Gas Turbine Contributions
to Cleaner Energy Systems

October 2016, Montreal

Minimizing GHG and Air Pollution Emissions

- Gas Turbines for Cleaner Energy
- NOx and GHG Emission Standards
- Balancing Emission Prevention & System Efficiency
- Linkages to Renewable Energy

GT Cogen (GE)

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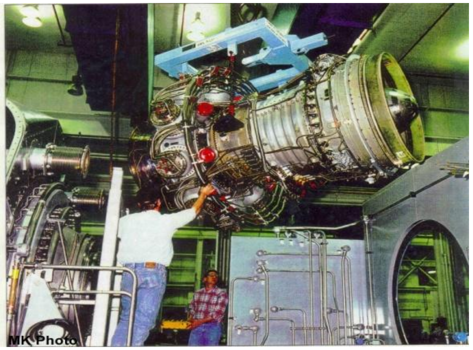
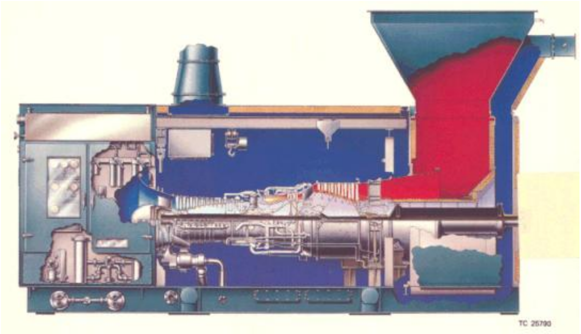


RB211 DLN

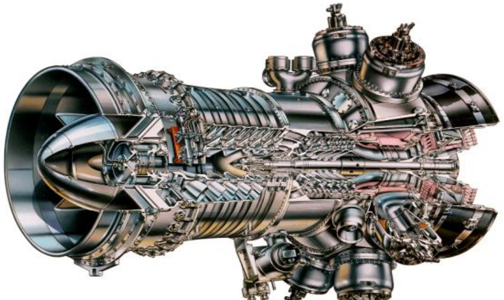
Many different types of units;

- Aeroderivative Gas Turbines
- Small & Large Industrial GTs
- Steam Turbines & HRSGs
- Microturbines

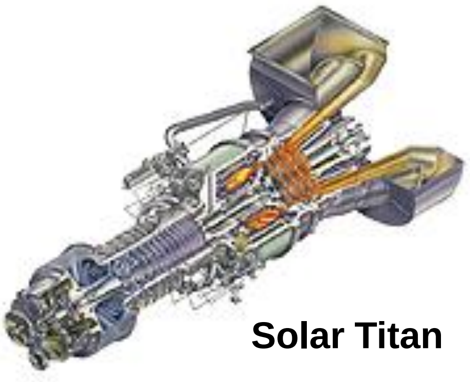
Capstone Microturbine



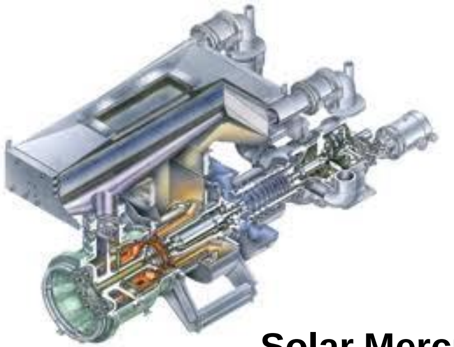
GE LM2500



RB211 DLE

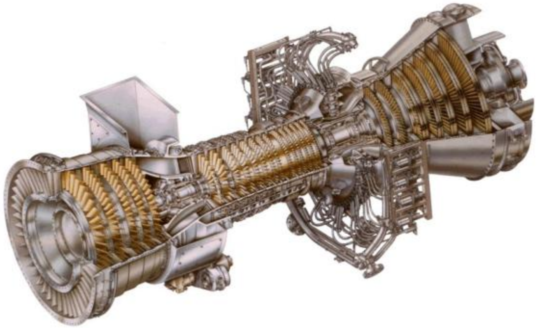


Solar Titan



Solar Mercury

IST OTSG



GE LM6000 DLE

GE Frame 7

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 27 000 MWe installed in Canada
(~ 470 plants, 1150 units)

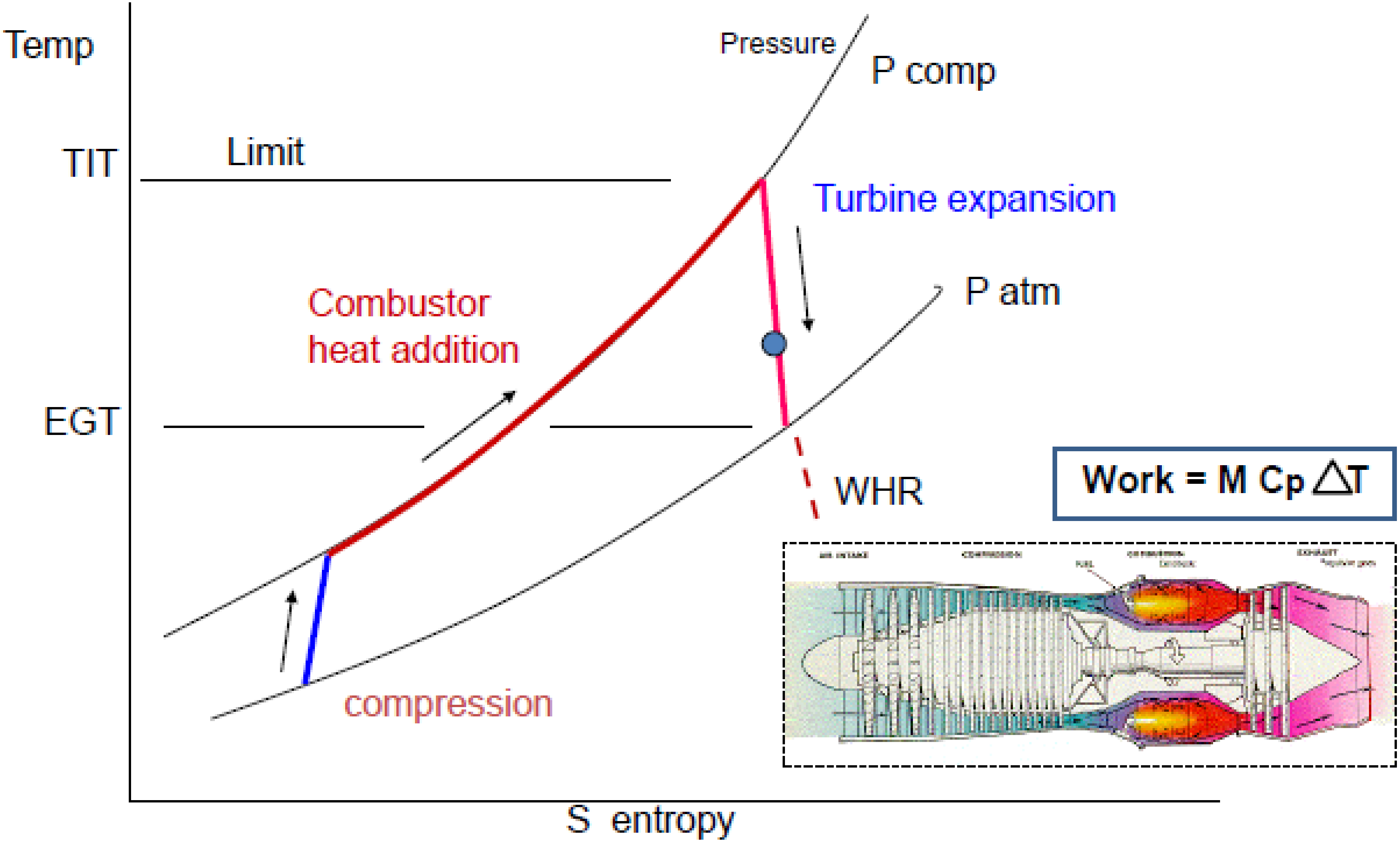
Gas Turbine Systems in Canadian Industrial Sectors

2015 estimate (M.Klein)

Installed MW	Simple Cycle	Combined Cycles	Comb. Cycle Cogen	Simple Cogen	Sector total
Electric Power	4640	8310			12950
Gas Pipelines	5170	140			5310
Upstream Gas	360		120	380	860
Oilsands & Refineries	115		575	1860	2550
Chemicals, Forestry, Metals			3175	400	3575
Manufacturing	40		1150	190	1380
Institutional			210	95	305
Est. Total	10325	8450	5230	2925	26930

- Not incl. retired units
- 22950 MW GTs, and 4000 MW of steam turbines

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)

Air Emissions

Air Pollution

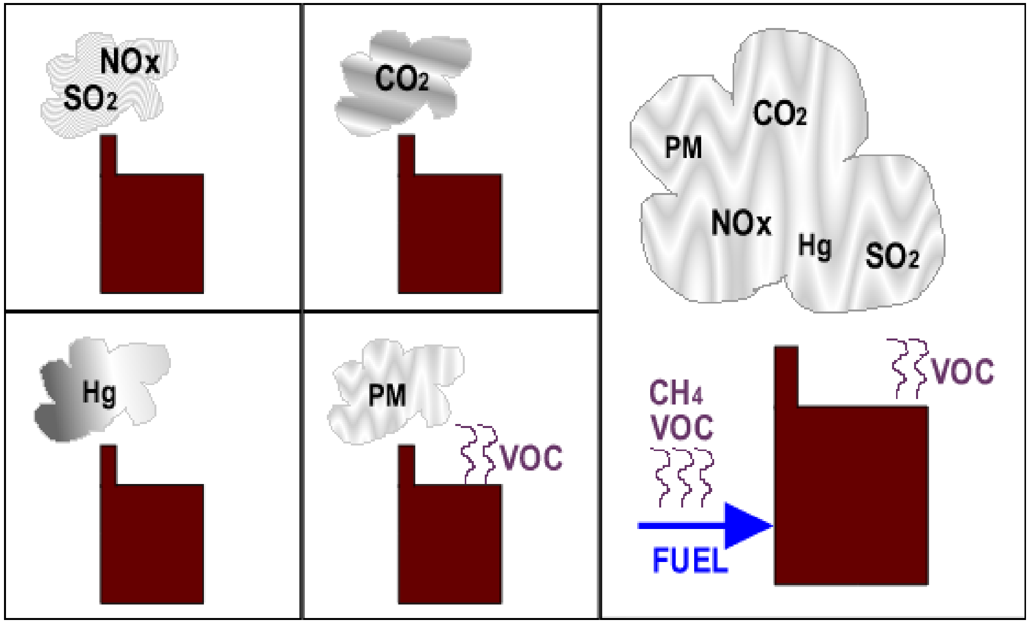
- Sulphur Dioxide SO_2
- **Nitrogen Oxides NO_2**
- Volatile Organics VOC
- Fine Particulates PM
- Mercury & Heavy Metals
- Ammonia NH_3
- Carbon Monoxide CO

Ozone Depletion

- CFCs

GHGs

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



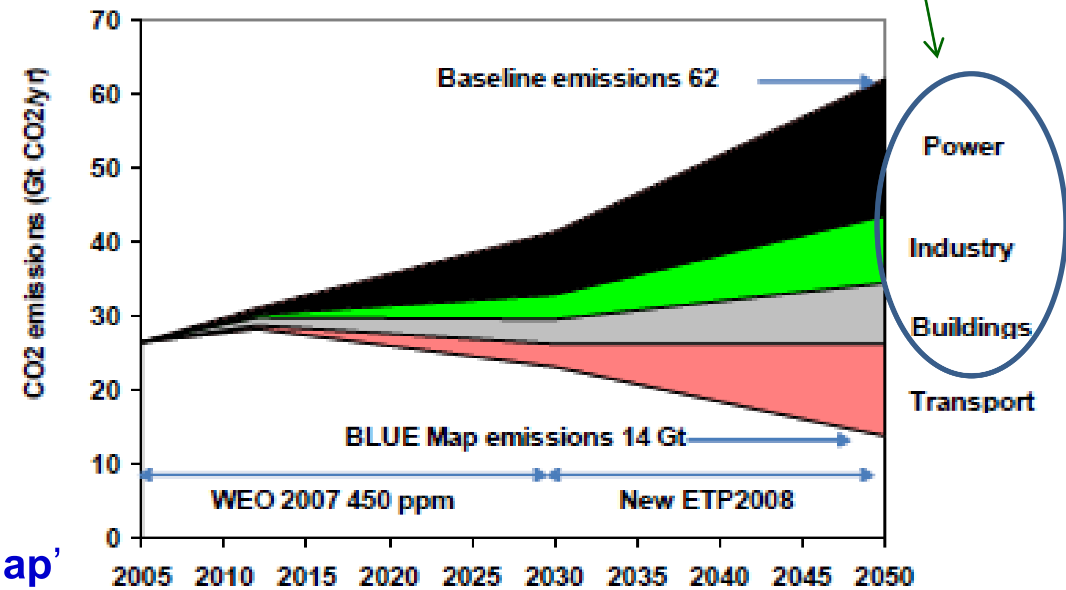
Individual .. or … System

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**
- **Coal & Bitumen Gasification, Polygen w/CCS**

GT systems can do 25-30% of these reductions

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



IEA WEO 'Blue Map'

Siemens Aero Gas Turbines

(Former Rolls Royce Energy)

Montreal manufacturing

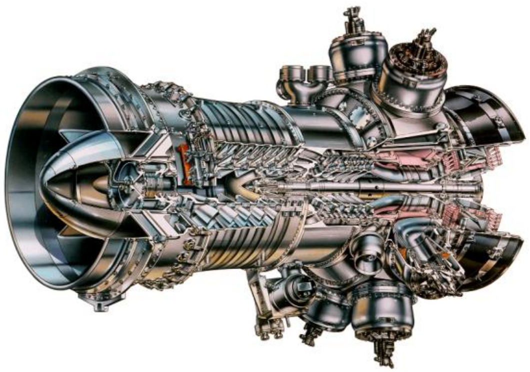
Facilities in Canada

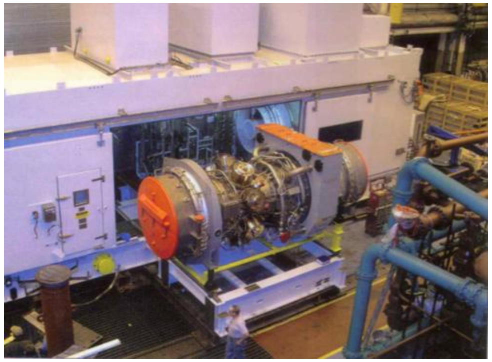
215 units, 3700 MW

- Peak and Standby Power
- Large Industrial Cogeneration
- Pipeline Compression
- Offshore Oil & Gas Energy
- w/ Waste Heat Recovery

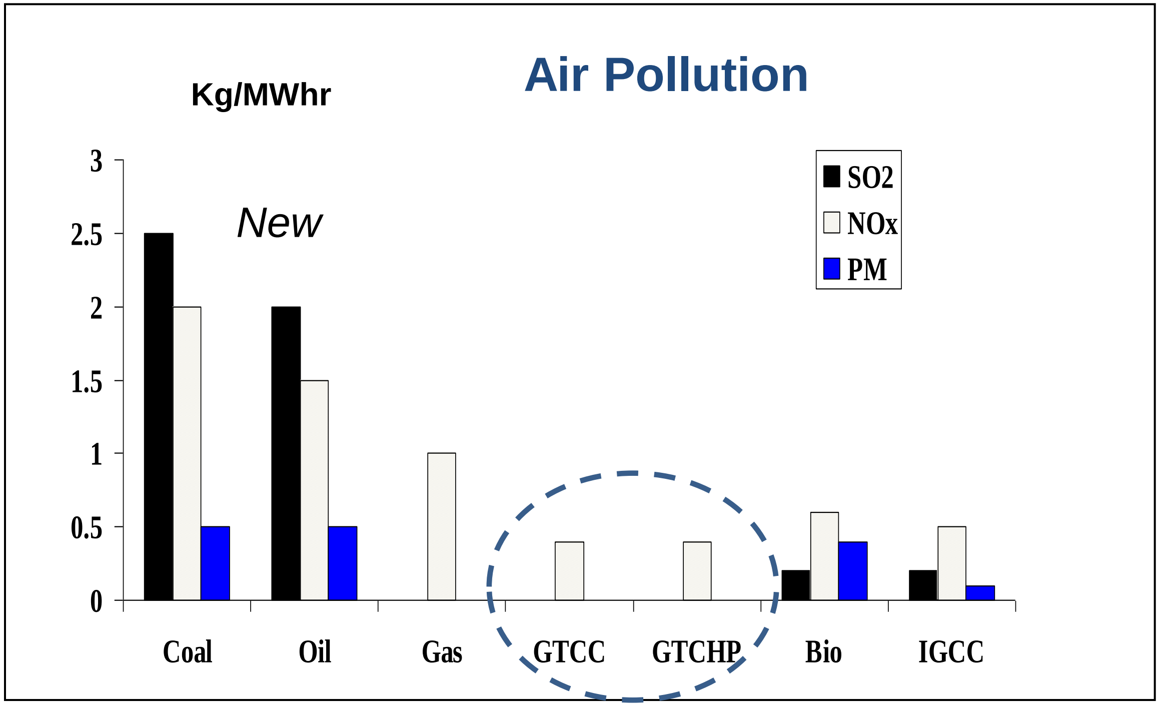
Gas Compression

(~ 80 RB211 units)

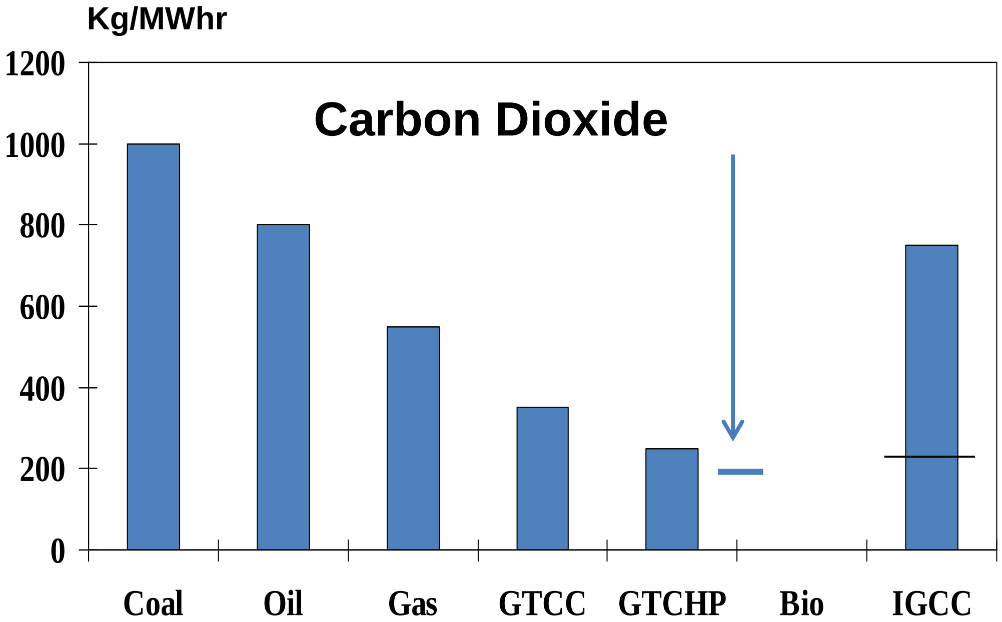




Comparison of Air Emissions from Various New Energy Generating Plants



Gas Turbine CHP plants have both Low CO_2 and Very Low Air Pollution



(Common Solutions)

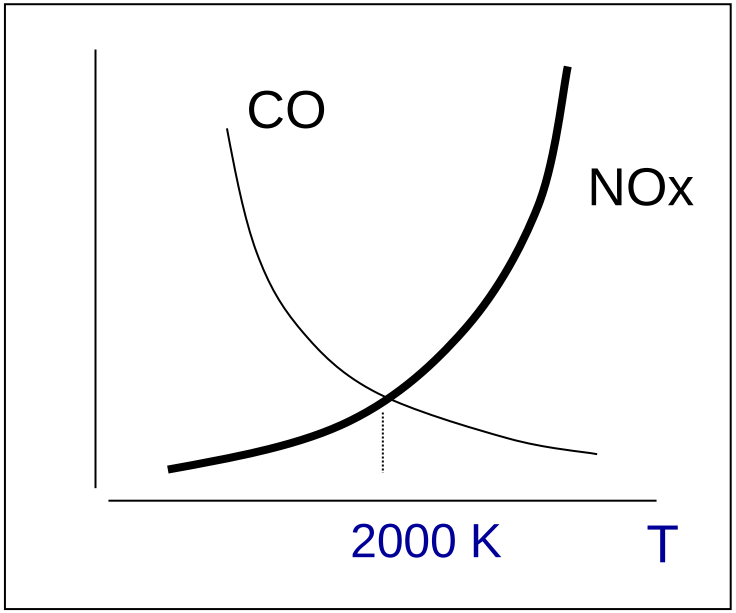
Air Pollution - *NOx Emissions*

$O + N_2 \longrightarrow NO + N$

$N + O_2 \longrightarrow NO + O$

3 Compounds of Concern:

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



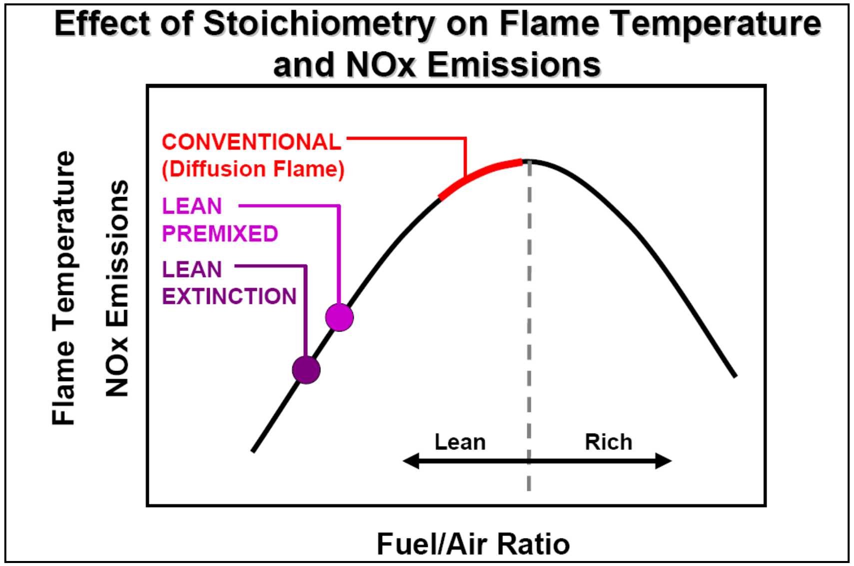
Thermal NOx:

High Temperature Combustion

Fuel NOx:

From N_2 Content of Oil, Coal

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

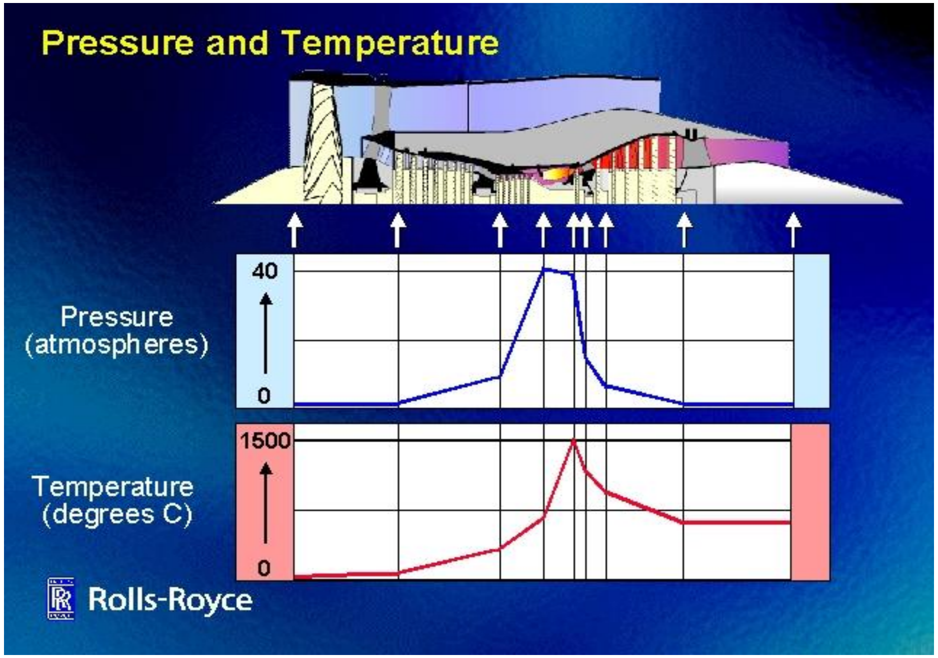


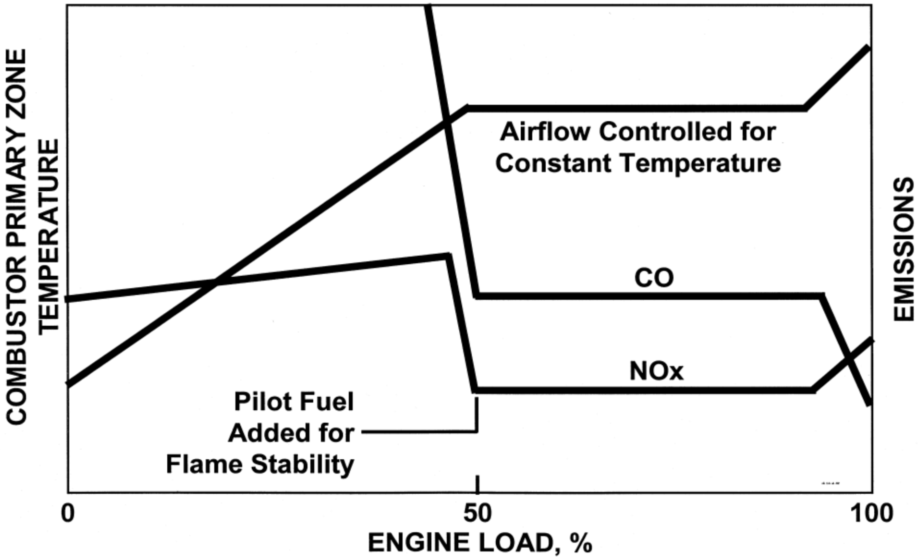
(Solar Turbines)

Emissions in Gas Turbine Engines

Factors Affecting NOx Emissions

- 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
- Ramp-up rates, Cycling
- Specific Power (kW, per lb/sec air)
- NOx Concentration vs Mass Flow



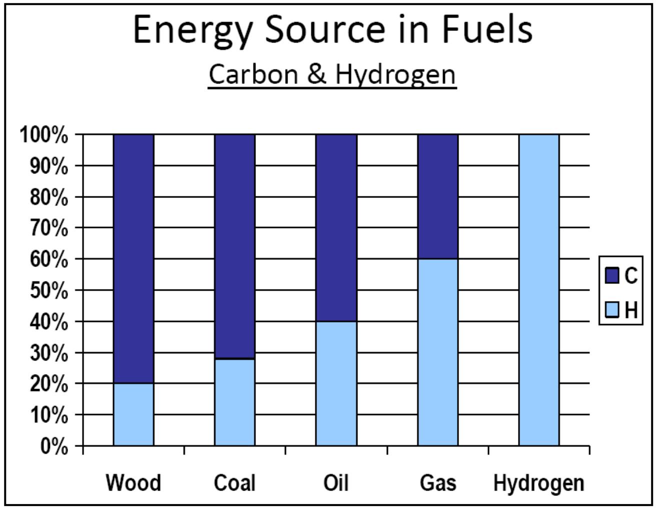


Fuel Combustion

$$C_xH_y + (x + y/4)\ O_2 = x\ CO_2 + y/2\ H_2O + \text{heat}$$

Energy Content	*BTU / lb*	*GJ / tonne*
Carbon	14 000	33
Hydrogen	61 000	142
Sulphur	4 000	9
CO	4 400	10

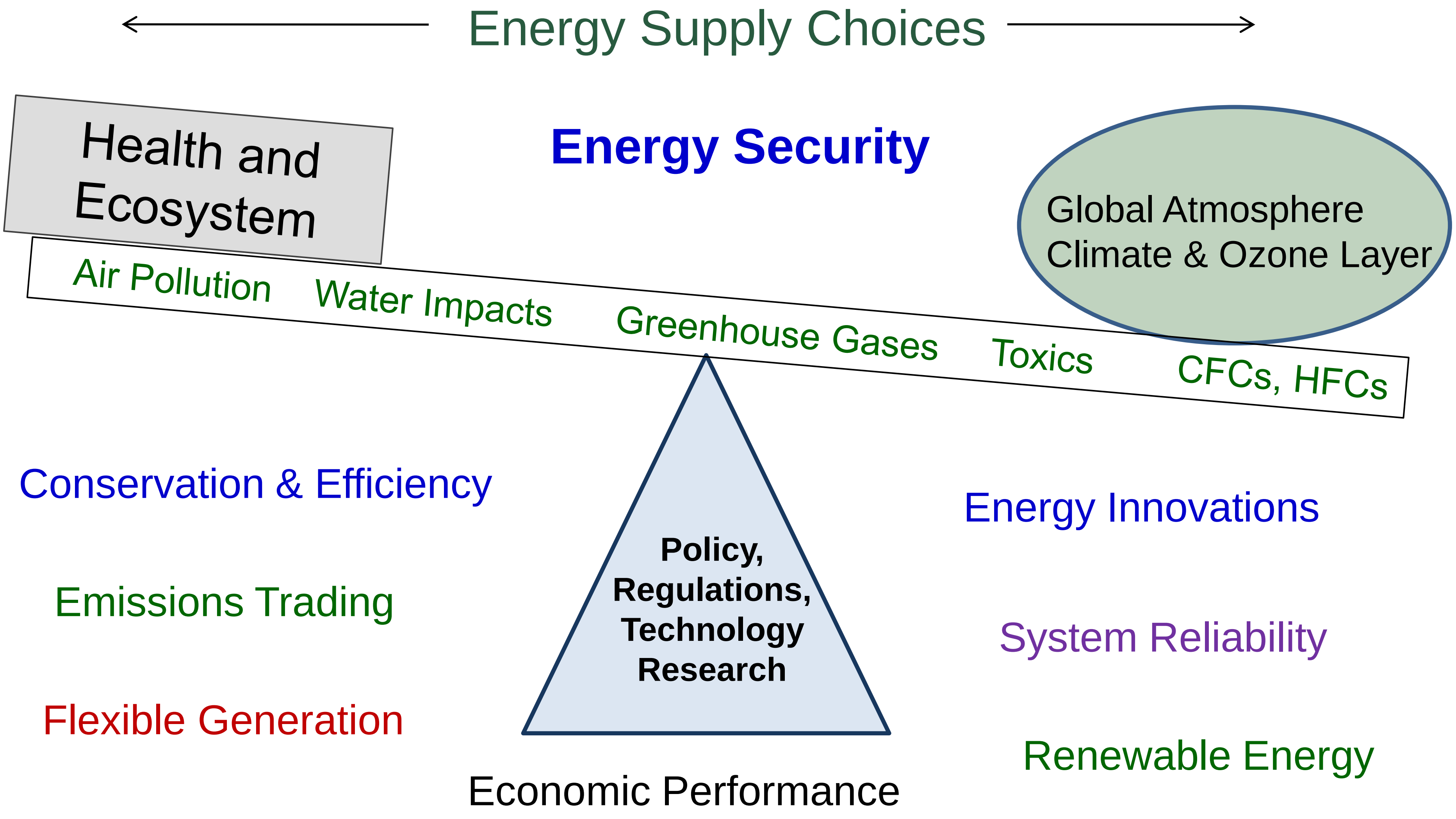
Coal ~ CH   Oil ~ CH_2 Nat. Gas CH_4



CO_2 Rate Examples (Heat Rate$_{HHV}$ x CO_2 factor)

Coal Boiler	10 GJ/MWhr x 90 kg$_{CO2}$/GJ	=	900 kg$_{CO2}$/MWhr
Gas Cogen	6 GJ/MWhr x 50 kg$_{CO2}$/GJ	=	300 kg$_{CO2}$/MWhr
Car	10 l /100km x 20000 km x 2.4 kg/l	=	4.8 t$_{CO2}$/yr

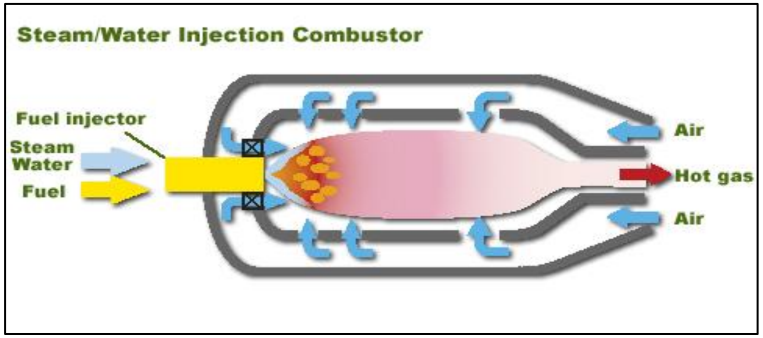
Clean Energy Balancing Act



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

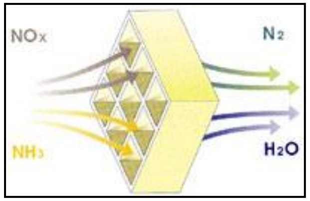


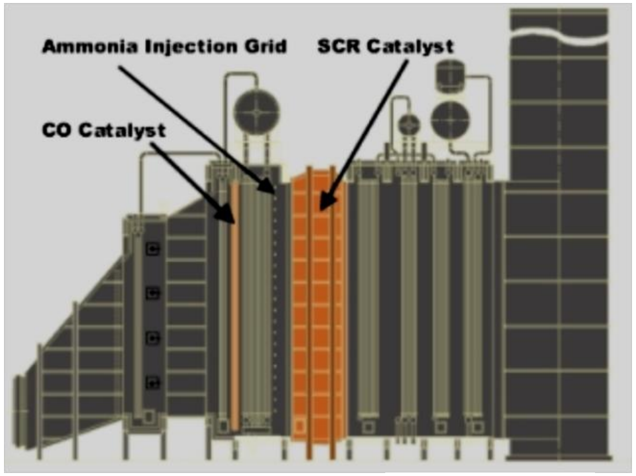
(Kawasaki)

Selective Catalytic Reduction (SCR)

- NH_3 injection in HRSG catalyst, ~ 80% NOx Red'n

- Backend Control
  - Ammonia emissions & handling (toxic)
  - transport risk, rail & truck
  - produces fine PM, N_2O ?
  - Cold Weather, Cycling duty - ammonia slip
  - Efficiency loss in HRSG … CO_2
  - Full Fuel Cycle impact – NH_3 Prod'n, Delivery



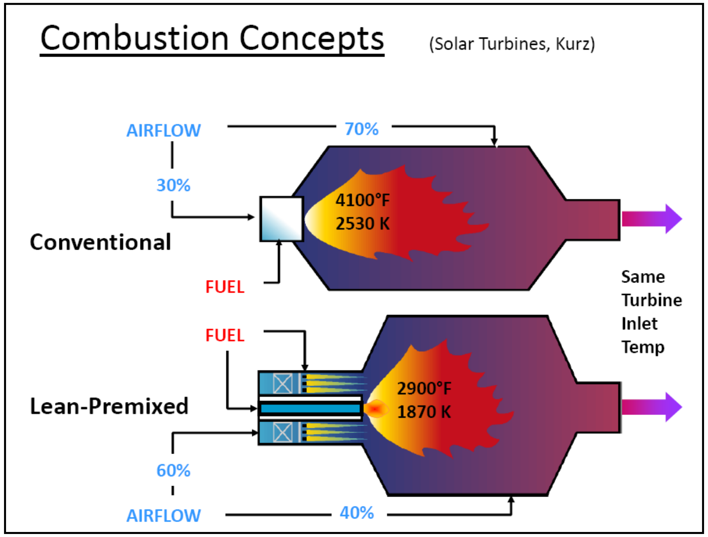


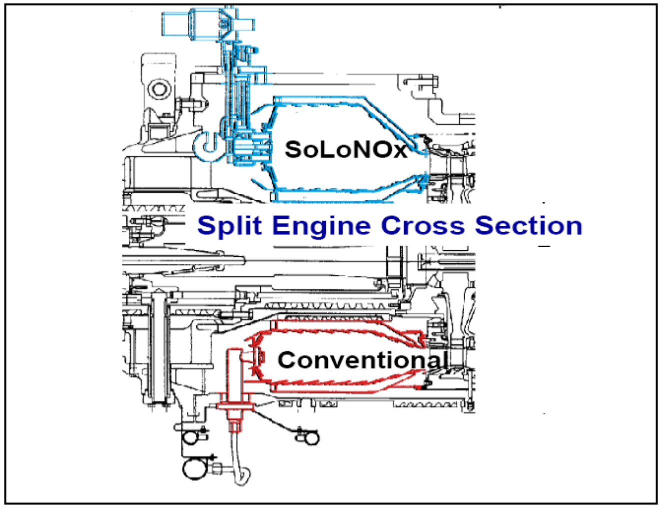
IST Aecon

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
- Applied to LNG fuel combustion

  (wider Wobbe range ?)





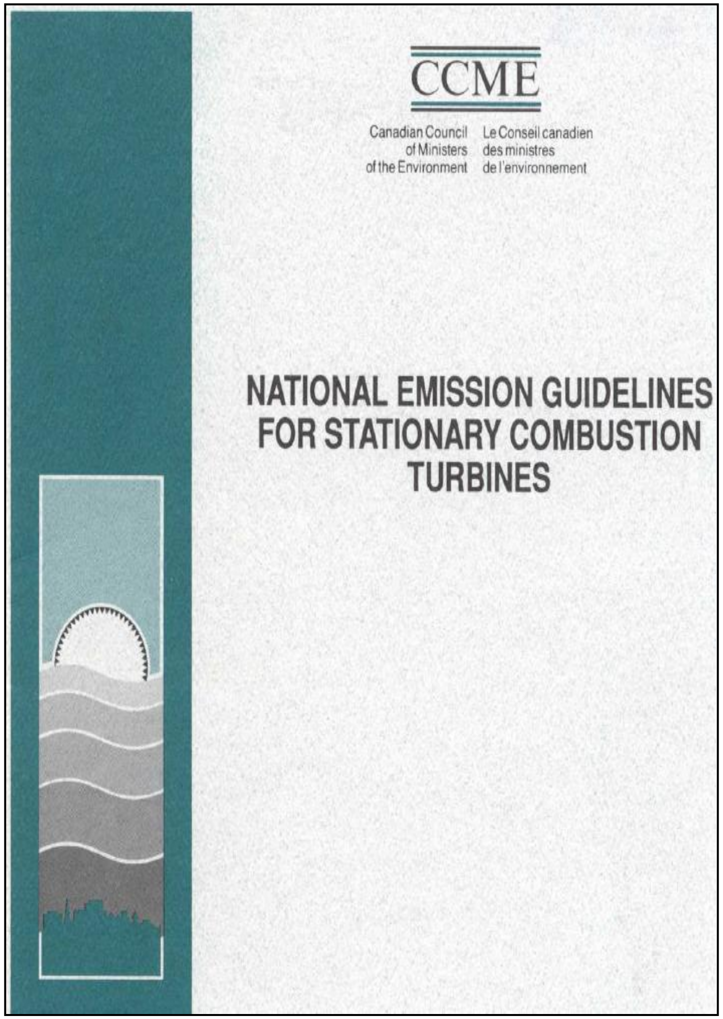
Solar SoLoNox

Canadian GT Emission Guidelines (1992)

- Guideline Reflects National Consensus
- Balanced NOx Prevention & Efficiency
- Regulatory Clarity

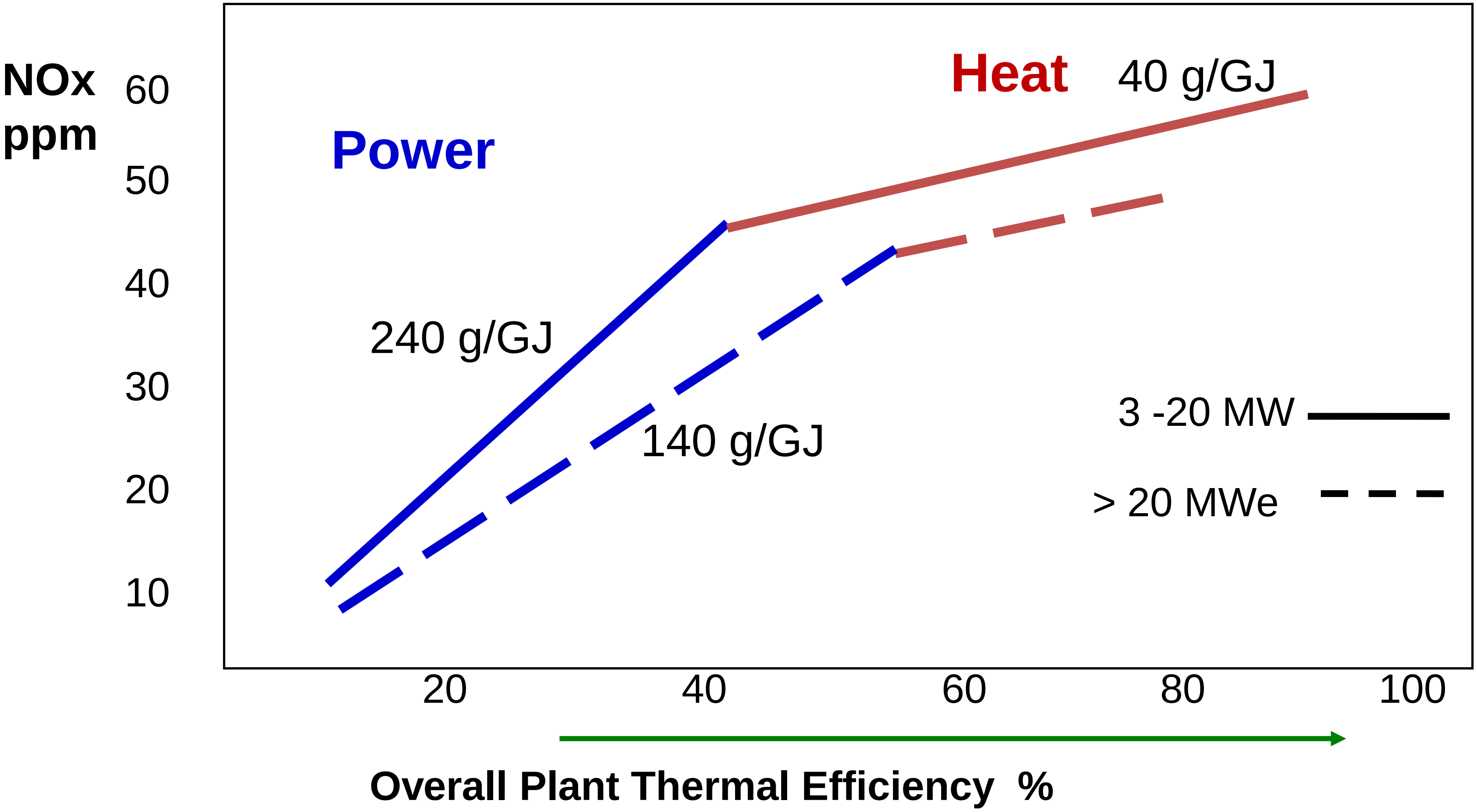
- Output-Based Standard for Efficiency
  (140 g/GJ_{out} Power + 40 g/GJ Heat)

- Engine Sizing Considerations
- Promotes WHR, Cogen, and low CO_2
- Peaking units (<1500 hrs/yr)
- Margin for operating flexibility
- Special applications exemptions
- Flexible Emissions Monitoring
- Energy Output reporting (?)



Canadian CCME Gas Turbine Emissions Guideline, 1992

Energy Output-based Standard (kg/MWhr), allows higher NOx for smaller units, which have higher system CHP efficiency (g/GJ x 3.6 GJ/MWhr)



Revised 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

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*

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

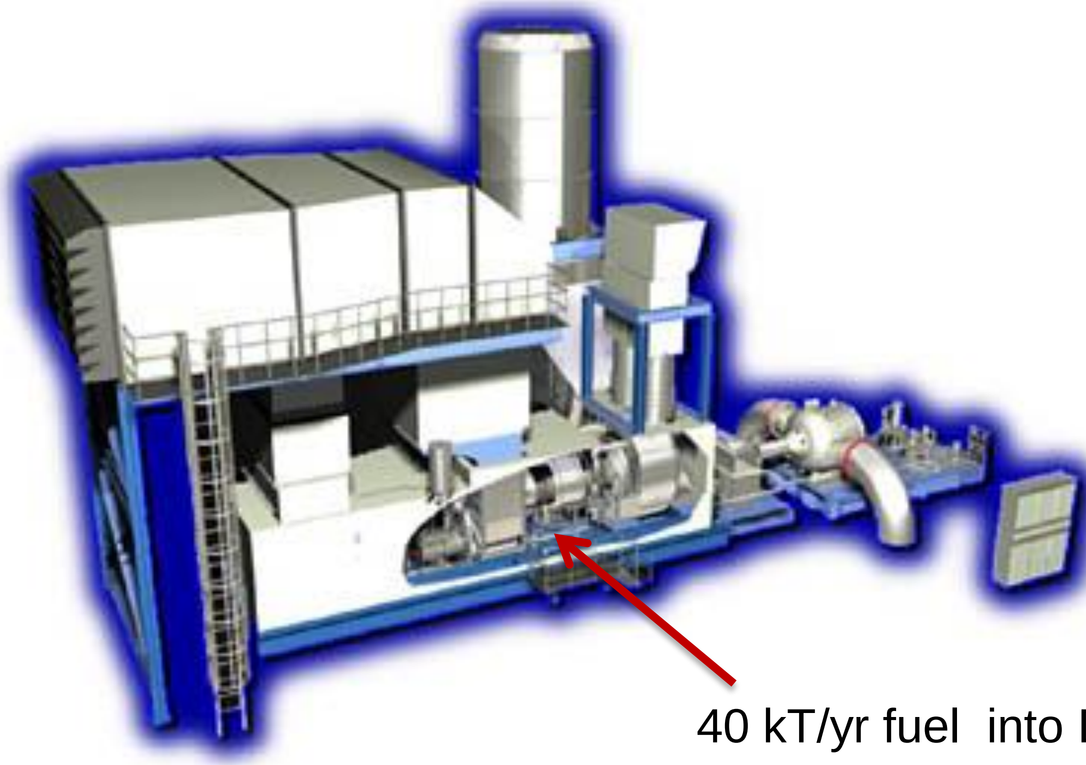
Environment Canada **December 2012**

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

(AP42 - 0.07 lb/MWhr ?)

?

2 million t/yr Air



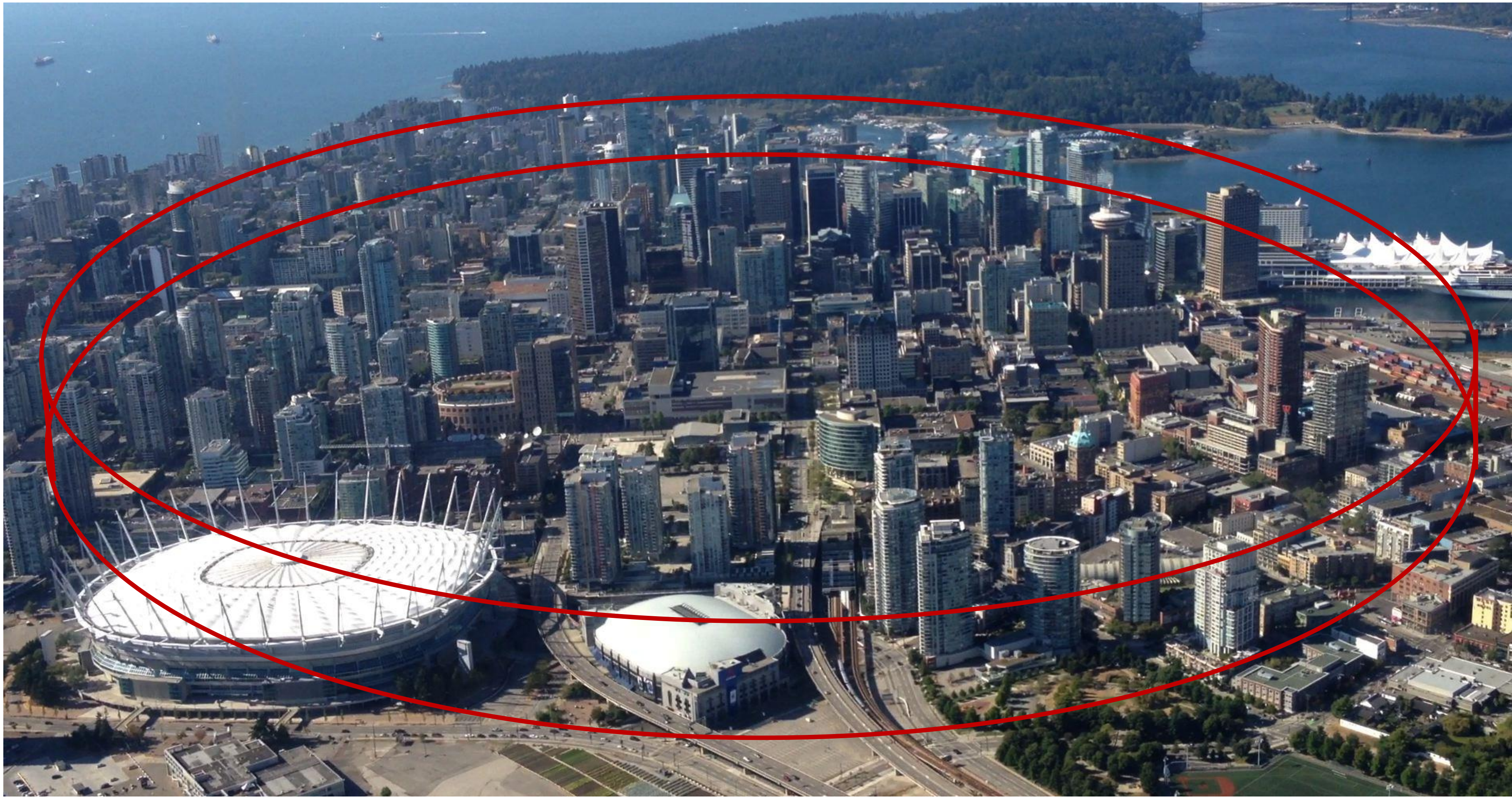
40 kT/yr fuel into DLE

Air Filter 99.8%

Does dry NG combustion produce fine PM emissions?

What is the Inlet-Exhaust mass balance ?

Are there any Air Toxics ?



<u>45 MW LM6000 gas turbine,   7000 hrs</u>

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 ?

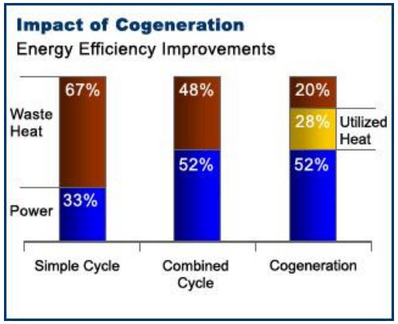
Critical Elements for Cogen (CHP) Systems

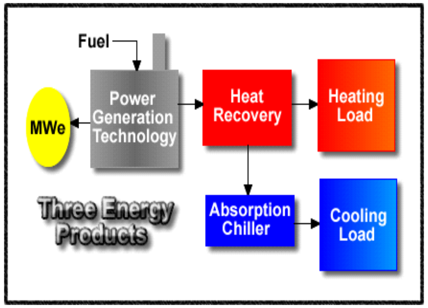
CHP - Producing 2-3 forms of energy from the same fuel, in same process

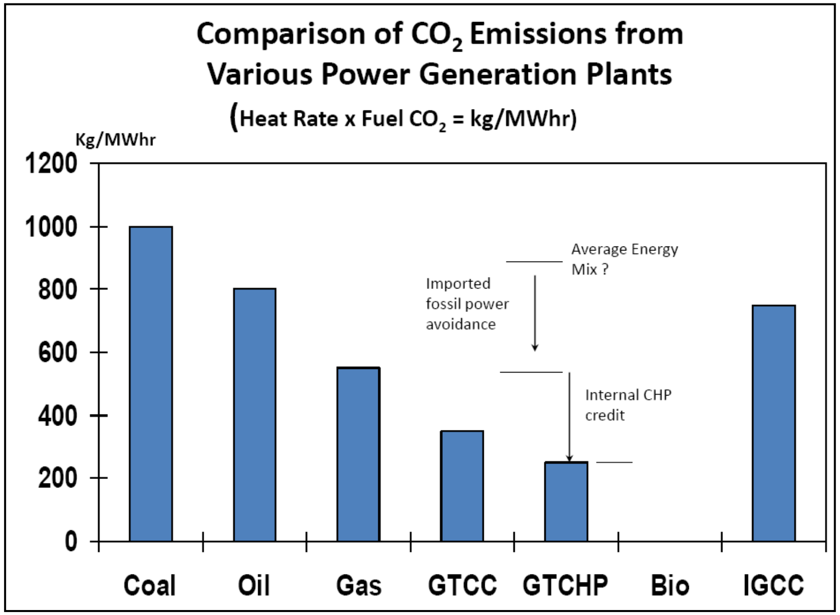
- **Awareness of Opportunities**
- **Site, Sizing to Match Thermal Load**
- **Seasonal Heat/Cooling Design**
- **Electrical Utility Interconnection**
- **Energy Quality, Heat:Power ratio**

- **Low Air Pollution, Local Impacts**
- **GHGs and Allocation**
- **Output-based Emission Rules**
- **Integrated Business Case**

(CHP more effective, than CCS for GTCC)







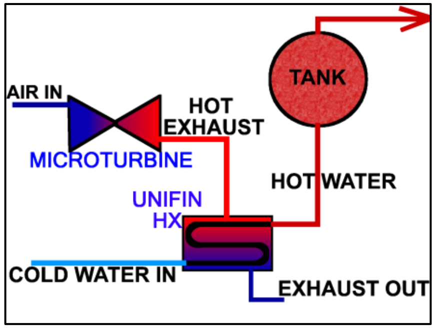
Objectives & Value Proposition for CHP & DES

Energy Reliability

Security, Resilience

Low Air Pollution

CFCs, Air Toxics



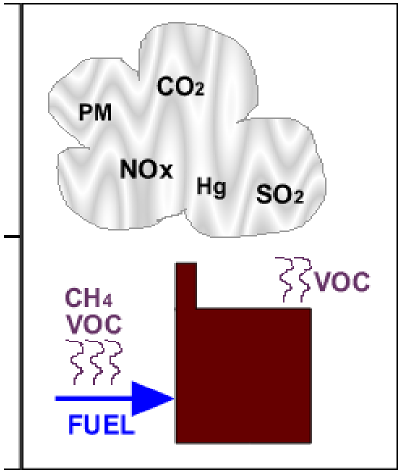
Avoid; Boiler Repairs

T&D Losses

Water Impacts

CO_2 and Methane

System Efficiency

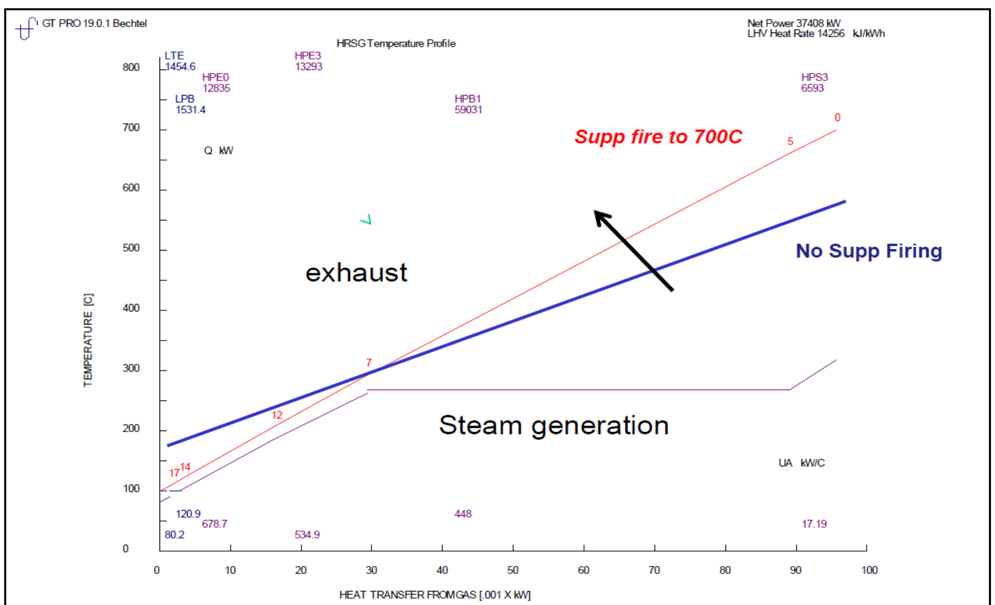


System

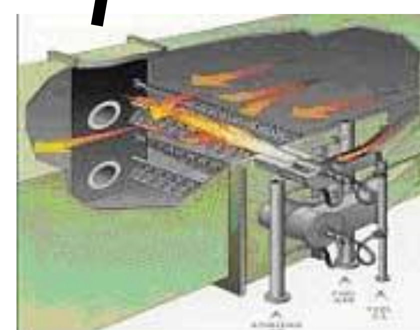
- **Cost-effective Investments, Innovation**
- **Multiple Quantifiable Long Term Benefits**

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

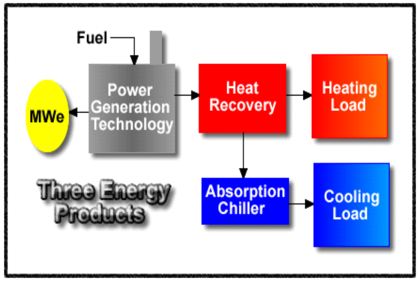


C. Meyer-Homji, Bechtel Corp.

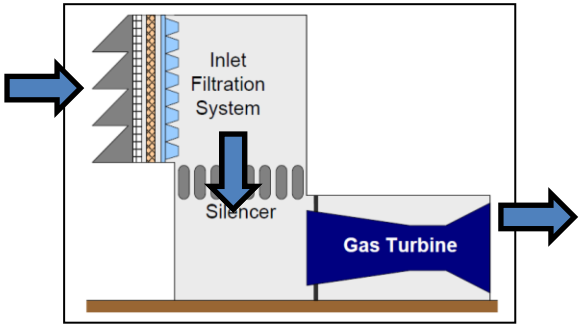


(Coen)

Air Emissions; System Synergies



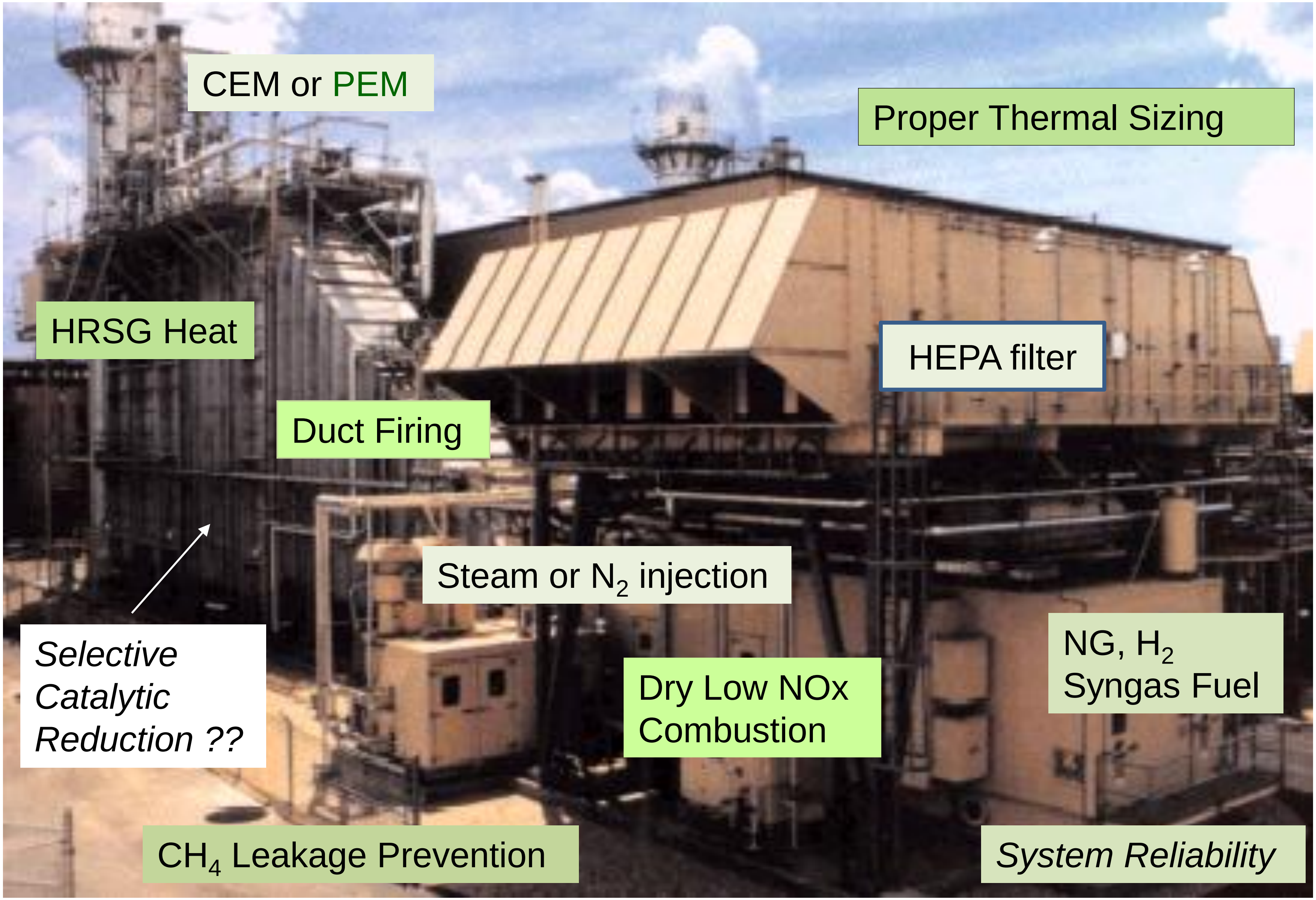
- CAC, toxic & CO_2 emissions must occur together;
  - NG has a good total profile
- All power generated from a ‘Heat’ system
- Small gas turbines, high CHP efficiency
- Renewable energies & integration of GTs
- GT power from Inlet Airflow ; reduce local PM



Air Emissions; System Tradeoffs

- High pressure Dry Low NOx combustors, Efficiency
- SCR systems and collateral impacts
- Pipeline upsets from unreliable DLN (CH_4 venting)
- Plant cycling affects efficiency & visible emissions

Gas Turbine Emission Prevention & Control (NOx, GHGs)



GE Power Systems

Maximizing System Output CHP Efficiency

Applications of Industrial Waste Heat Recovery

TransGas; 1 MWe project, Rosetown compressor unit
Pratt & Whitney's Turboden ORC system

Spruce Products sawmill, Swan River AB,
using GE 125 ORC, LP steam from wood waste.

Nechako Green Energy pellet mill, Vanderhoof, BC
Pratt & Whitney 2 MWe Turboden biomass WHR

West Fraser, Chetwynd Forest system biomass plant,
P&W two Turboden 65 ORC gensets

TransCanada Pipeline; Crowsnest BC ORC Waste Heat (7 MW) Mistral/Kensington

Gas Turbines and Renewable Energy

Distributed Energy

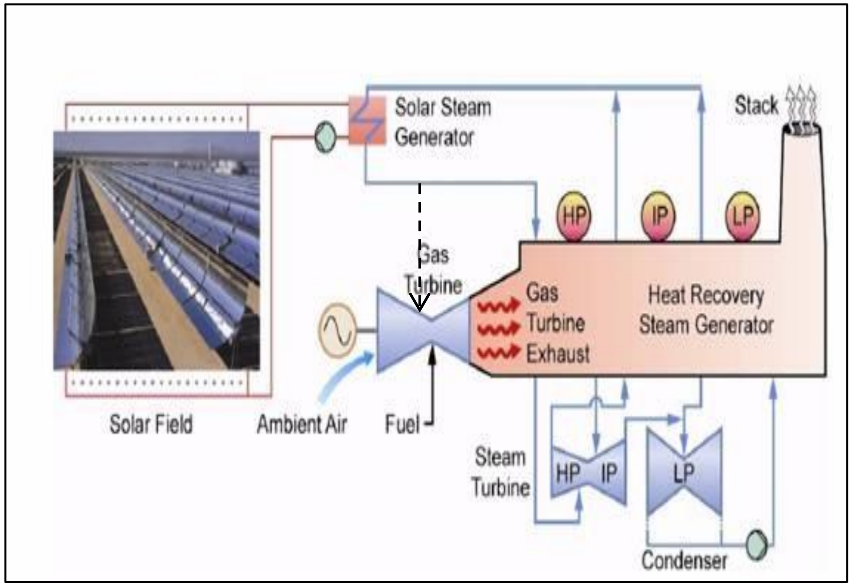
Diversity in Unit Size

Waste Heat Recovery, CHP

Fuel Flexibility

Fast Starts and Stops

Ramp Rates



Hybrid Solar Energy GT System

Examples of complementary system linkages for NG, GT & Renewable energy, in national policy and 'Smart Grid' solutions

1. Gas Turbine Backup for Renewables (Simple & combined cycle, flexible cogen)
2. District energy matched to solar thermal and geothermal
3. Waste Heat Recovery 'zero-emission' energy using steam or hot water
4. Organic Rankine Cycles, or Supercritical CO_2 WHR cycles
5. Pressure Energy Recovery with TurboExpanders
6. Biomass integration with GT combined cycles
7. Liquid bio-fuels for small gas turbines
8. Biomass gasification, with syngas fuels for gas turbines
9. Renewable Gas Fuel blending with Bio-gases
10. Hydrogen Co-Production with NG
11. Solar Energy Integration with Gas Turbines
12. Small Solar Devices on Gas Transmission Facilities
13. Compressed NG and Renewable/WHR Electricity into Hybrid vehicles
14. Compressed Air Energy Storage with Gas Turbines

Canadian ‘*Clean Energy Strategy*’

Opportunities for WHR and CHP

Promote Diversity and Conservation

Collaboration with Renewable Energy

National CHP and waste heat objectives, or Portfolio standards

H_2-based Natural Gas solutions

Recognize Ancillary Benefits

Help to develop a national cogeneration & WHR association (industries and cities, buildings)

Canadian Energy Strategy ?

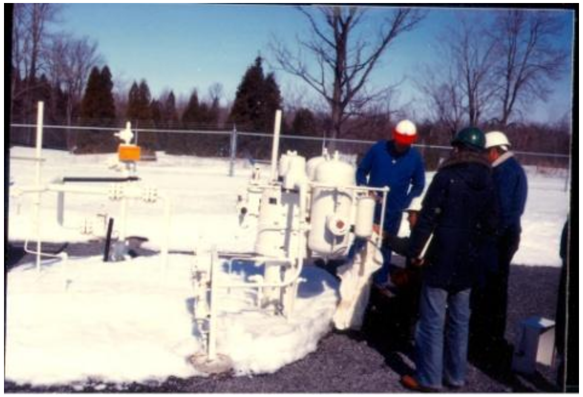
‘Smart Grid’ ?

Training and Outreach Opportunities

- **Canada-wide skills shortage**
- **Huge CAPex & OPex implications**

Technical Training & Plant Tours

- **Concepts, Examples, Rules of Thumb**
- **Energy systems, Emissions, O&M**
- **For scientists, engineers, analysts, economists, students - young and old**
- **Cost-effective investments**



- Consensus
- Policy Clarity
- Balanced solutions
- Cost-effectiveness