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Sixty Years of Clean Energy with Canadian Gas Turbine Applications

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Abstract

Industrial gas turbine systems fuelled by natural gas or synthetic gases have many attributes required by clean energy systems for thermal, electrical and mechanical energy with low air emissions. Canada has been a world leader in the development, manufacture, application and operations of both aircraft-derivative and industrial heavy duty gas turbine energy systems. These facilities have provided a diverse range of reliable and cleaner energy solutions using a flexible combination of fuels and high pressure airflow that provide reliable power and thermal energy. From initial western Canadian power installations in the late-1950's and the gas pipeline, peak power and naval ship applications in the 1960's, they have now been applied across many industrial and utility power systems.

The 1970's saw the increased the use of these systems, as they became larger and more fuel-efficient from developments in aircraft turbofan engines. New efficient simple cycle units now have higher air compression ratios and exhaust temperatures, and low emission combustors, to enhance efficiency and system power. Additional efficiencies beginning in the 1980's were realized by waste heat recovery in combined cycles, cogeneration and district heating.

This paper will summarize developments in R&D innovation, 'first-unit' applications and operations during those past six decades. Content is taken from extensive experience of the two authors, in technical development, education, many facility visits, government policy, regulation and research. New gas turbine-based systems will make contributions to cleaner choices around energy efficiency, reliability and resilience, as well as future hydrogen applications with renewable energy that can help to solve many objectives at once.

1.0 Basics of Gas Turbine Applications

Along with energy conservation and all types of renewable energy, gas turbine systems are an important source of Cleaner Energy production, with low air pollution and GHG emissions. Gas turbines are engines which use a steady inflow of a gas, mostly air, compressed and fired with gaseous or liquid fuel in a high pressure combustor *(note "gas turbine" is a general term regardless of fuel used*). As seen in Fig.1, this airflow is expanded through a turbine to generate output power for thrust in an aircraft engine, marine propulsion, or as shaft power for pipeline compression and electrical power production.

Gas turbine Brayton cycles are different than Rankine cycle steam turbines, as the turbine blades are directly driven by the pressurized combustion gases, rather than by a boiler's water-to-steam intermediate working fluid. Advancements that improve air compressor aerodynamics, low NOx emissions combustion, and turbine blade cooling have been instrumental in increasing power output, thermal efficiency and improved air emissions.

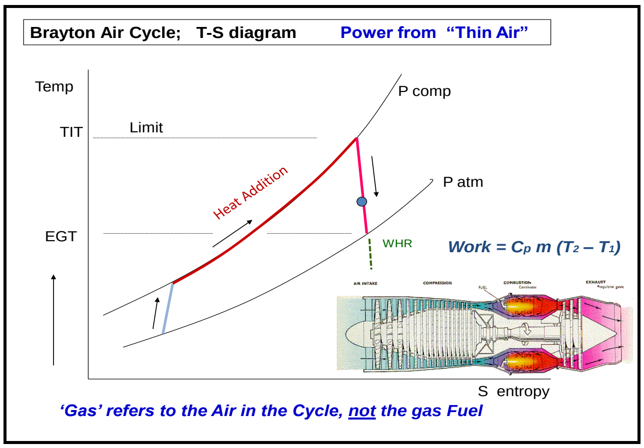


Figure 1. Basic Gas Turbine Cycle

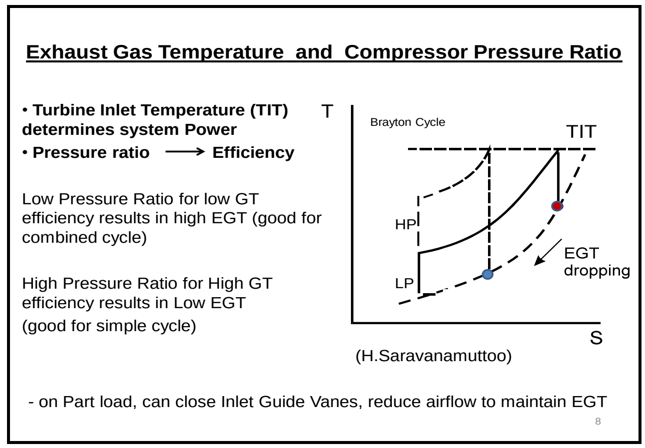


Figure 2. Importance of Air Compressor

There is considerable heat still available in the exhaust stream to provide energy for heat recovery steam generators (HRSGs) to drive steam turbines, and/or to produce thermal energy for heating and cooling purposes in industries and communities. However system efficiency will depend on the purpose of the plant, whether that is thermal heat or mechanical/electrical power. This is because exhaust heat is diminished with high air compressor pressure ratios (Fig 2), so very efficient GT units may need supplementary firing to increase HRSG performance. Some units may also use heat exchange for improving combustion efficiency through regeneration. Fast starting and ramp-up capabilities have advanced for many types, so that they are compatible in partnering with intermittent renewables.

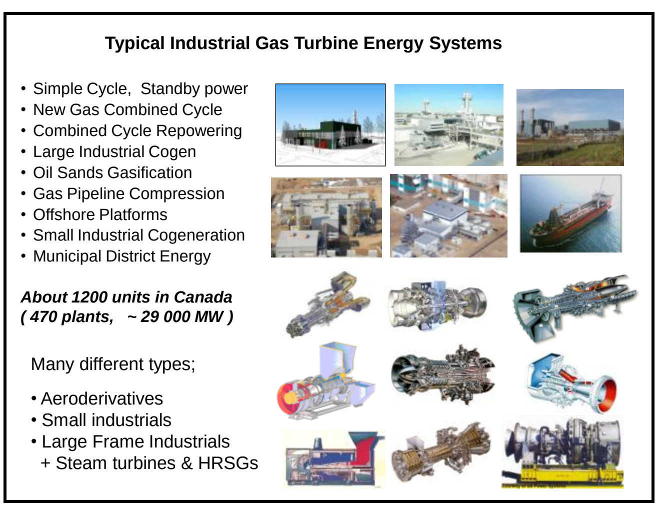


Fig. 3 Typical GT Applications

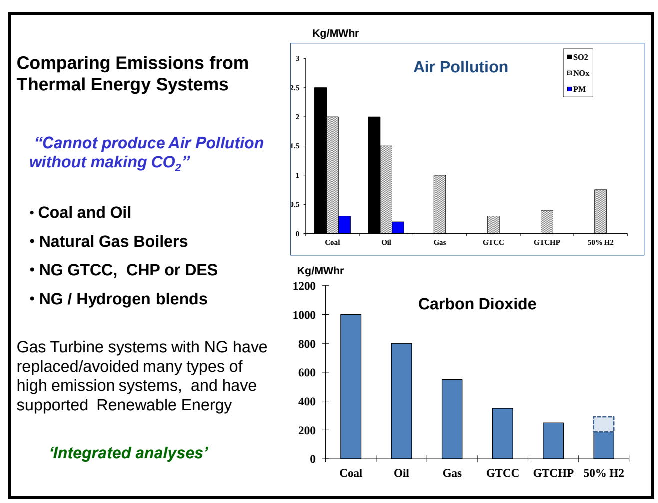


Fig. 4 Integrated Emissions Comparison

With respect to clean energy considerations, discussed more in Section 5, gas turbine systems with low NOx combustion, natural gas fuels, and various types of heat recovery for cogeneration and district energy, will have common solutions of low air pollutants, low GHG emissions and almost no air toxics when compared to coal power plants (Fig 4). Future hydrogen fuel blends will improve on these objectives (but NOx is challenging), and certain applications will enhance the performance of regional intermittent renewable energy systems.

There are about 1200 small and large gas turbine units in Canadian stationary applications, with over 29 000 MWe of aero-derivative and industrial frame systems in service by end of 2020 (Figs 3 & 18, mostly installed since 1995). Cogeneration and combined cycle systems have employed GT units across the full size range (1 to 250 MW), and represent a high growth potential in Canada, having already helped to avoid about 40 Mt/yr of CO_2 in the energy sectors. About 150 units provide 7000 MWe and 100 PJ/yr of thermal energy in cogeneration-related service, and about 440 units are also used for pipeline compression (5500 MW).

2.0 A Historical Review – Early Years; 1950's and 1960's

The mid-1950's saw the early beginnings of the Canadian gas turbine energy industry, both in power plants and in natural gas pipelines. Toronto had just completed the shift from coal burning to oil burning furnaces and natural gas was just starting to appear. Ontario Hydro had recently introduced the first thermal coal power plant, the Richard L Hearn facility, in the Toronto harbour area and it was producing 400 MWe with eventual growth to 1200 MWe. Toronto was in the final stages of converting from 25 to 60 Hz and it was interesting to move from the flickering 25 Hz lighting to 60 Hz, sometimes just by crossing the road.

Orenda, who were a well established presence in the aircraft gas turbine engine field, already had about 4,000 aircraft engines in service, powering both the F86 Sabre and the all-Canadian CF100 jets, and the Orenda was competitive with the British Avon and the US GE J47. All engineering at Orenda was focussed on development of the Iroquois engine for the Avro Arrow, with the exception of in-service support of existing engines. The Iroquois was an advanced engine, pioneering the use of titanium and was significantly lighter than competitors such as the Olympus or J75. At that time the jet engine and industrial gas turbines had little in common and there was no industrial gas turbine activity in Canada.

It was fully understood that to get a high efficiency gas turbine it required both a high pressure ratio and a high turbine inlet temperature, but these were limited to PR= 4-5 and TIT of 850^{o}C for military jet engines and 650^{o}C for industrial engines based on current developments in aerodynamics, metallurgy and manufacturing . Complex cycles were required to achieve high efficiency to deal with fuel conservation which was important during that time. So most initial energy utility applications were on heavy frame industrial units.

Brown Boveri was one of the pioneers in this field and developed the world's largest gas turbine with an output of 27 MWe and a maximum cycle temperature of 650^{o}C. With a pressure ratio of 18:1, this achieved a thermal efficiency of 30% but required 3 compressors, 2 turbines, 2 intercoolers, 2 combustors and two shaft lines each with their own starter.

Canada's first major gas turbine power plants were built with these units during the mid-1950's in the west. Four of these fairly complex intercooled systems were installed at the Port Mann station of British Columbia Electric Company (today BC Hydro) near Vancouver in 1958, where 100 MWe at that time was the largest GT power station in the world (Fig 5). The units would burn natural gas in summer and crude oil in winter in their single-burner HP and LP silo combustors, and could be at full power within 30 minutes. NOx emissions were minimized with water injection to reduce the visible brown plume. They were remotely controlled from headquarters with innovative directional radio links, electro-hydraulic controls and mechanical relays. An automatic clutch system permitted fast power dispatch from a synchronous condenser mode of operation.

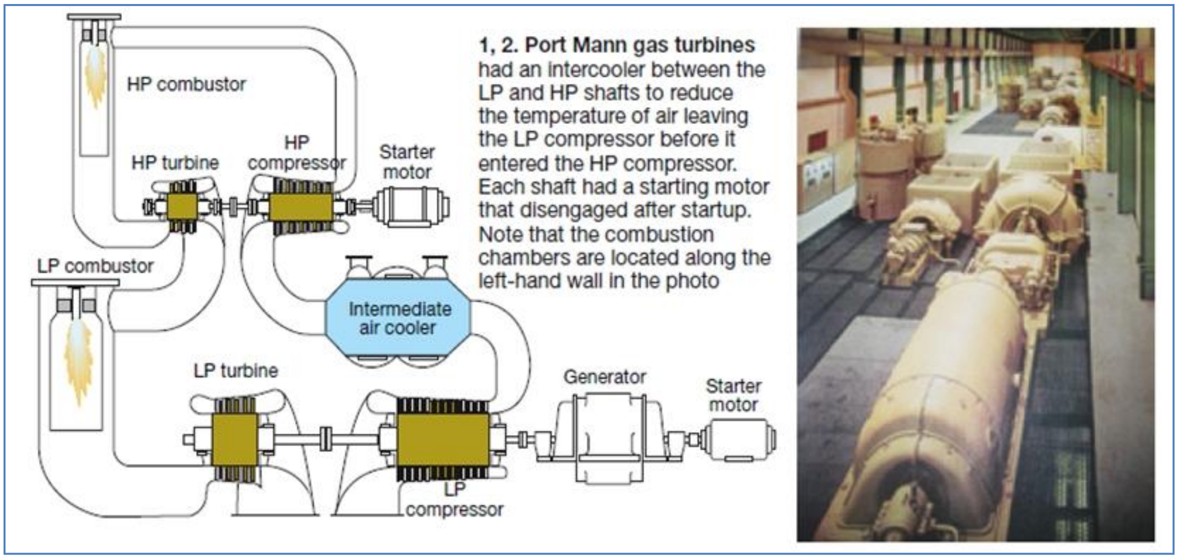


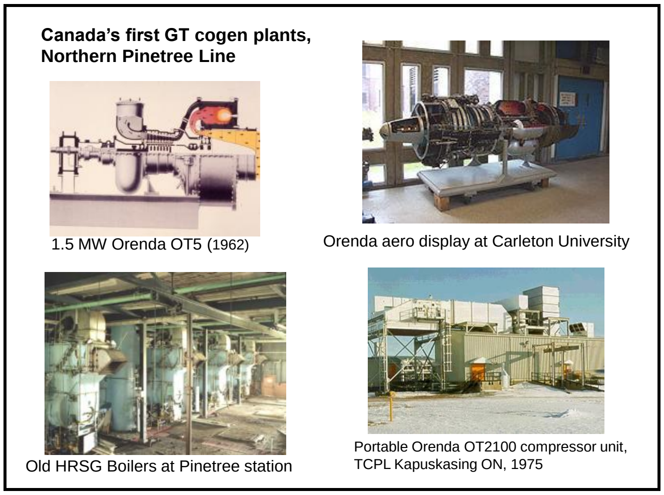
Fig. 5 (from Sep van der Linden, Combined Cycle Journal, 2012)

Around the same time in Alberta, the Rossdale steam power plant in downtown Edmonton had been converted from coal to natural gas, and were enlarged to about 100 MWe with several boiler steam turbine combinations. The next expansion in 1958-59 was with two 30 MWe Brown Boveri gas turbine systems in peaking operation, assembled onsite as the world's largest GT units at that time. Although the SO_2, NOx and PM air pollution from coal had been much reduced, there was still a mysterious yellow/brown cloud from GT exhaust in cold weather operations; so the first problems with NOx came at 650^{o}C TIT. Along with some additional noise, these units both became peaking units and were not repeated. Rossdale generation was increased with three high pressure steam turbines in 1963, and other local supply was moved to Clover Bar, and to the coal plants near Lake Wabuman.

Fig. 6 Two 30 MW BBC GT units in foreground, Rossdale Edmonton, 1958 (www.ephf.ca)

In 1955 the first major natural gas transmission pipeline was being built as the Westcoast gas processing and delivery system in northern BC. A much longer gas pipeline from Alberta across Canada was being proposed for both domestic and export service. There was heated discussion between the Liberal government and the Conservative opposition, which resulted in the fall of the government in 1957. The first TransCanada line from Burstall AB to Toronto was completed in October 1958 (as the world's longest system until 1980), and was integrated with the existing Union Gas system in SW Ontario to Montreal. It used mostly reciprocating compressors in the 1-2 MW range, with some early 5-8 MW gas turbines on TCPL in 1962 by Dresser-Clark and Westinghouse. The Westinghouse units (WR62RM and WR92RM) were usually two shaft regenerative units, with waste heat exchange for combustion air that was needed to give a reasonable thermal efficiency.

In mid-1958 Orenda also decided to enter the market, using the existing jet engine as a starting point. One idea was to refurbish aero engines and replace the final nozzle with a separate power turbine and another was to keep the aerodynamics of the jet engine in a heavy frame, resulting in the 5 MW OT-3 and OT-2. A market survey showed 3:1 in favour of the heavy frame, but in the long run the aeroderivative outsold the heavy frame by 3:1. The OT-2 was quite a good engine but was surpassed by the new Rolls Royce Avon and the eventual domination of the Canadian pipeline market by the aeroderivatives that had quick maintenance turnaround. The Avon was first used on gas pipelines in 1964 at TransCanada's Stn 13 in Saskatchewan, and complemented with GE LM1500 units on Westcoast Energy in BC and with NOVA in Alberta. This began the more widespread application of high-flow centrifugal gas compression with aeroderivative gas turbine units across these systems.



Figs. 7 and 8 Early Applications of Aeroderivative and Industrial Power units

Orenda also built the OT-5, a 1.5 MWe generator drive based on their scaled down jet engine compressor. This was used in the early 60's for the first major cogeneration systems in Canada, providing all power and heat on the Pinetree Line. This system was part of the NORAD 3-stage radar early warning system during the Cold War and ran approximately along the 50th parallel. The OT-5s produced all the power for the radar scanner and station utilities, with exhaust heat used for station heating and absorption refrigeration. Because of the remote locations natural gas was supplied on an interruptible basis, and the OT-5s were capable of switching to standby oil fuel automatically on full load (maybe the first time this was done). The Orenda (now Magellan) units were installed on 19 stations and operated successfully until the Pinetree Line closed in 1991, with 14 of the stations operating up to 1988 (although nothing appears to have been published on these achievements).

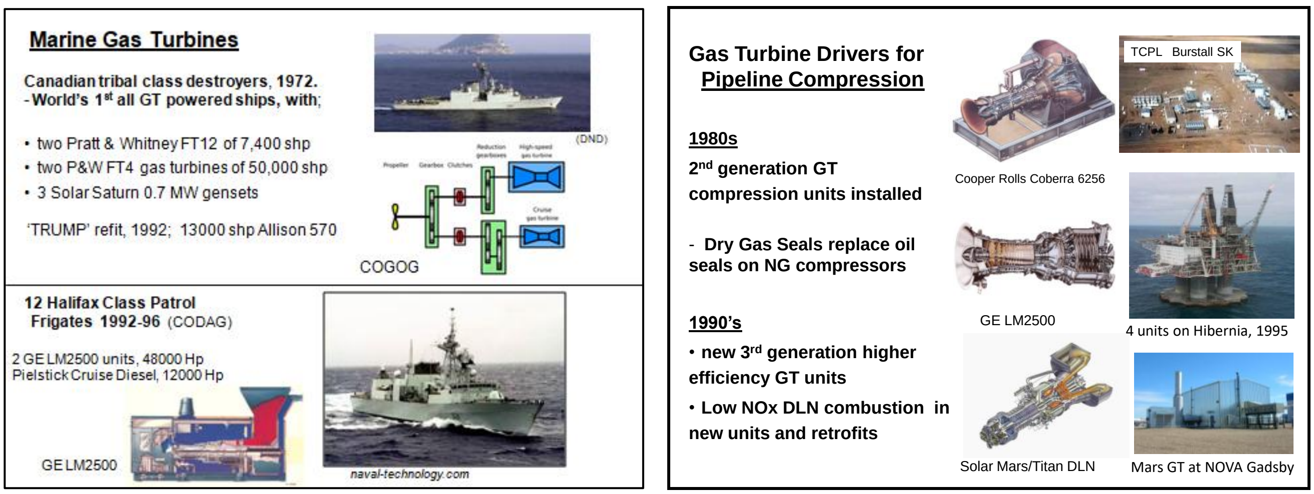
Simple cycle peak power later became more important in the eastern part of North America, when in November 1965 the large northeast blackout caused a significant 1-day disruption in the power grid of Ontario and several US northeast states. The value of quick start modular backup systems became apparent, and mid-sized aeroderivative gas turbines were widely deployed to mitigate similar possible events. (1969, total installed power of < 1000 MW).

3.0 Expansion and Efficiency in the Seventies and Eighties

In response to reliability and resilience needs following the 1965 major power outage, about fifty aero-derived Orenda, Solar Centaur & Mars, Rolls Royce Avon & Olympus, and Pratt & Whitney units were installed across Canada as electric peaking plants, some mobile units, and later as standby units for nuclear and coal steam plants;

Quebec	Cadillac, 200 MWe (8 x PW FT-4A) and La Citiere, 150 MWe (6 x Olympus)
Nova Scotia	Burnside, Victoria Junction, Tusket stations; 200 MWe (seven FT-4A)
Ontario	Nuclear; Bruce (8 x RR Avon) and Darlington (4 x Olympus, 2 Solar Mars)
British Columbia	Keogh (two FT4A) Prince Rupert (four Olympus)
New Brunswick	Grand Manan Island (one GE LM5000)

In 1971 the Canadian navy launched the world's first all-gas turbine frigates (four Tribal class ships) with Pratt&Whitney FT4 and FT12 units. The combination of these marine systems, and the above peak power, pipeline compression systems, led Canada to be a leader in the application of aeroderivative GT units (with over 400 units in simple cycle applications by year 2000). This growth also resulted in the new *'Industrial Applications of Gas Turbines*' (IAGT, now GTEN) committee events, initiated in 1974 by Herb Saravanamuttoo at Carleton University, the National Research Council, and later supported in 1990 with the Canadian Gas Association.



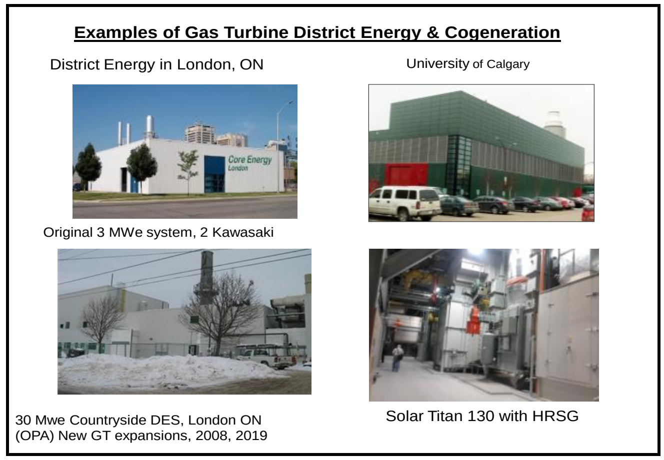
Figs. 9 and 10 Innovations in Marine Propulsion, and in Gas Pipeline Compression

This following period saw high growth in the natural gas export industry, partly due to cleaner fuel energy solutions needed to combat the acid rain problem from various high sulphur coal plants. New applications were developed through the GE LM2500 units with Westcoast and NOVA Alberta in 1972, and some 3 MW Allison 501 units on small pipelines. More efficient twin-spool units began with TCPL - the first 20 MW Rolls Royce RB211 unit at Burstall in 1974, and a 12 MW Spey unit near Winnipeg in 1976, with LHV efficiencies of about 33 %. Some large Westinghouse CW352 and a few GE Frame 5 heavy duty units, were installed for gas processing and pipelines in the west. However, the aeros had more advantages in flexibility, as Foothills, TransCanada and NOVA pipelines installed dozens of RB211 and LM2500 units and upgraded most of the existing Avon fleet. The trend continued with Union Gas facilities in Ontario using mostly Rolls Royce (now Siemens) units, with the Dawn storage facility later having the largest compressor station complex in Canada.

As modern pipeline operations also needed flexible and reliable lightweight power in the 1-10 MW range, the smaller compressor and oil pumping market became dominated by Solar Turbines with 1 MW Saturn and 3 MW Centaur units, and later the larger 5 MW Taurus and 10 MW Mars types of units. One of the key system changes was the replacement of most pipeline recip compressors over a 20 year period. The first major project was in 1981 at Alberta Natural Gas (TCPL, now TC Energy) Crowsnest BC station with an 8 MW Solar Mars unit replacing four existing recip units for lower NOx and PM, higher flows and lower methane emissions. Many small GT units such as the 0.2 MW Solar Spartan, 1 MW Saturn and 0.6 MW Pratt&Whitney ST6 also became standby power units for critical telecom and reliable building services, and some became trailer-mounted mobile power units.

Utility coal and gas boiler steam plants began seeing competition from the gas turbine industry, with new large industrial power and energy projects using Heat Recovery Steam Generators. The 1970's saw the first large GT cogeneration facilities, notably the at DOW Sarnia petrochemical facility in Ontario with the first two GE Frame 7B units (100 MWe) with exhaust heat recovery for 1 million lb/hour of steam. The HRSGs were used to replace the coal-fired boilers that supplied those industrial steam systems, and was the first major coal repowering in Canada. As an integrated onsite facility with electrical islanding design, it was mostly justified on the basis of mitigation of local power outages. A similar new plant was built by DOW in 1978 just east of Edmonton.

Another type of innovative repowering project was done in 1980 at the Medicine Hat power plant in southern Alberta, which became the first utility combined cycle plant in Canada. Two 33 MWe Westinghouse CW251 gas turbines replaced four gas-fired boilers, keeping some existing steam turbines to raise the total plant output from 55 MWe to 120 MWe, with an overall heat rate reduction of 30 percent. An additional 150 MWe of similar combined cycle capacity was installed there in 1995-2005 with several LM2500 and LM6000 aero units replacing those first Westinghouse units. By 1989, the total installed electrical and compression power was about 4500 MW in Canada.



Figs. 11 and 12 Examples of Large and Small Gas Turbine Cogeneration and District Energy Plants

4.0 'Third Generation' Gas Turbine Systems, 1990-2020

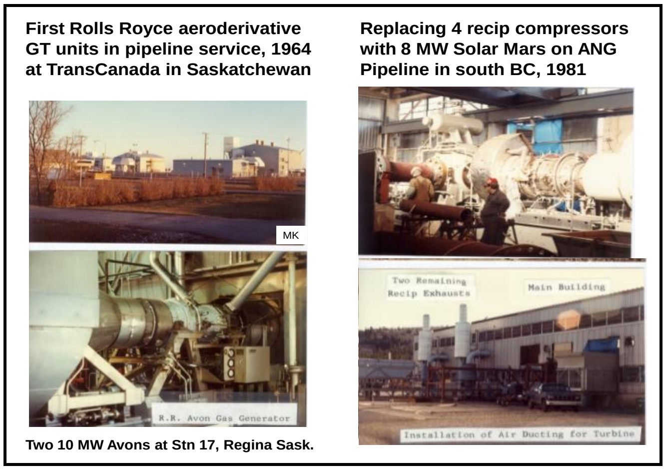
With advanced air compressor blading and turbine cooling designs, new efficient simple cycle units were developed with higher air compression ratios to enhance efficiency and power. Pressure ratios were doubled towards 30:1, and turbine temperatures rose towards 1500^{o}C with enhanced downstream blade cooling. This also became the era of overall system efficiency, where exhaust temperatures are utilized with waste heat recovery with HRSGs in combined cycles, cogeneration and district heating. Recent additions of gas turbine plants and generation MWhrs have been the most prolific of any technology choice in Canada. In 1990 there was only about 4500 MW in total capacity, but the addition of almost 1000 MW annually (with some older retirements) has brought the total gas turbine electrical and compression power in Canada to almost 30 000 MW by 2021 (Fig 17).

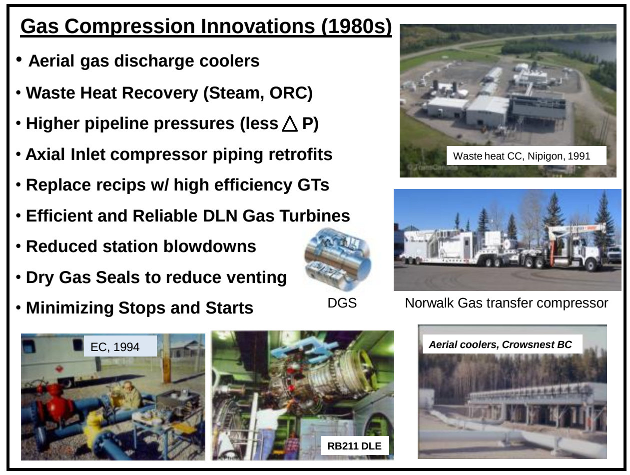
The early 90's also brought in the need for reducing both air pollutants and greenhouse gases. Steam injection to prevent NOx emissions was an early option on natural gas-fired combined cycles and cogen plants. However a more cost-effective pollution prevention method for thermal NOx was to modify the combustion process with ‘lean pre-mix’ Dry Low NOx (DLN) combustors. When used in combination with waste heat recovery and cogeneration, improved air filtration (zero net PM emission), these systems have become very successful with a combination of low air pollution, low GHGs and high system reliability.

One of the leaders in these combustion systems was Solar Turbines, with the first widely used DLN combustion systems in 1993, as well as many innovative applications of waste heat utilization and district energy for its light industrial Taurus, Mars and Titan series of 5-20 MW units. Subsequently DLN/DLE soon became the standard for most new pipeline additions and many retrofits of Rolls Royce and GE aeroderivative units, and new large heavy-duty units from GE, Siemens and MHI. These innovations on most new GT engines have likely represented the most successful air emissions technology success story of any industrial sector.

For the Canadian natural gas industry, several new GHG emission solutions were developed during this period for transmission and distribution systems to improve lifecycle air emissions. This included widespread turbine compressor upgrades, axial inlet compressors, dry gas seals, discharge aerial coolers, reduced NG blowdowns, gas transfer compressors, recip retirements and methane leakage monitoring (Figs 13, 14).

In the 1990-2010 period a series of fifteen innovative pipeline waste heat combined cycle plants were built, some using IST 'once through steam generators' and steam turbines in northern Ontario, and more recently with Organic Rankine cycle expanders on TC Energy, Spectra/Enbridge in BC and on the Alliance pipeline.





Figures 13 and 14 Examples of Innovations in the Canadian Natural Gas Sector

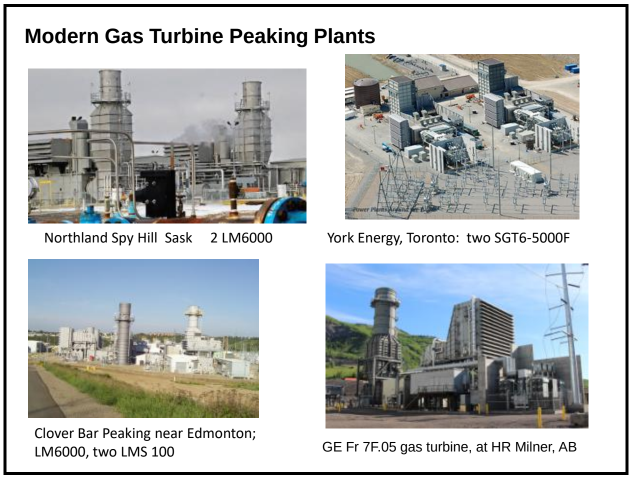
Cogeneration and district energy have become important clean energy solutions with fairly low CO_2 rates, using both gas and extraction steam turbines (as well as recip engines for hot water district energy). Another series of gas turbine ‘firsts’ can be seen in the growth of seventy industrial and municipal GT cogen facilities in Canada;

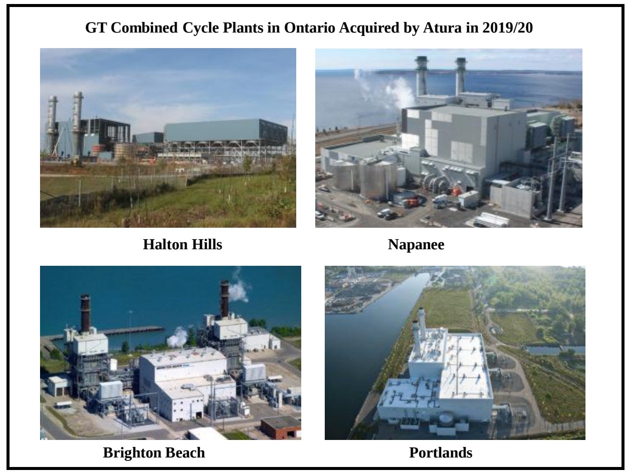
- world's first unique GE LM6000 gas turbine installed by TransAlta in Ottawa in late 1991, followed closely by the second in Toronto a few months later (both with Alstom 2-speed extraction steam turbines)
- first 4 MW EGT Typhoon (now Siemens SGT100) at the National Research Council in Ottawa, 1993
- the first large Canadian DLN application on the Cardinal Power W501D cogen unit, 1994
- first DLE LM6000 at the TransAlta/Chrysler Windsor cogen, 1996
- first Rolls Royce Trent engine at the Whitby cogen plant (with DLE combustion, 1997)
- first 70 MWe GE Frame 6FA unit at the Kingston cogen plant for Celanese, 1997
- the first DLE LM1600 unit on the TCPL/ANG pipeline in southeast BC (2003)

The clean energy market has also grown with the steady phaseout of coal plant operations, from power generation being replaced by about 15 repowering and greenfield combined cycle plants, as well as a mixture of the above cogeneration and simple cycle facilities across Canada. Most of these large gas turbine designs have incorporated aero-derived technology for compressor flow and turbine blade cooling. The first large new greenfield utility combined cycle was the 250 MWe Calpine (now ENMAX) Calgary Energy center in 2003, based on a Siemens Westinghouse W501F unit. This was followed by a string of other new GTCC facilities across Canada totalling about 12 000 MWe, notably some examples;

- 12 x 25-30 MWe Hitachi units at SaskPower QEPS repowering (only such project w/12 units, + IST OTSGs)
- large twin 250 MWe MHPS M501G units at ENMAX Shepard (Calgary), and at TCE/Atura (Napanee ON)
- 350 MWe Chinook GTCC in Saskatchewan with one Siemens SGT5000 in 2020
- repowering of Alberta coal units at Sundance (GE Fr7F) and HR Milner in 2022-23 (Siemens SGT5000)

The utility grids have also been supported by simple cycles, with fast start, small unit portability, and the critical ability to backup renewable wind and solar intermittency. Some plants can be used as synchronous condensers in remote areas, and some simple cycle units perform a critical standby function in nuclear plants for black start electrical service. The combination of these various fixed and portable systems will support electrification and allow the retirement of existing coal and inefficient gas plants.





Figs 15 and 16 Some examples of Simple and Combined Cycle GT Systems

5.0 Clean Energy Considerations and Opportunities

Industrial gas turbine systems fuelled by natural gas, hydrogen blends or synthetic gases have many attributes required by clean energy systems for thermal, electrical and mechanical energy with low emissions of both air pollutants, toxics and greenhouse gases. Important system efficiencies are realized by high air compression ratios, waste heat recovery in combined cycles, cogeneration and district heating to replace commercial boilers in cities.

Natural gas is the cleanest burning fuel and due to its high hydrogen content, these integrated cogen systems could have a lifecycle net rate of 200-350 kg/MWhr (adding H_2 blends can help this). Significant improvements in methane leakage and venting prevention have been employed on gas delivery systems. This represents a 60-80% net GHG reduction from current coal technology, with 90-95 per cent fewer NOx, SOx and PM (oxides of nitrogen, sulphur and particulate) emissions. Onsite CHP and district energy can also have important local co-benefits of;

- energy process reliability,
- fewer power transmission losses,
- some CFC reductions with absorption chilling, as well as
- being a 'climate adaptation measure' as resilience against extreme events.

Additional methane emissions prevention is needed in the upstream oil and gas sector to allow the GHG lifecycle of natural gas based cogeneration to maintain a net rate of less than 350 kg_{GHG} per MWhr.

But there are many synergies and tradeoffs in how air pollution and GHG emissions can be prevented for clean energy, because various air emissions from any combustion system cannot occur individually, but as a system. Some specific examples of balancing various issues are summarized below;

- Small high pressure combustors may have difficulty in lean premix DLN design, but they may be better on both unit and cogen efficiency considerations compared to large combined cycles
- Pipeline system upsets can result from overly stringent NOx regs, with unreliable DLN combustion causing problematic shutdowns and station blowdowns with increased methane emissions and venting noise
- Backend SCR NOx controls (for very stringent NOx regs) may be less cost-effective than prevention, as they can give rise to other collateral air, water or health/safety impacts (transport safety, increased fine PM, N_2O, ammonia slip and efficiency drop), with increased GHGs and a reduced ability to cycle in support of renewables
- Duct burners for cogeneration are effective in allowing use of smaller GT units, and intermittent cycling flexibility for doubling the steam production of ‘unfired’ HRSG systems.
- For cogeneration and district energy, small and medium sized gas turbines are well suited for synergistic onsite energy with reliability, and a low lifecycle carbon footprint to match thermal loads

- As inlet air filtration is vital for GT operation, so there should be no net fine particulate emissions at the exhaust
- Output-based NOx emission standards are superior to concentration-based criteria, based on GHG objectives
- An important synergy exists with renewable energies, with the integration of gas turbine systems and future hydrogen fuel blends, to provide fast start, cycling or peaking power when wind/solar have reduced capability
- H_2 fuels have significant flame speed, auto-ignition and flashback characteristics in high pressure combustion, and must be adapted for safety and reliability, possibly with additional allowances for higher NOx emissions

Future innovations around advanced cycles, hydrogen integration, district energy, hybrids and energy storage, electrification, public transportation, and carbon capture should continue these trends, as new flexible gas turbine systems are developed to meet climate change, diversity, energy security and other environmental objectives for various sectors of the economy (Fig 17). The evaluation of multiple co-benefits, output-based emission standards, and fugitive methane reductions, may become an important economic driver for cost-effective solutions.

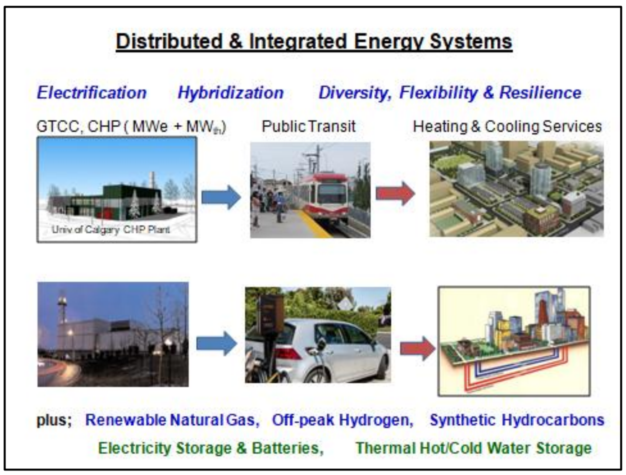


Fig 17 Future Potential

Gas Turbine Systems in Canadian Industrial Sectors
2020 estimate (M.Klein)

Installed MW	Simple Cycle	Combined Cycles	Comb. Cycle Cogen	Simple Cogen	Sector total
Electric Power	4640	9910			14550
Gas Pipelines	5470	140			5610
Upstream Gas	360		120	440	920
Oilsands & Refineries	115		575	2170	2860
Chemicals, Forestry, Metals			3175	400	3575
Manufacturing	40		1150	190	1380
Institutional			210	145	355
Est. Total	10625	10050	5230	3345	29250

Aero-derived GTs; (about 400 units, 8800 MW)

- Not incl. retired units
- 24350 MW GTs, and 4900 MW of steam turbines

Fig 18 Estimates of Installed Power (MK)

6.0 Conclusion

Canada has a strong historical record over the last six decades in the development of innovative aeroderivative and heavy duty gas turbine units, and their applications in energy systems. The combination of these cycles has contributed to Canada's cleaner and reliable energy production, in part by supporting a large increase in intermittent renewable wind/solar operations, avoiding GHG increases, and good progress in near-term phaseout of coal plants.

New opportunities are coming in some degree of carbon capture, fuel flexibility with hydrogen and biofuels, continuing mitigation of upstream methane leakage, and a greater use of low-grade heat for municipal district energy. Various types of small, medium and large gas turbines based on new cycle innovations will be part of a cleaner energy future. To help achieve these objectives, there will be an increased need for training in technical and economics topics around integrated energy system design, long term planning and assessment of co-benefits.

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