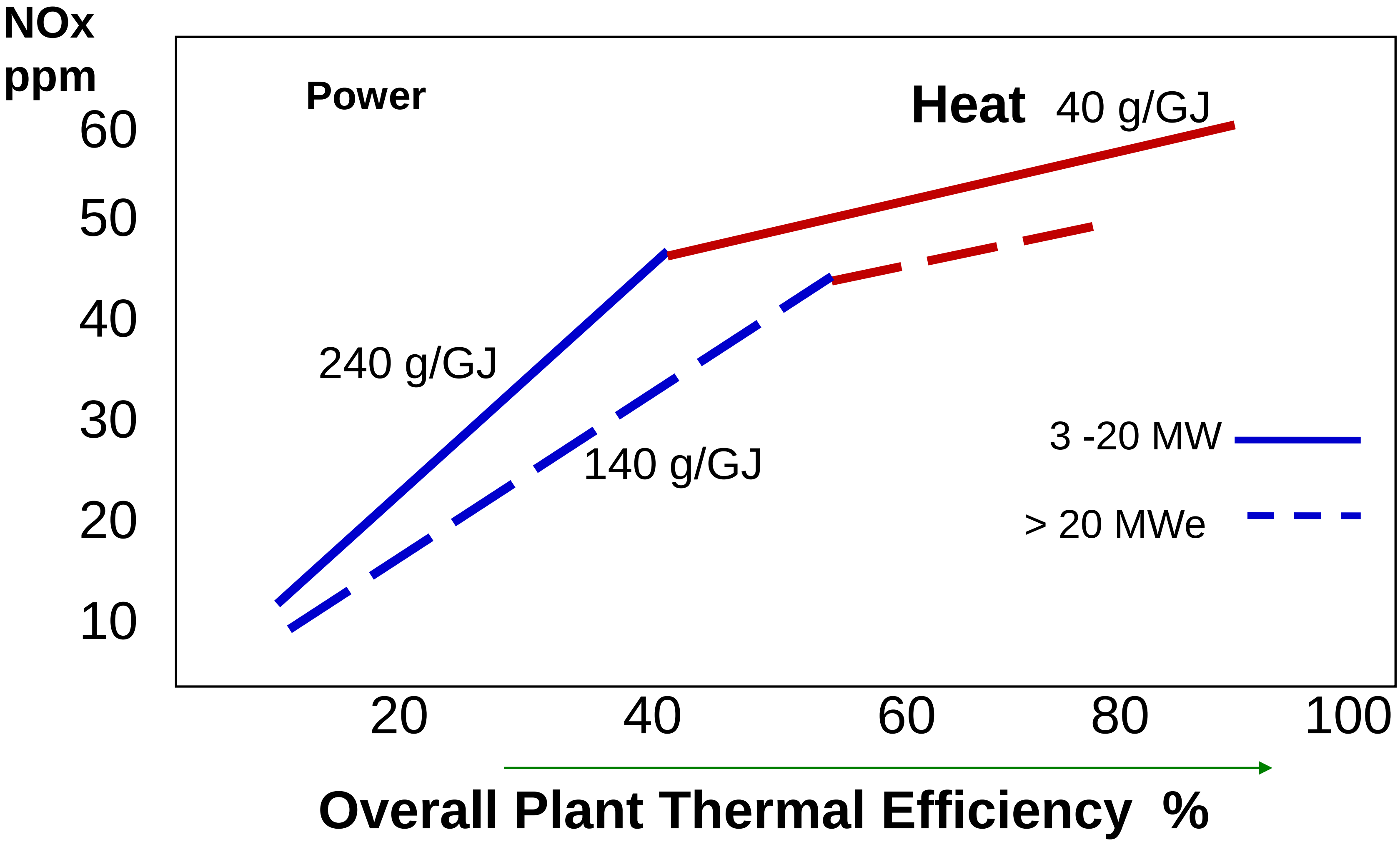
Rolls Royce RB211 DLE

TransAlta Ottawa Hospital Cogen, 1991

GE LM6000 steam injection

Canadian CCME Gas Turbine Guideline (1992)

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



British Columbia MOE Emission Rules (developed in 1992)

Turbine Size (MW)	Emission Limit (mg/m^3)[1]			Emission Monitoring Requirement
	NO_X	CO	NH_3[3]	
3.3 - 25	80	80	- -	As specified by Regional Manager
>25	17 or 48[2]	58	7	Continuous

Note:

* This is based on the 1992 document, which still applies.

[1] Referenced to 20°C, 101.325 kPa, and dry gas conditions, corrected to 15% O_2. Averaging Period 1-hour.

[2] 48 mg/m^3 applies to gas pipeline application and other installations where SCR is demonstrated to be inappropriate

[3] The Ammonia limit is based on the assumption that selective catalytic reduction (SCR) technology has been employed to control NO_X emissions.

Alberta Environment NOx Emission Guidelines

(Gas Turbines for Electricity Generation, 2005)

Size	Alberta 2005 (kg/MWhr)	*CCME* (kg/MWhr)
3 - 20 MWe	**0.6**	*0.86*
20 - 60 MWe	**0.4**	*0.5*
over 60 MWe	**0.3**	*0.5*

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)		ppm	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

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

?

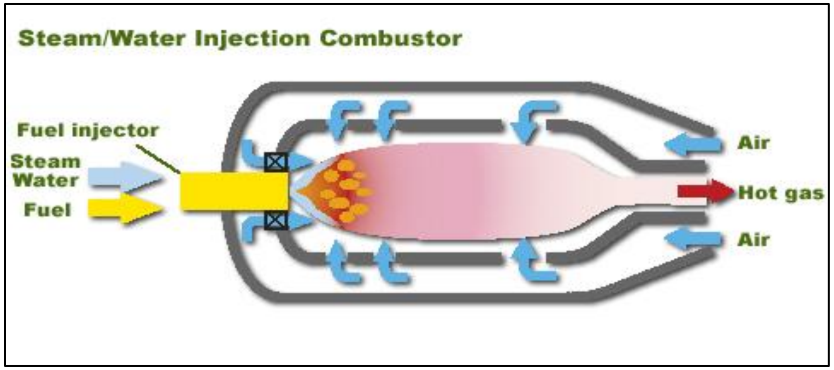
Application	Turbine Power Rating (MW)	NO_x Emission Limits (g/GJ$_{\text{(power output)}}$)	NO_x Emission limits (ppmv)@ 15% O_2
Non-peaking combustion turbines - Mechanical Drive	$\geq$ 1 and < 4	500	75
Non-peaking combustion turbines - Electricity Generation	$\geq$ 1 and < 4	290	42
Peaking combustion 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 Canada May 2016

NOx Reduction Methods

Steam/Water Injection

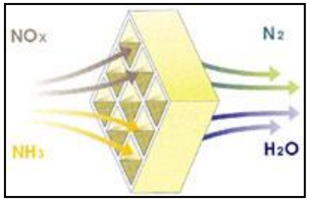
- Prevention, 2/3 red'n to 1 kg/MWhr
- Some Combustion Component Wear
- Plant Efficiency Penalty
- Depends upon value of plant steam

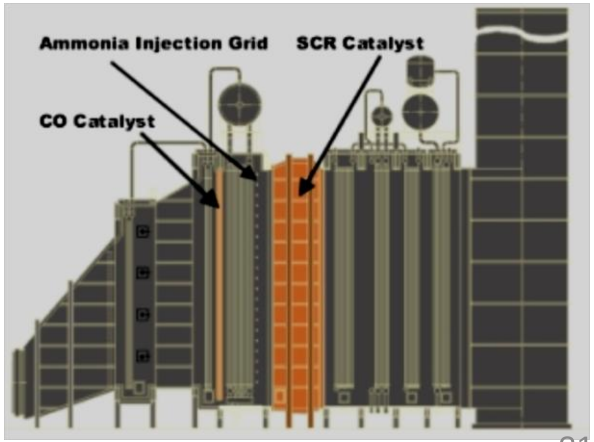


(Kawasaki)

Selective Catalytic Reduction (SCR)

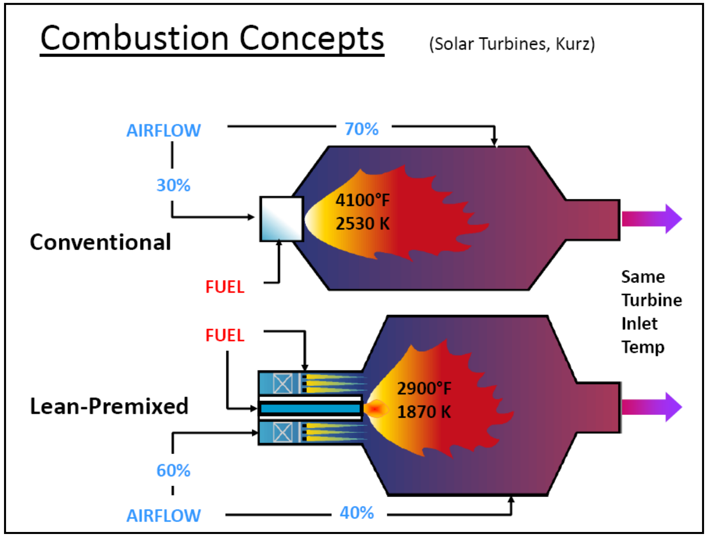
- NH_3 injection into catalyst in HRSG
- ~ 80% NOx Reduction
- **Backend Control**
  - **- Ammonia emissions & handling (toxic)**
  - **- fine PM emissions, N_2O ?**
  - **- Cycling duty - ammonia slip**
  - **- Efficiency loss in HRSG**
- **Marginal, low $/tonne benefit after DLN**

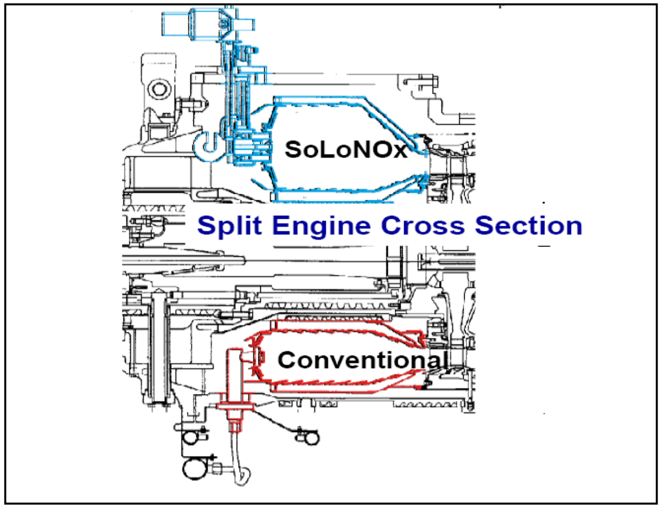




Dry Low Emissions Combustion

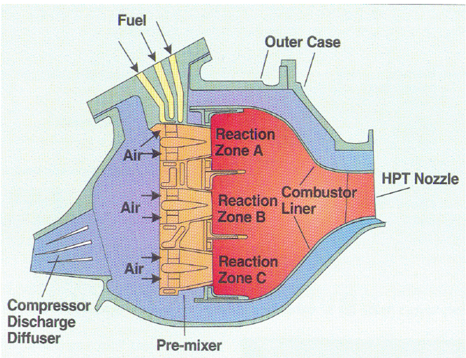
- <u>Preventative</u> reduction by 60-90%
- Maintains High Efficiency
- Good experience with large industrial units
- Some Reliability Issues for Aeroderivatives
- Too Low Values may lead to inoperability and combustor problems
- How important are CO emissions?
- Mech. drives need wide operating range
- Effects of Plant Cycling, Transients
- Operating range, fuel Wobbe range ?

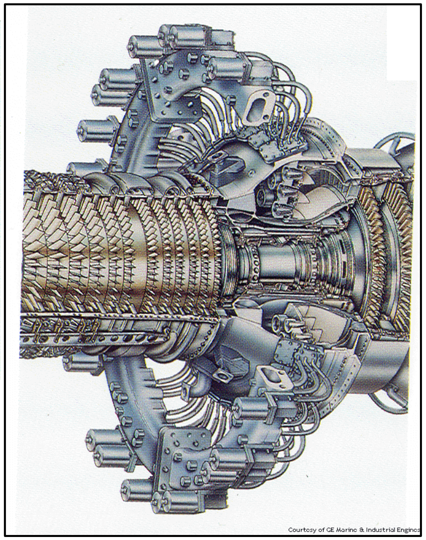




Solar SoLoNox

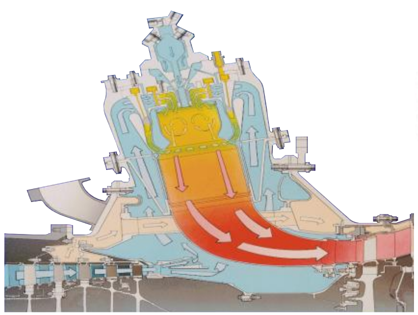
Aero-Derived DLN Systems

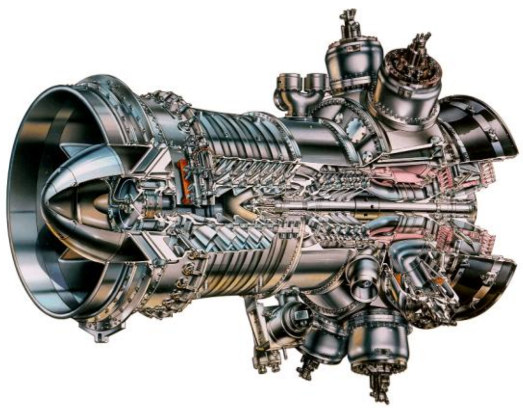




General Electric LM6000 DLE

Triple Annular Dome

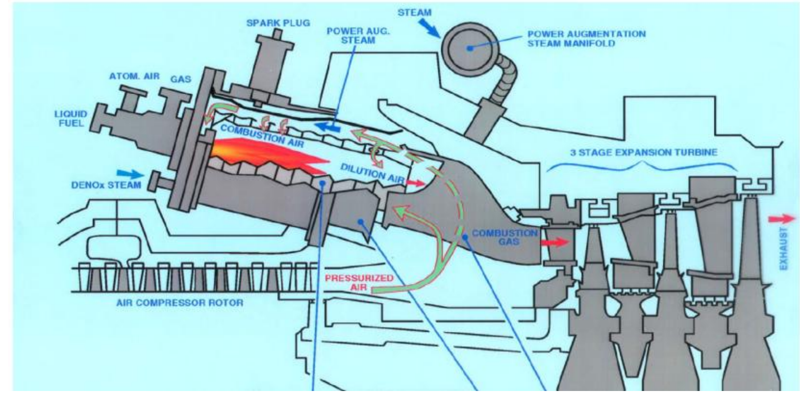




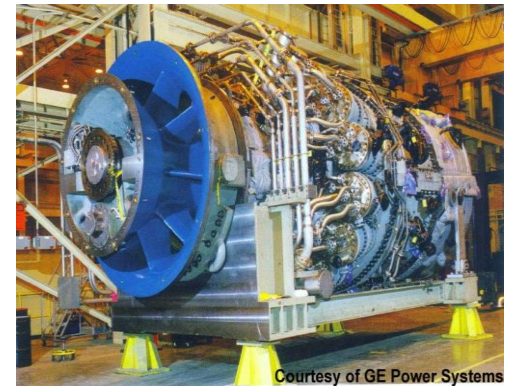
Rolls Royce RB211 DLE

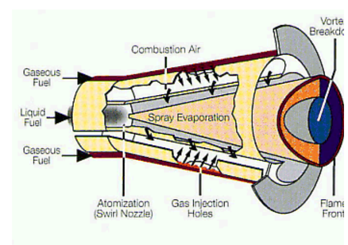
(Series staged)

Large Frame Unit DLN



GE Frame 7 DLN2

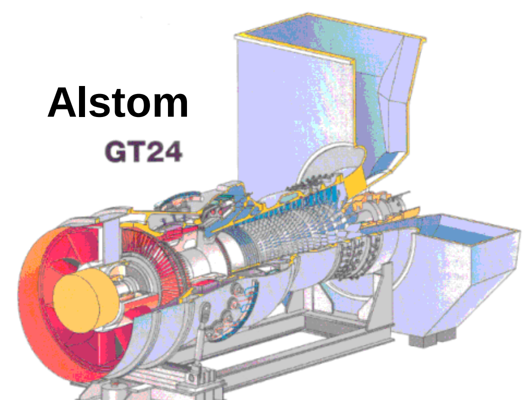




Annular EV burner

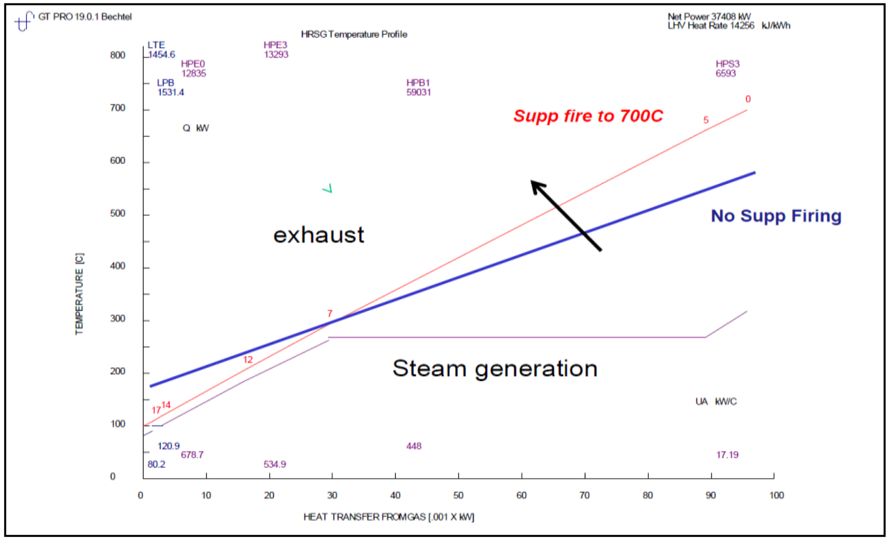
Alstom

GT24



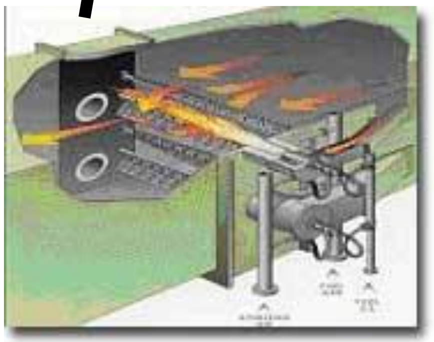
Waste Heat and Duct Burners in CHP

- 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



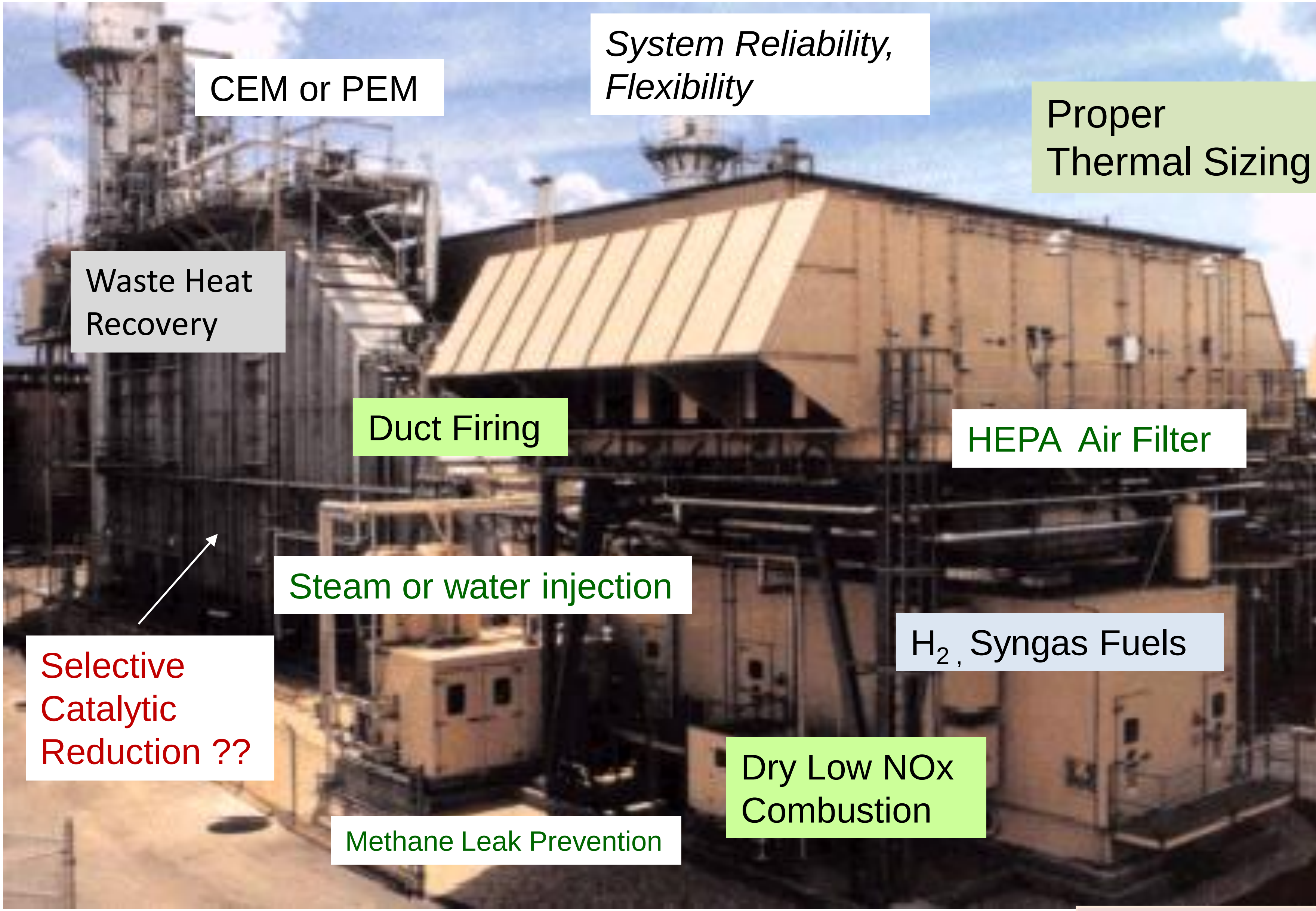
C. Meyer-Homji, Bechtel Corp.

JOHN ZINK COMPANY



(Coen)

Gas Turbine Emission Prevention & Control (NOx, GHGs)



GE Power Systems

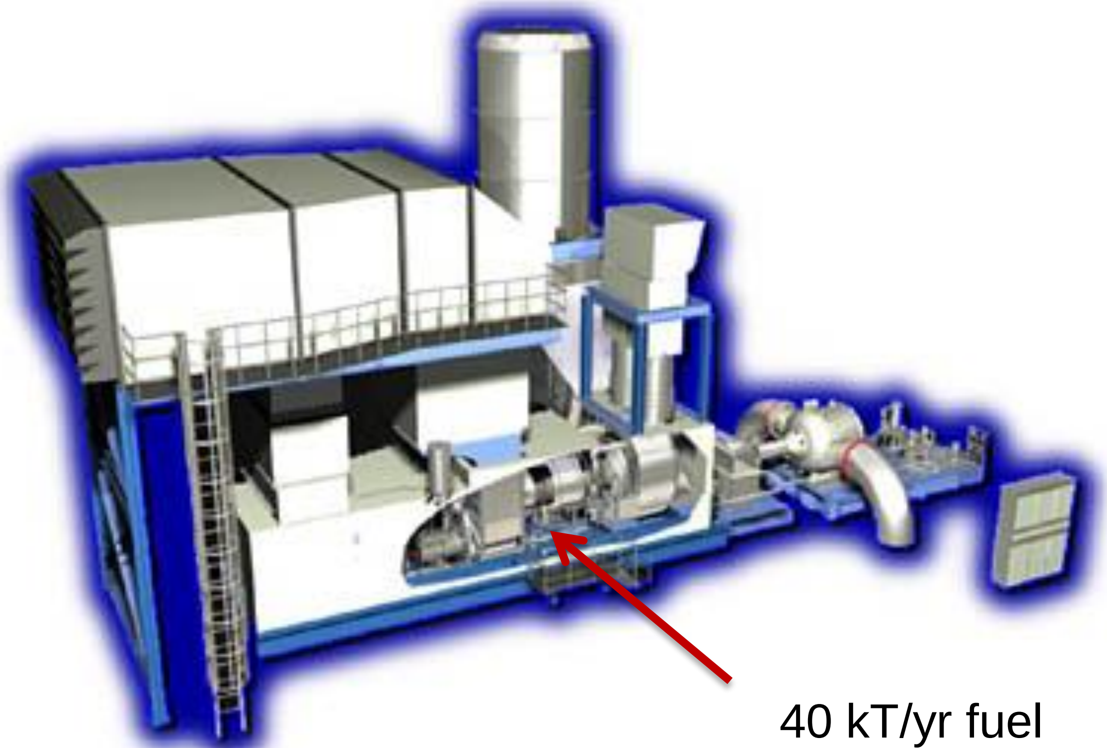
Maximizing System Output CHP Efficiency

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

(AP42 - 0.07 lb/MWhr ?)

?

2 million t/yr Air



40 kT/yr fuel

Air Filter
99.8%

Does dry NG combustion produce fine PM emissions?

What is the Inlet-Exhaust mass balance ?

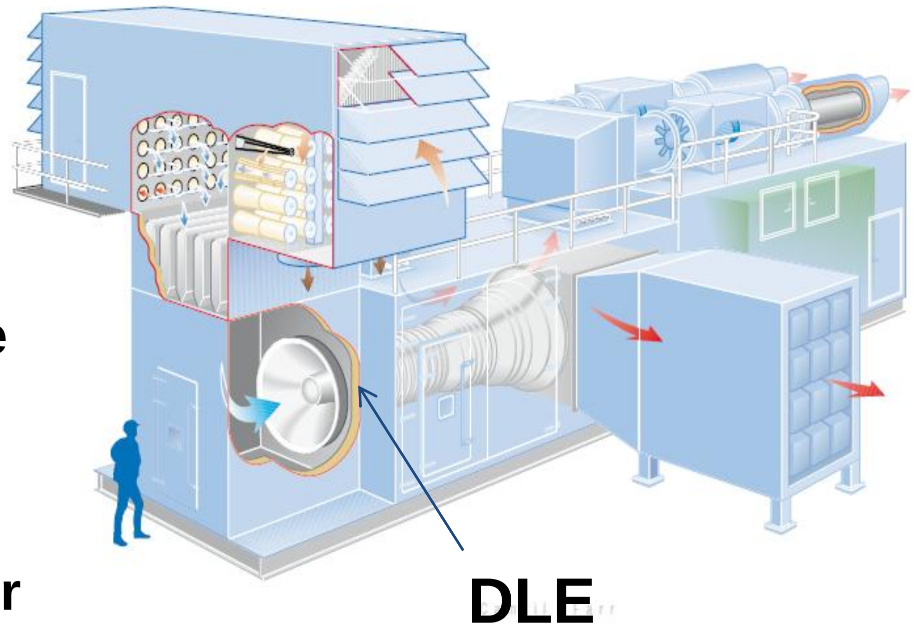
Are there any Air Toxics ?

New Gas Turbine Systems

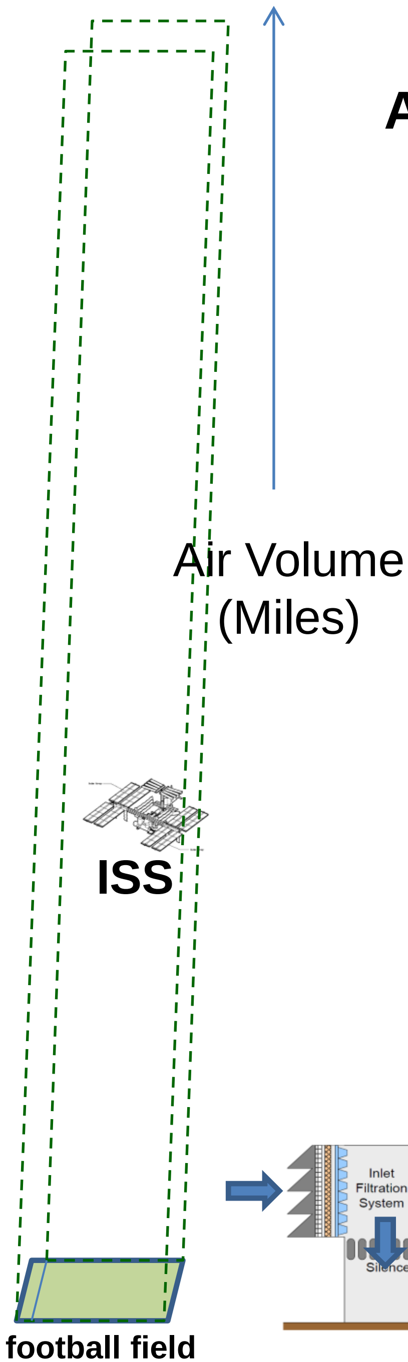
New pre-mix DLE combustors have most incoming air going through direct combustion

Modern turbine air filter systems are cleaning the incoming air by 99 %

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

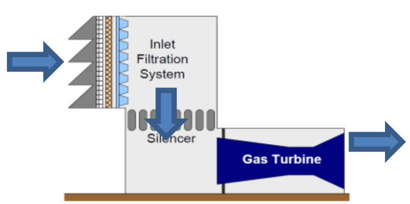


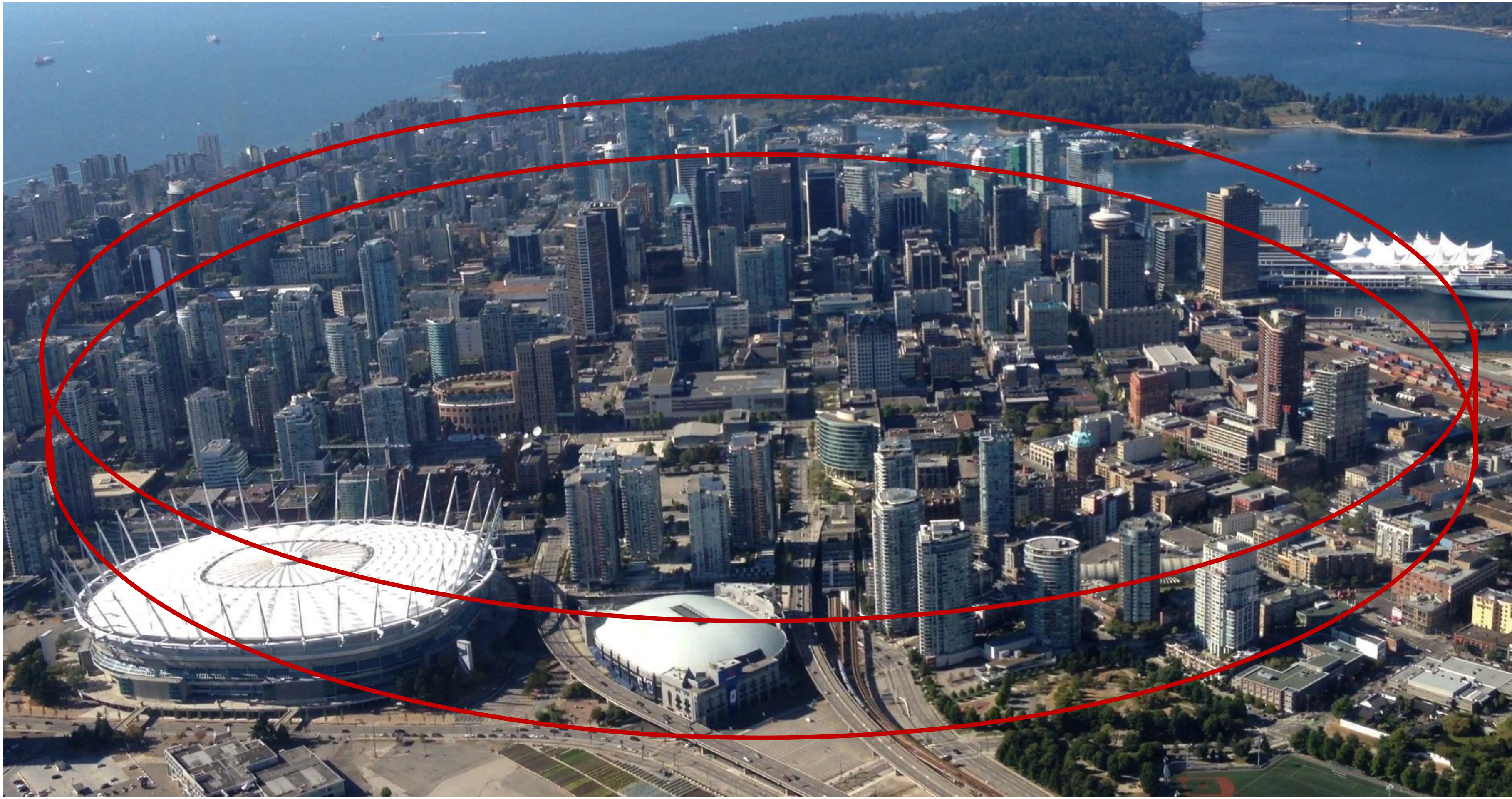
Airflow for Power Output; Parameters for Gas Turbines



Gas Turbine	ISO (MW)	airflow (lb/sec)	Air ingested per year (Miles above football field)	Foulant ingested per year at 1 ppm ambient (lb)
SGT 100	5	39	53	1230
Solar Mars	10	92	126	2900
RB-211	27	199	272	6276
Trent 50	51	340	464	10722
Frame 7EA	85	655	894	20656
Frame 7FA	173	971	1,325	30620

(C. Meher-Homji, Bechtel)





45 MW LM6000 gas turbine,   7000 hrs

AP-42;   PM @ 10 000 kg/yr ?

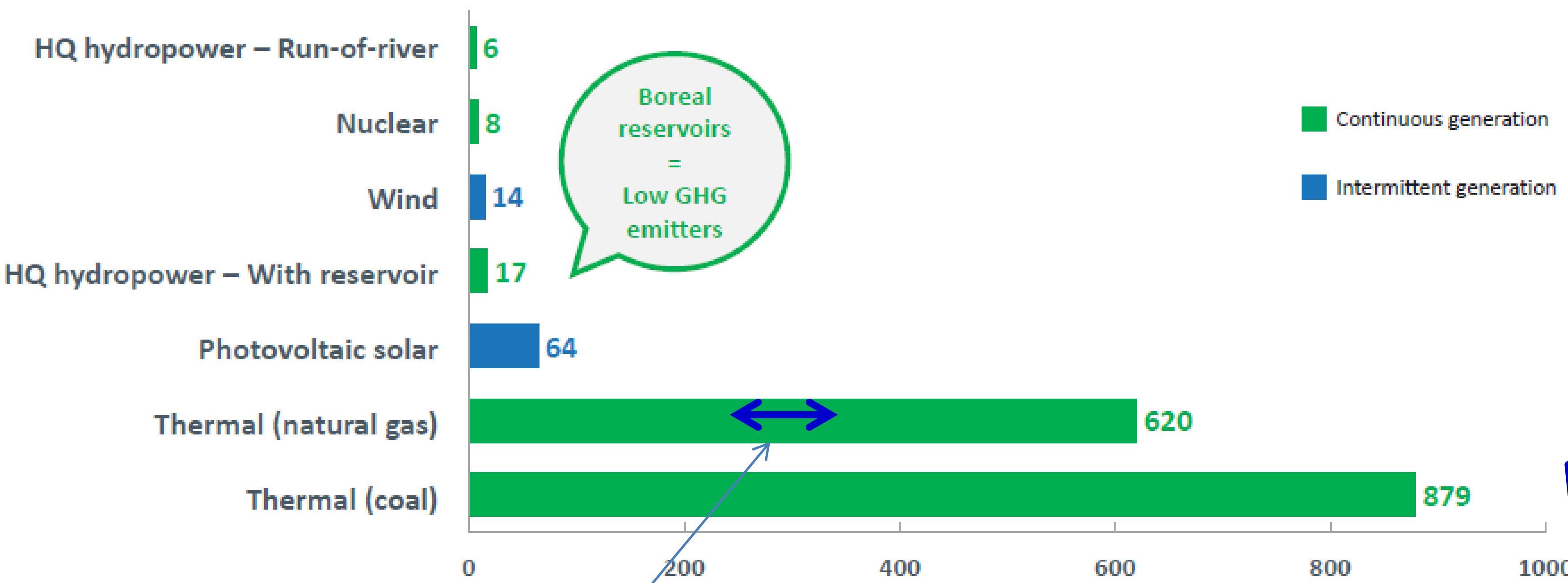
0.13 tonnes of air ingested per sec;

3.3 million tpy air,   or 2.5 billion m^3 (volume of Vancouver)

Ambient PM_{10} @ 40 ug/m^3 = 100 kg of PM_{10} ingested (incl. 10 kg of $PM_{2.5}$)

Air filter can capture 95+ % of $PM_{2.5}$ < 1 kg released, + a few kg from fuel ?

Greenhouse Gas Emissions from Different Power Generation Options



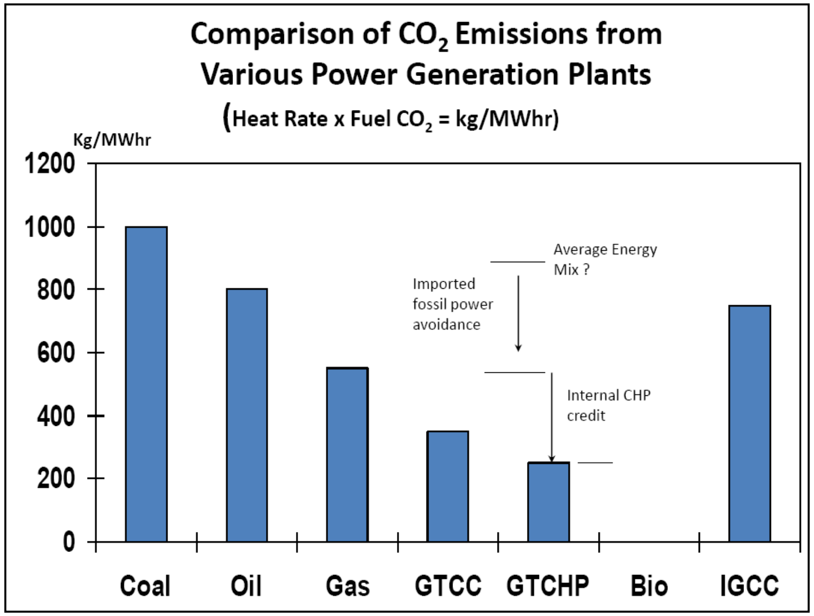
5

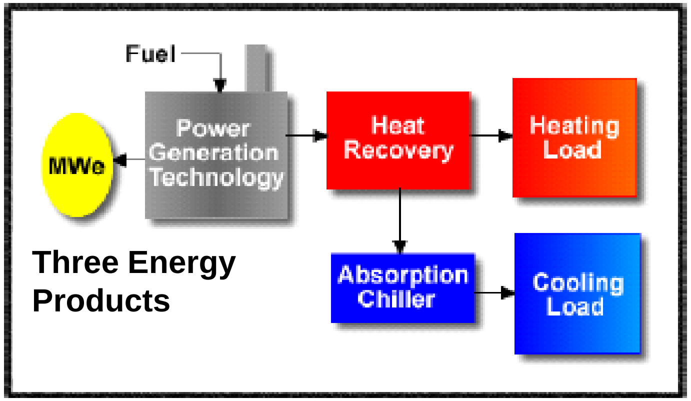
From Hydro Quebec, 2016

NG Cogen (MK)

Critical Elements for Cogen (CHP) Systems

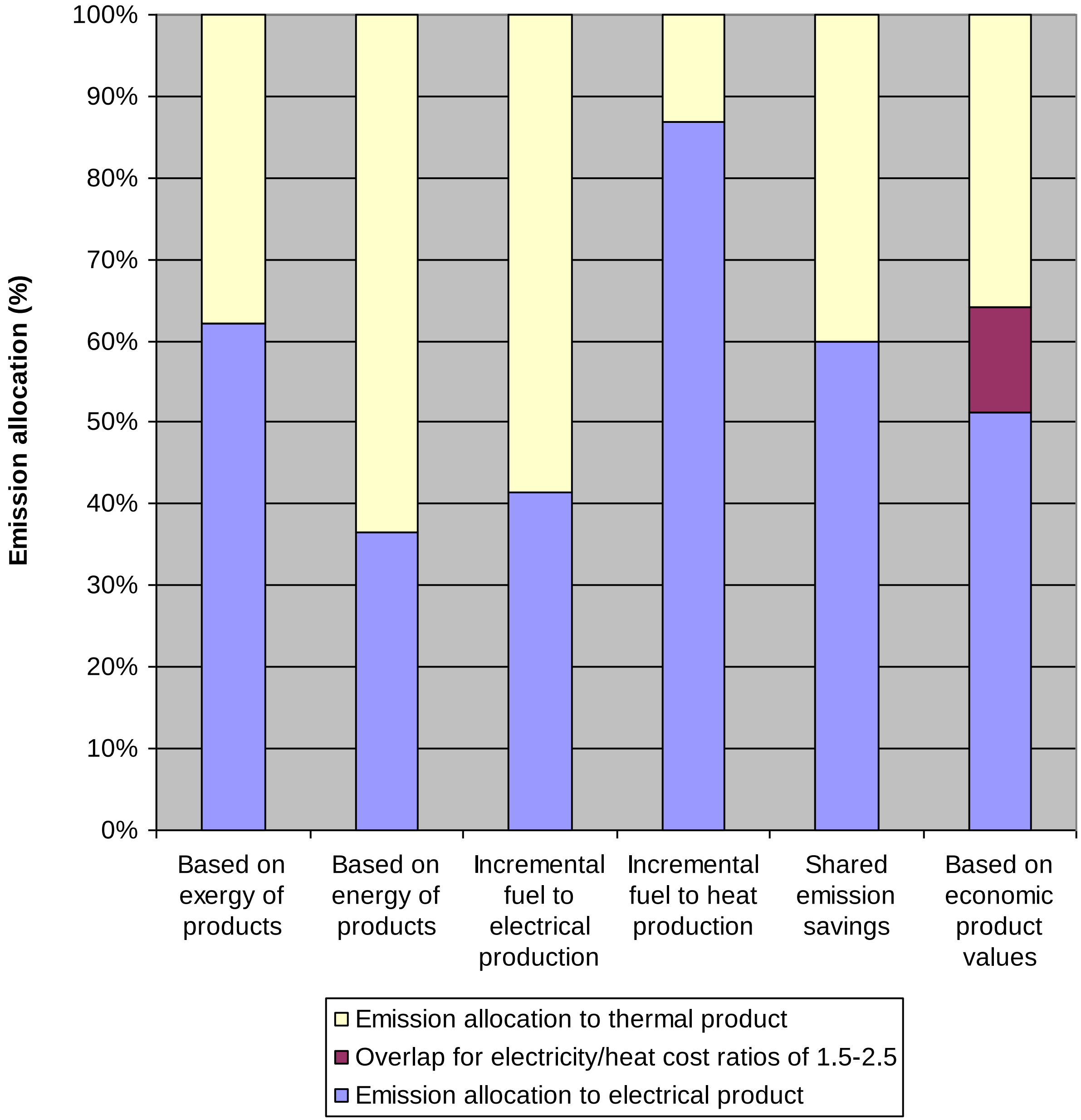
- **Site, Sizing to Match Thermal Load**
- **Seasonal Heat/Cooling Design**
- **Electrical Utility Interconnection**
- **Energy Quality, Heat:Power ratio**
- **Low Air Pollution, Local Impacts**
- **Greenhouse Gases & Allocation**
- **Output-based Emission Rules**
- **Integrated Business Case**
- **CHP also an 'Adaptation' measure**





(CHP more effective than CCS for GTCC)

. Allocation of emissions for University of Toronto cogeneration plant



Measures for Allocating Energy System Emissions

Marc Rosen, M. Klein 2003

University of Toronto

6 MWe EGT gas turbine

Campus Heat;
6 km steam tunnels

30,000 lb/hr 200 psi, steam
- duct fired to 90,000 lb/hr

Water injection, 42 ppm

Full Fuel Cycle Emissions

Fuel Production

Fuel Processing

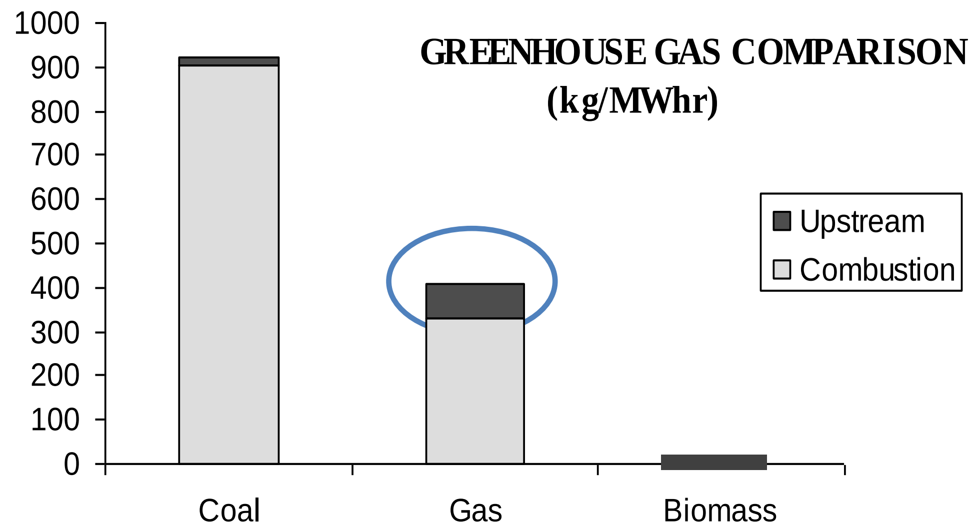
Fuel Delivery

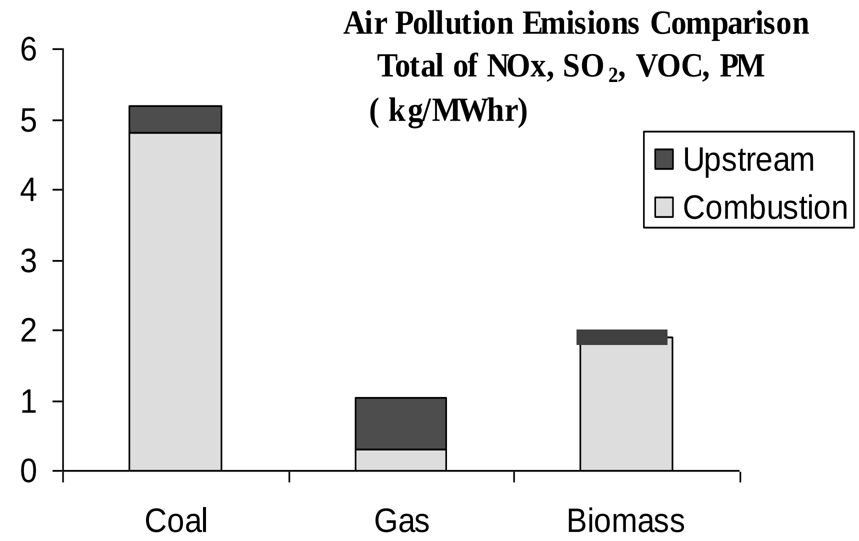
End Use Combustion

Air Emissions:

CH_4 CO_2 N_2O

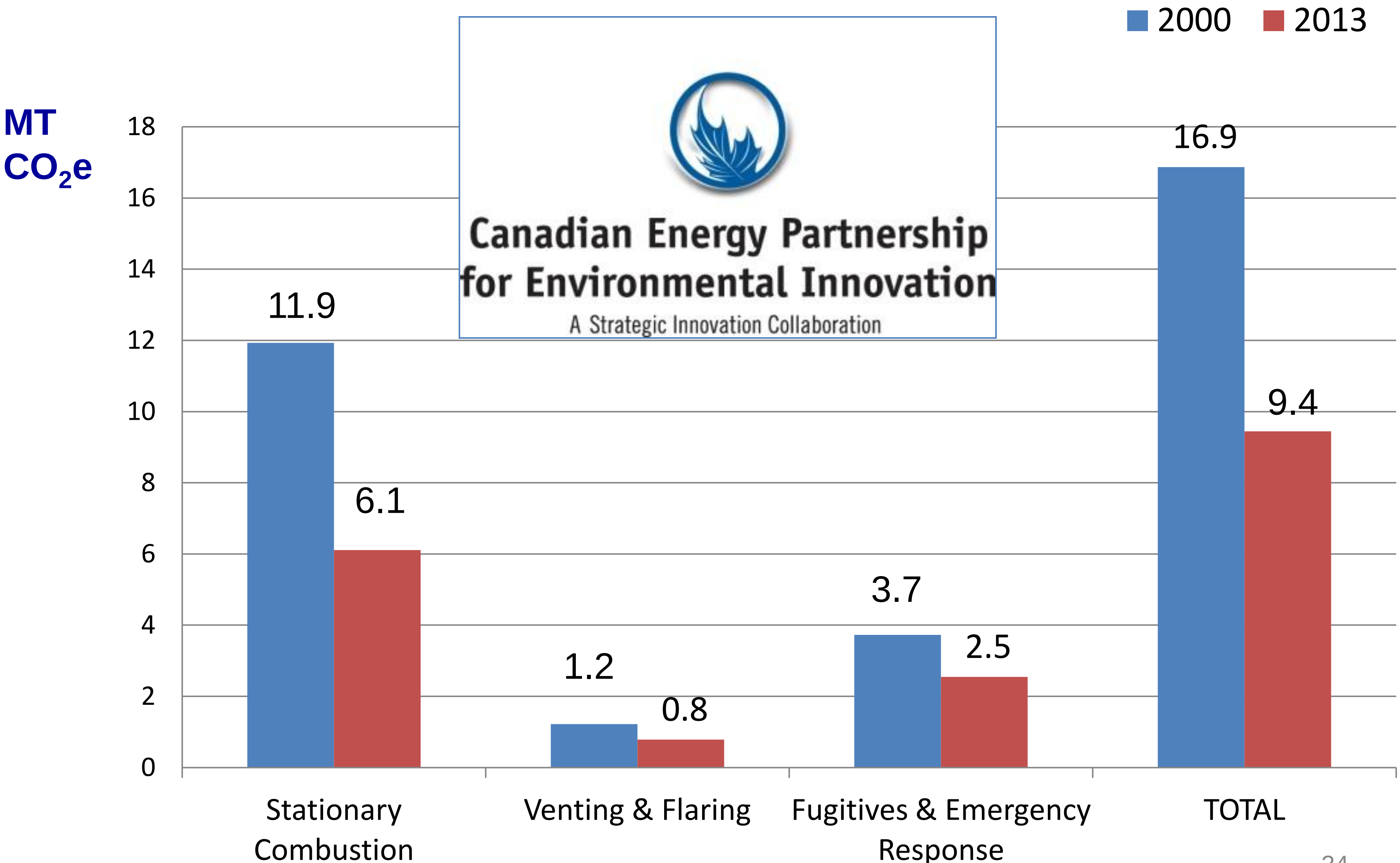
SO_2 NOx PM VOC





M.Klein, 1999

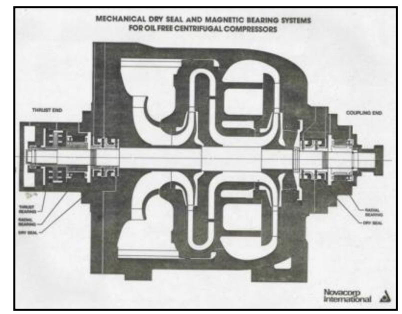
Pipeline Sector GHG Emissions (2000–2013)



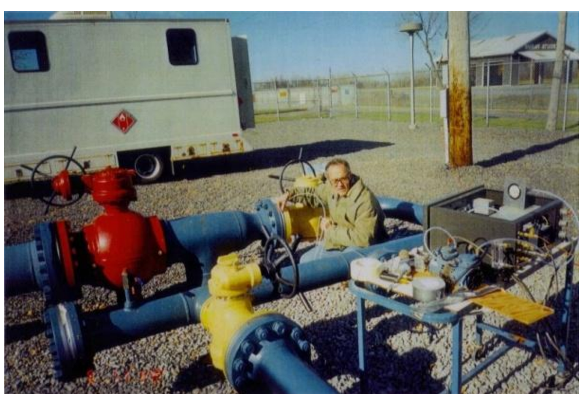
Env’tl Solutions for Gas Pipeline Compression

- High Operating Pressure (lowΔP)
- 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

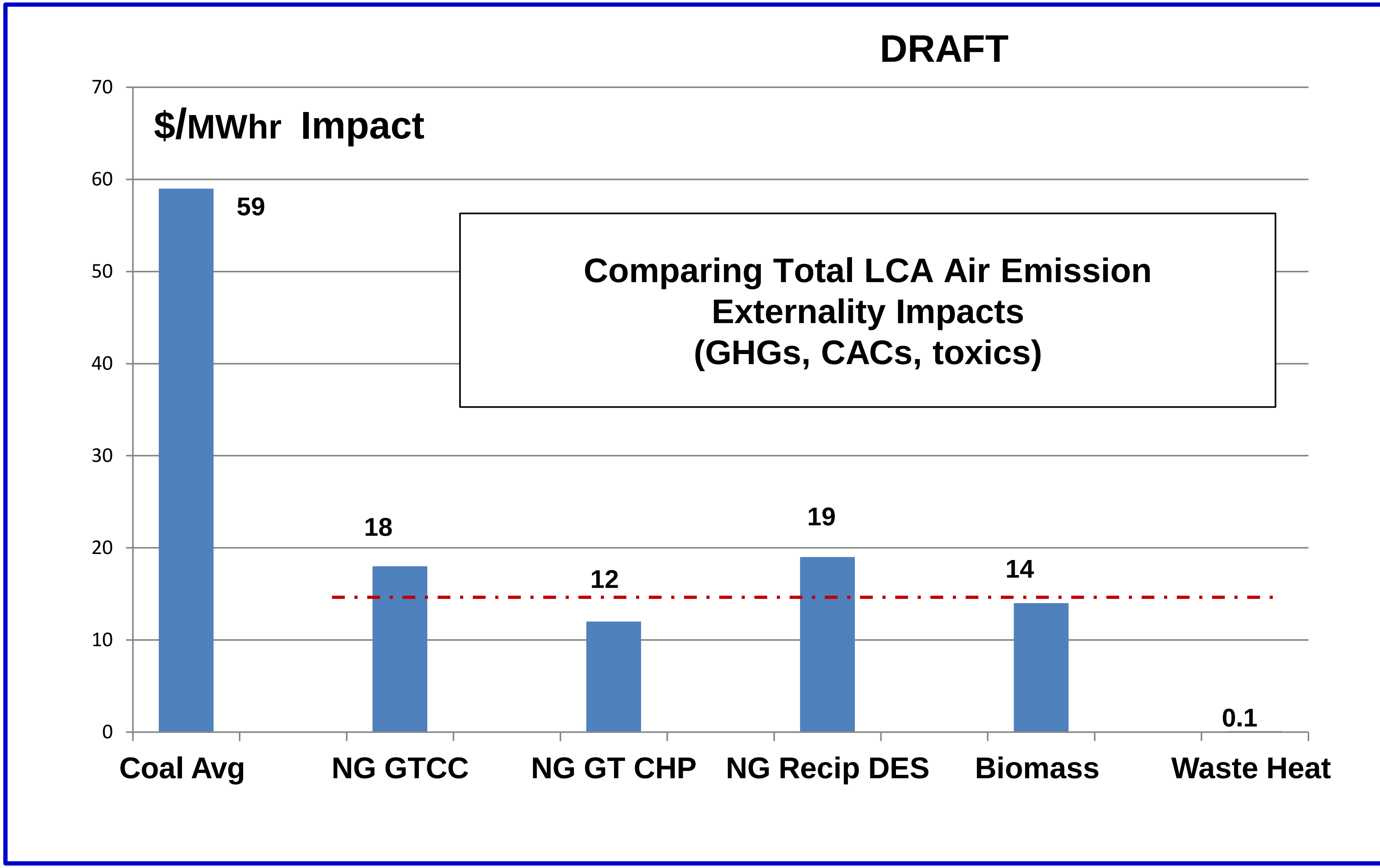


Gas Compressor Dry Gas Seals




Crowsnest ORC


Aerial coolers, Crowsnest BC

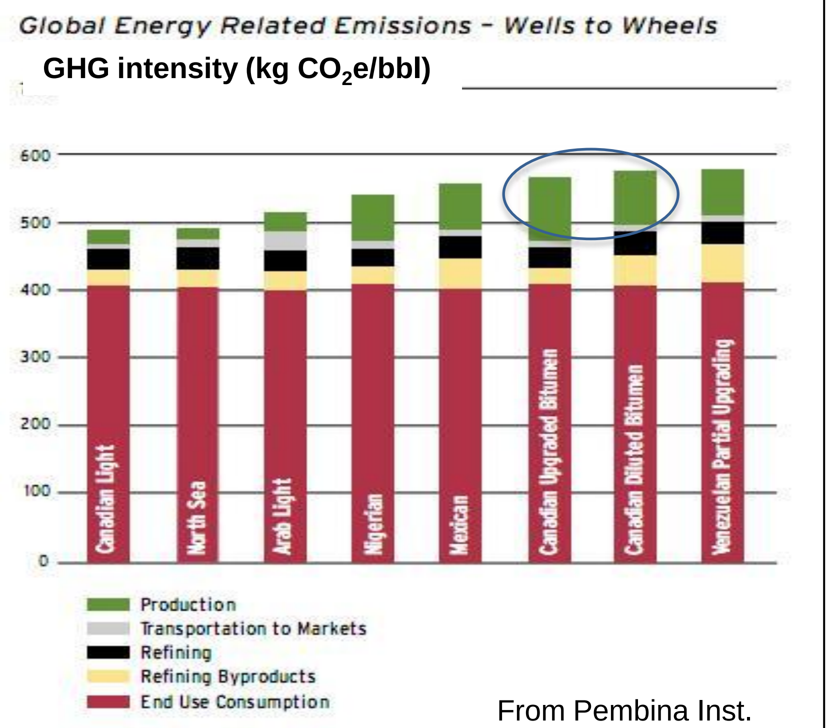


Life Cycle Analysis; Evaluating projects with low combined values (costs);

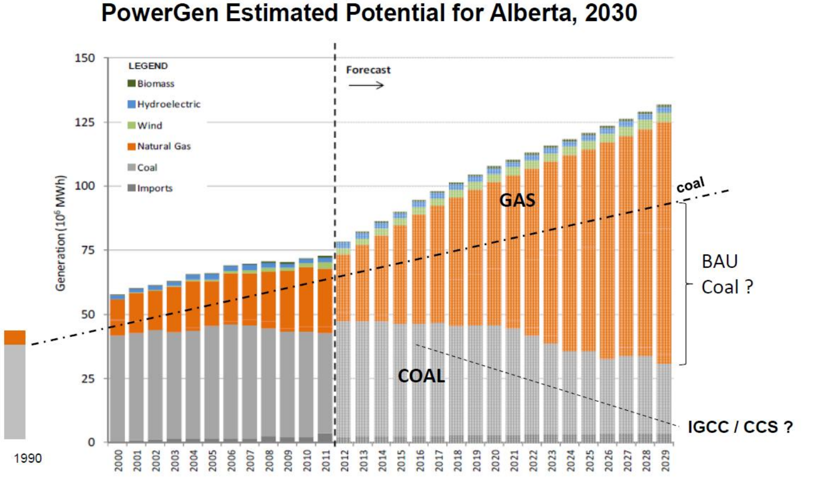
- CO_2 **$30** / tonne, NOx/SO_2 **$3000** / tonne
- particulates at **$5000** / tonne air toxics at **$0.5 million** / tonne

A Strategy to Reduce the CO_2 Footprint of Alberta SAGD Oil Sands Recovery

Layzell and Klein, Sept 2015



From Pembina Inst.



Gas-fueled CHP & GTCC systems with new 70 TWhrs could avoid 30 Mt/yr of GHGs & 400 kT/yr of air pollution

Adapted from (from AESO, 2012)

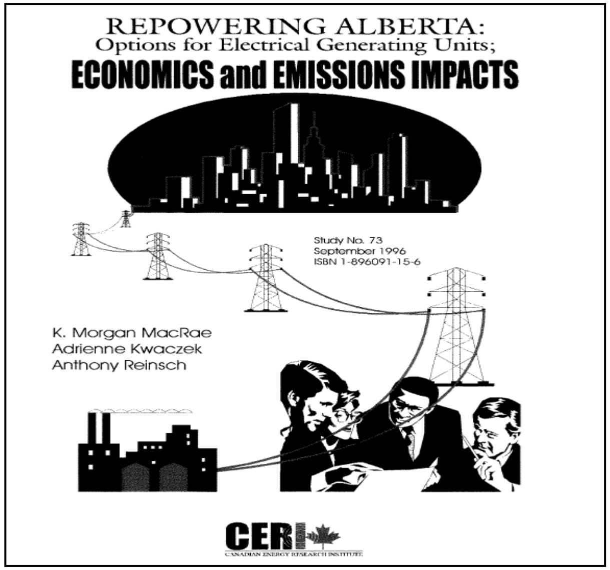
Water Conservation, Efficiency, and Productivity Plan – Electric Power Generation

Can Early Coal Retirement improve Oil Sands footprint ?

Some Things Done in Support of NG & CHP (1990-2005)

CERI / EnvCan Economic Studies

- *Alberta Repowering, Sept 1996*
- *Natural Gas Utilization for Nova Scotia Power Generation, Oct 1997*



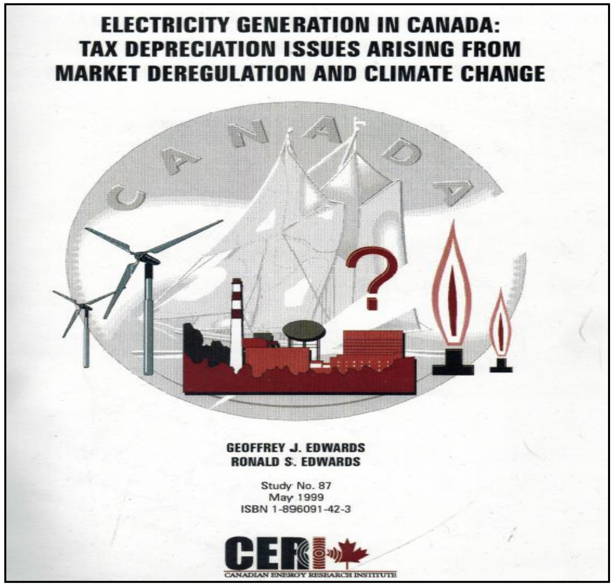
Accelerated Capital Cost Allowance

- Federal budget changes;

2000 – Class 1; from 4% to 8%,
15% for gas turbines

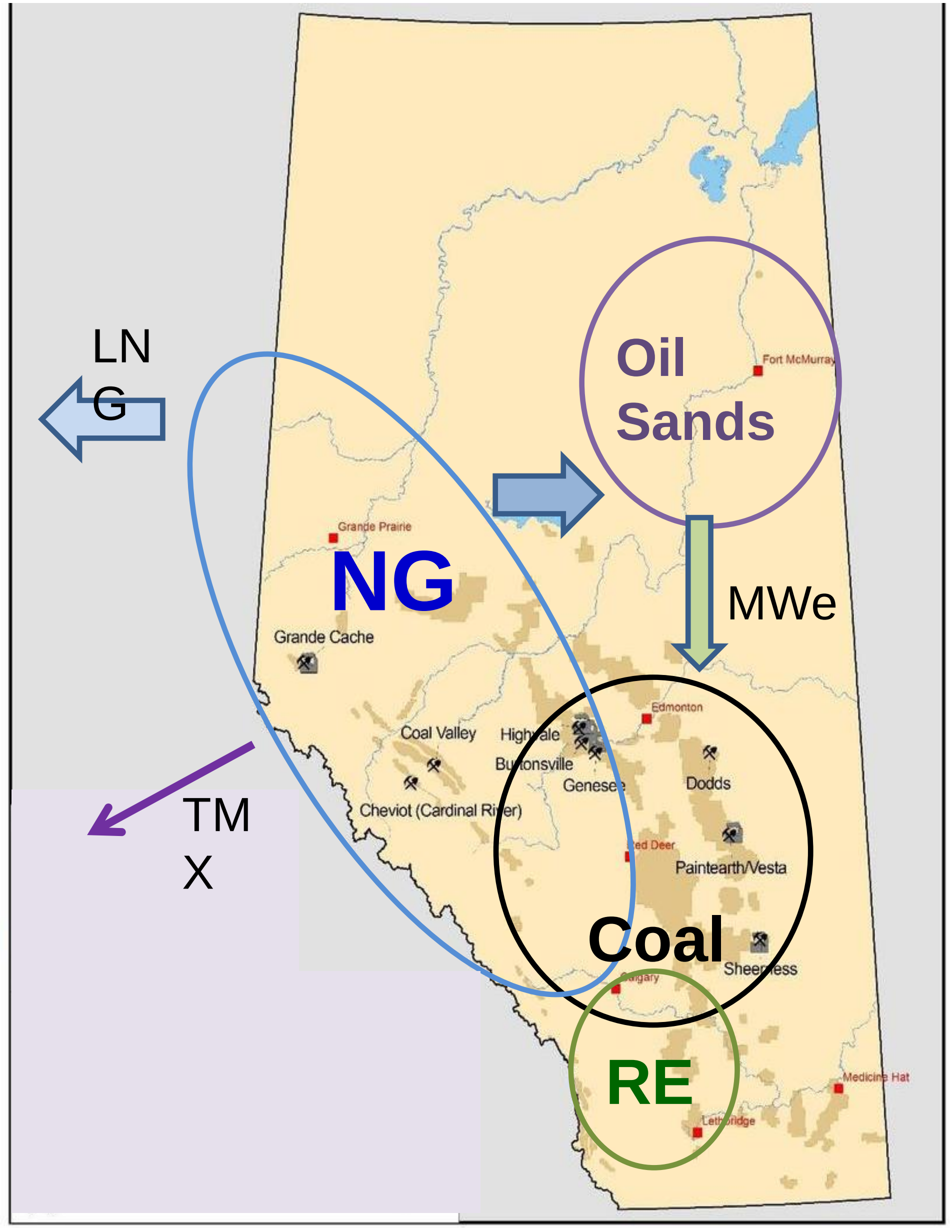
2005 - Class 43.2

- **new 50% ACCA rate (> 72% eff'y)**
- **District Energy piping included**



Western Energy Challenges

- Coal boiler phaseout by 2030
- Natural Gas into inefficient coal boilers
  - High lifecycle emissions ?
- Oil sands GHGs, and BC resistance to TMX oil expansion
- Federal Clean Fuel Standard
- LNG Exports to Asia ?



Improved System Synergies

More NG cogen & CHP in oil sands, refineries and petrochemicals, and cities

Export byproduct power to the AB grid

Lower lifecycle Air Emissions profile for oil, gas and power sectors

Integrated solutions for benefits across West Canada + renewable energy

LNG System Environmental Performance

Process Efficiency

- Liquefaction design choices
- Feed conditions, Precooling methods
- Compressor speeds, Axial Inlet
- Variable Speed Electric Drives
- TurboExpanders, Abs.Chillers
- Flaring reduction, use BOG fuel

Fuel Efficiency

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

"Cleanest LNG" ?

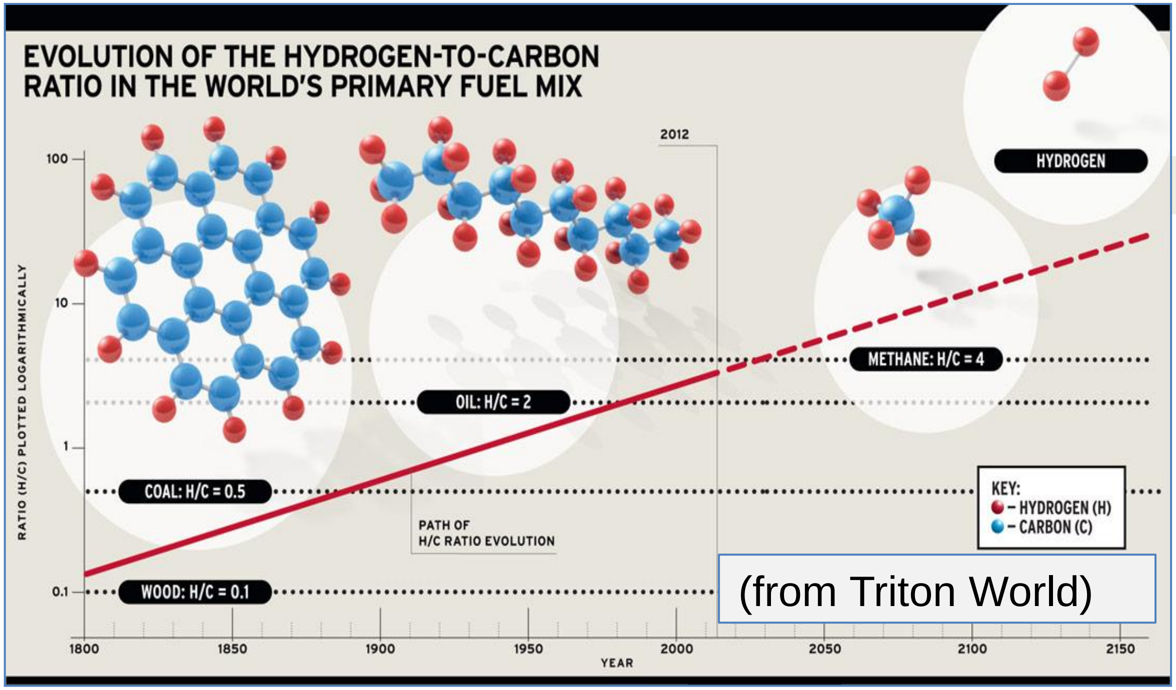
$<$ 0.2 t_{CO2} per t_{LNG}

- other impacts

- End use benefits

Concluding Remarks

- *A gas turbine* is an *engine* in a system, *uses Clean Air for power*
- Maximize Energy Conservation, System Efficiency, Innovation
- Clean Energy: Gas Turbine Systems ⟷ Renewable Energy
- Combustor Reliability & Operating Range are a Challenge



(from Triton World)

- **Is there a Roadmap for H_2-based Natural Gas energy systems ?**