Gas-Fired Power

HIGHLIGHTS

- **PROCESS AND TECHNOLOGY STATUS –** Approximately 21% of the world's electricity production is based on natural gas. The global gas-fired generation capacity amounts to 1168 GW_e (2007). In Europe, the total electricity generation capacity is about 804 GW_e, of which 22% is based on natural gas. In the United States, the total capacity is about 1039 GW_e, with 400 GW_e based on natural gas. There are two types of gas-fired power plants, viz. open-cycle gas turbine (OCGT) plants and combined-cycle gas turbine (CCGT) plants. **OCGT** plants consist of a single compressor/gas-turbine that is connected to an electricity generator via a shaft. They are used to meet peak-load demand and offer moderate electrical efficiency of between 35% and 42% (lower heating value, LHV) at full load. Their efficiency is expected to reach 45% by 2020. **CCGT** is the dominant gas-based technology for intermediate and base-load power generation. CCGT plants have basic components the same as the OCGT plants but the heat associated to the gas-turbine exhaust is used in a heat recovery steam generator (HRSG) to produce steam that drives a steam turbine and generates additional electric power. Large CCGT plants may have more than one gas turbine. Over the last few decades, impressive advancement in technology has meant a significant increase of the CCGT efficiency by raising the gas-turbine inlet temperature, with simultaneous reduction of investment costs and emissions. The CCGT electrical efficiency is expected to increase from the current 52–60% (LHV) to some 64% by 2020. CCGT plants offer flexible operation. They are designed to respond relatively quickly to changes in electricity demand and may be operated at 50% of the nominal capacity with a moderate reduction of electrical efficiency (50–52% at 50% load compared to 58–59% at full load). In general, because of the lower investment costs and the higher fuel (natural gas) cost vs. coal-fired power, CCGT plants are lower in the merit order for base-load operation, although the competition also depends on local conditions, variable fuel prices and environmental implications.

- **COSTS –** Due to the high price of materials and equipment and the increasing demand for new CCGT plants, the investment cost of CCGT power plants has been increasing almost continuously from some $800/$kW_e$ in 2002 to $1100/$kW_e$ in 2009 (costs quoted in 2008 US dollars). At present, if compared with the 2008 peak cost, the CCGT investment costs might be slightly declining because of the reduction of material costs and the low demand for new capacity due to the ongoing economic crisis. While technology learning is not expected to significantly reduce the investment cost of mature technologies, technical developments in CCGT plants may still drive cost reductions from today's $1100/$kW_e$ to $1000/$kW_e$ in 2020, and to $900/$kW_e$ in 2030. The investment cost of OCGT plants is approximately $900/$kW_e$. Modest cost reductions are also expected for OCGT plants, namely $850/$kW_e$ in 2020, and $800/$kW_e$ in 2030. The annual operation and maintenance costs of CCGT and OCGT plants are estimated at 4% of the investment costs per year. The generation costs of CCGT range between $65 and $80/MWh (typically, $73/MWh), of which $30–45/MWh is for the fuel. Generation costs of OCGT are much higher, e.g. $200–225/MWh (typically, $210/MWh), of which $45–70/MWh is for the fuel. In the OCGT plants, the fuel cost may be up to 50% higher than in CCGT as the efficiency is about two-thirds that of a combined cycle. However, the main reason for the OCGT high generation cost is the low load-factor of the peak-load services, typically 10% vs. 50-60% for the CCGT plants.

- **POTENTIAL & BARRIERS –** CCGT technology is a strong competitor for all power generation technology. Its share in electricity generation has been growing fast over the past decades. In comparison with coal-fired power, CCGT plants offer shorter construction time, lower investment costs, half as much CO_2 per kWh and high service flexibility, but higher fuel costs. Non-greenhouse gas (GHG) emissions such as SO_2, NO_x, and particulate matter are also relatively low. The current CO_2 price is low (see European emission trading) and moderately affects the electricity cost. In the future, however, it may rise and have a strong impact on the competition between coal- and gas-fired power, renewable and nuclear energy. In addition, current uncertainties on natural gas prices make it difficult to adopt robust strategies for CCGT deployment and may result in a changing economic balance between gas- and coal-fired power.

PROCESS AND TECHNOLOGY STATUS – Open-cycle gas turbines (**OCGT**) for electricity generation were introduced decades ago for peak-load service. Simple OCGT plants consist basically of an air compressor and a gas turbine aligned on a single shaft connected to an electricity generator. Filtered air is compressed by the compressor and used to fire natural gas in the combustion chamber of the gas-turbine that drives both the compressor and the electricity generator. Almost two-thirds of the gross power output of the gas-turbine is needed to compress air, and the remaining one-third drives the electricity generator. OCGT plants have relatively low electrical efficiency ranging between 35% and 42% (lower heating value, LHV). Aero-derivative gas-turbines provide efficiency of 41–42%, but their size is limited to 40–50 MW_e. Since the early 1990s, combined-cycle gas turbines (**CCGT,** Fig. 1) have become the technology of choice for new gas-fired power plants (IEA, 2008). CCGT plants consist of compressor/gas-turbine groups – the same as the OCGT plants – but the hot gas-turbine exhaust is not discharged into the atmosphere. Instead it is re-used in a

Please send comments to A. J. Seebregts, Author (seebregts@ecn.nl) and to
Giorgio.Simbolotti@enea.it and Giancarlo Tosato (gct@etsap.org), Project Coordinators

heat recovery steam generator (HRSG) to generate steam that drives a steam-turbine generator and produces additional power. Gas-turbine exhausts then leave the HRSG at about 90°C and are discharged into the atmosphere. CCGT plants commonly consist of one gas turbine and one steam turbine. Approximately two-thirds of the total power is generated by the gas turbine and one-third by the steam turbine. Large CCGT power plants may have more than one gas turbine.

State-of-the-art CCGTs have electric efficiency of between 52% and 60% (lower heating value, LHV) at full load. Figure 2 shows the efficiency of CCGT plants compared with pulverised coal (PC) power plants as a function of the maximum cycle temperature. Current supercritical coal-fired power plants (left hand) may reach a full-load efficiency of 45–46% (2010) while (right hand) the current full-load efficiency of CCGT power plants is close to 60%. Technological developments aim to increase the CCGT efficiency by raising the gas-turbine inlet temperature and simultaneously decreasing investment cost and emissions. Figure 3 shows the efficiency as a function of the gas turbine inlet temperature. According to Ishikawa et al. a CCGT plant with a 1700°C class gas-turbine may attain an electrical efficiency of 62–65% (LHV). Thus, the CCGT efficiency is expected to increase from today's 52%–60% to a maximum of 64% by 2020. OCGT efficiency is also expected to rise from its current 35%–42% (LHV) to 45% by 2020.

CCGT is a mature technology. It is one of the dominant options for both intermediate-load (2000 to 5000 hrs/yr) or base-load (>5000 hrs/yr) electricity generation. In the last decade, many CCGT plants have been built in North America, Europe, Asia, and in the Middle East. OCGT and CCGT capacity addition in the US from 1998 to 2008 is shown in Figure 4 (McManus et al, 2007). CCGT power plants have become the workhorses of independent power producers all over the world. With individual heavy-frame gas turbines available in unit sizes of up to 300 MW_e, CCGT plants offer modular flexibility and adaptability to the electricity demand and grid requirements. Figure 5 shows the range of gas turbines offered by a major producer, from relatively small 56-MW_e gas turbines, often used for combined heat and power (CHP) generation, to the largest 288-MW_e turbines used for base-load power generation. In general, gas-turbines can burn not only natural gas but also heavy/crude oil, distillate and other liquid and gaseous fuels. Obviously large, heavy-duty gas-turbines with big combustion chambers are more suitable for burning heavy fuels, while small, aero-derivate gas-turbines, with several little burners or combustion chambers, are more sensitive to changes of combustion parameters (Kehlhofer et al, 2009). In general, CCGT plants are designed to respond relatively fast to changes in electricity demand and service. They may be operated

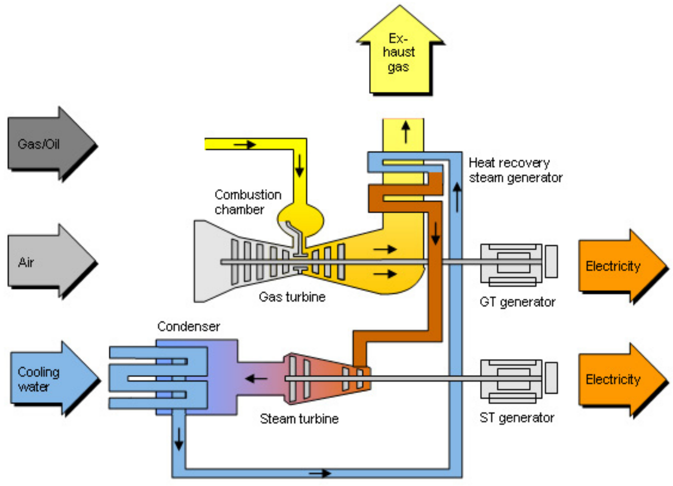

Fig. 1 - Gas-fired CCGT plant (Siemens, 2008)

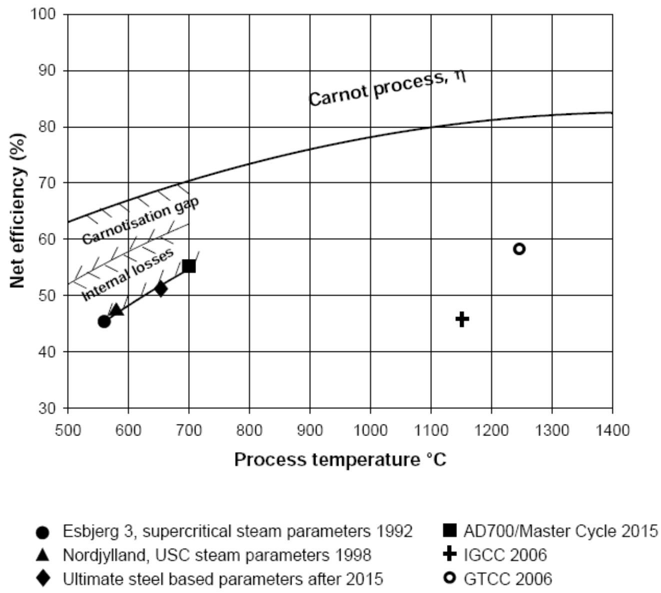

Fig. 2 - Efficiency of GTCC and PC power plants vs. gas and steam temperature (Blum et al., 2006)

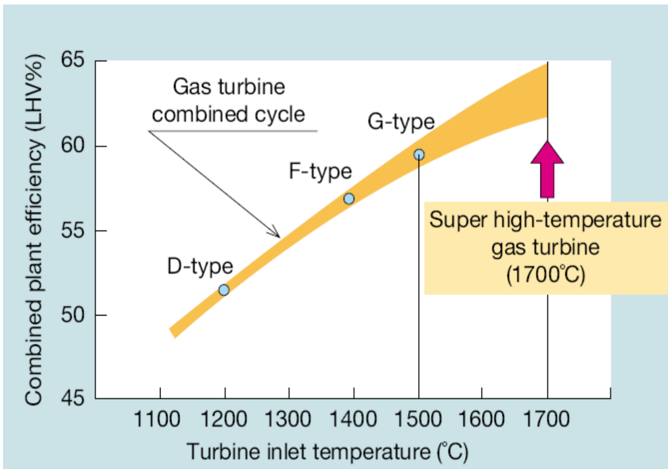

Fig. 3 – CCGT efficiency (Ishikawa et al, 2008)

between 40% and 100% of the nominal capacity with moderate efficiency drop (from 58-59% at full load to 50–52% at 50% of the full load). Due to the high efficiency and the use of natural gas, the best available CCGT power plants emit approximately 50% less CO_2 and up to nine times less NO_x per kWh than modern coal-fired power plants. The NO_x emissions of a CCGT plant may be reduced by using Selective Catalytic Reduction (SCR) systems. Table 1 provides typical data of NO_x emissions from a CCGT plant, with and without SCR.

COSTS – Because of the high price of steel, materials and equipment, the investment cost of the **CCGT** power plants has been growing rapidly over the past years from some $800/kW$_e$ (2008 US$) in 2002 to the current level of approximately $1100/kW$_e$ (King, 2008; Norske Shell, 2008). Figure 6 provides an overview of quoted investment costs of CCGT plants. Similar costs are also reported by other sources, e.g. €700 million for a 870-MW$_e$ CCGT, which is equivalent to €800/kW$_e$ (EBR, 2009). CCGT is a mature technology and its investment cost may decline over time to a limited extent as a result of technology learning. From today's $1100/kW$_e$, the investment cost is estimated to decline to $1000/kW$_e$ in 2020, and to $900/kW$_e$ in 2030. The current (2009) global economic crisis can make a contribution to the mitigation of the CCGT investment cost because of the slowing demand for materials, components and new capacity. The investment cost of **OCGT** plants is also expected to slightly decline from today's $900/kW$_e$, to $850/kW$_e$ in 2020 and to $800/kW$_e$ in 2030.

The operation and maintenance (O&M) cost is estimated at 4% of the investment cost per year for both OCGT and CCGT plants. Thus, CCGT O&M costs are estimated at $44/kW$_e$ per year in 2010, declining accordingly to $36/kW$_e$ per year in 2030. For OCGT plants, O&M costs are estimated at $36/kW$_e$ per year in 2010, down to $32/kW$_e$ in 2030. The overall generation cost of CCGT plants ranges from $65 to $80/MWh (typically, $72/MWh), of which $30 to $45/MWh is for the fuel (at a natural gas price of $5.0–6.5/GJ). Generation costs of OCGT are much higher and range from $200 to $225/MWh, of which $45-70/MWh is for the fuel (natural gas). In the OCGT plants, the fuel costs per kWh may be up to 50% higher than in CCGT, as a single-cycle gas turbine plant has an efficiency that is about two-thirds that of a combined cycle. However, the main reason for the high OCGT generation cost is the low load-factor associated to the peak-load services, typically 800 full-load hours vs. 4200-5200 full-load hours for the CCGT.

Fig 4 – Gas-turbine capacity addition in the US (McManus et al., 2007)

Fig. 5 - Gas turbine size range (Alstom, 2008)

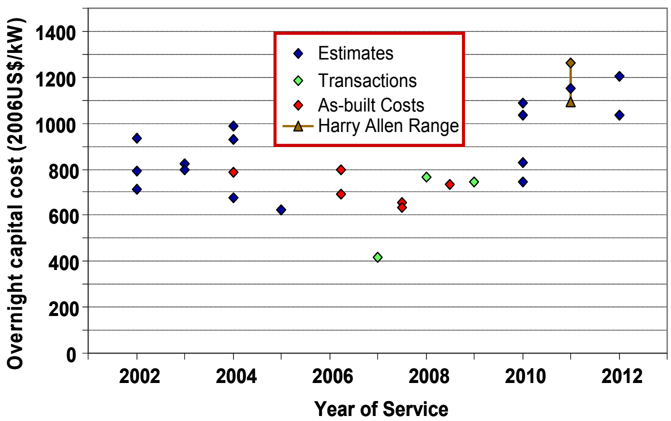

Fig. 6 - Investment costs of CCGT plants (King, 2008)

POTENTIAL AND BARRIERS – CCGT technology is a strong competitor for all power generation technology and its share in electricity generation has been growing fast over the past decades. In comparison with coal-fired power, CCGT plants offer lower investment costs and emissions (e.g. CO_2), shorter construction time, high service flexibility, but also higher fuel costs. The IEA in its Baseline scenario (IEA, 2008) estimates a need for new CCGT power plant capacity of about 110 GW per year for the period 2005-2050. The cumulative investment would be some $4000 billion, approximately equivalent to 5300 GW of CCGT plants. However, in the IEA emission mitigation scenarios, the investment in new CCGT capacity is considerably lower. While the current service flexibility, but also higher fuel costs. The IEA in its Baseline scenario (IEA, 2008) estimates a need for CO_2 price is low (e.g. the European Emission Trading System) and may relatively affect the electricity generation cost, in the near future CO_2 emissions may have a significant impact on the competition between coal-, gas-fired power, renewable and nuclear energy. In addition, current uncertainty about short-term prices of natural gas makes it difficult to adopt robust strategies for further CCGT deployment and may result in a changing economic balance between CCGT and coal-fired power.

Table 1 - NOx emissions of a CCGT plant with/out SCR

NO_x emission	CCGT no SCR	CCGT SCR
[mg/m^3]	52.5	23
[g/GJ$_{fuel}$]	45	20
[g/kWh]	0.30	0.13

Table 2 – Summary Table: Key Data and Figures for Natural Gas-based Power Technologies

Technical Performance	**Typical current international values and ranges**	
Energy input	Natural gas	
Output	Electricity	
Technologies	**OCGT**	**CCGT**
Efficiency, %	35–42%	52–60%
Construction time, months	Minimum 24; Typical 27; Maximum 30	
Technical lifetime, yr	30	
Load (capacity) factor, %	10–20	20–60
Max. (plant) availability, %	92	
Typical (capacity) size, MW_e	10–300	60–430
Installed (existing) capacity, GW_e	1168 (end of 2007)	
Average capacity aging	Differs from country to country. CCGT construction started end of 1980s.	
Environmental Impact		
CO_2 and other GHG emissions, kg/MWh	480–575	340–400
NO_x, g/MWh	50	30
Costs (US$ 2008)		
Investment cost, incl. IDC, $/kW	800 – 1000; Typical 900 (2010)	1000 – 1250; Typical 1100 (2010)
O&M cost (fixed and variable), $/kW/a	36	44
Fuel cost, $/MWh	45–70	30–45
Economic lifetime, yr	25	
Interest rate, %	10	
Total production cost, $/MWh	200 – 225 / Typical 210	65 – 80 / Typical 72.5
Market share	20	

Data Projections	**2010**		**2020**		**2030**		
Technology	OCGT	CCGT	OCGT	CCGT	OCGT	CCGT	
Net Efficiency (LHV), %	35-42	52-60	≤ 45	≤ 64	≤ 45	≤ 64	
Investment cost, incl. IDC, $/kW	900	1100	850	1000	800	900	
Total production cost, $/MWh	100	72.5	95	70	95	70	
Market share, % global electricity output	20		18		15		

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References and Further Information

1. Alstom (2009): Gas Turbines for simple and combined cycle applications. Alstom, 2009. http://www.power.alstom.com/home/new_plants/gas/products/gas_turbines/39930.EN.php?languageId=EN&dir=/home/new_plants/gas/products/gas_turbines/
2. Blum, R. et al (2006): Development of a PF Fired High Efficiency Power Plant (AD700). DONG Energy Generation, Fredericia, Denmark, 2006. http://www.risoe.dk/rispubl/reports/ris-r-1608_69-80.pdf.
3. BP (2009): BP Statistical Review of World Energy, BP, London, UK, June 2009. http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2008/STAGING/local_assets/2009_downloads/statistical_review_of_world_energy_full_report_2009.pdf.
4. EBR (2009): Siemens Bags EUR700 Million Order From Eneco To Construct CCG plant In The Netherlands. Energy Business Review (EBR), 26-May-2009. http://www.energy-business-review.com/news/siemens_bags_eur700_million_order_from_eneco_to_construct_combined_cycle_gas_plant_in_the_netherlands_090526.
5. IEA (2008): Energy Technology Perspectives 2008 - in support of the G8 Plan of Action. International Energy Agency (IEA), Paris, June 2008.
6. Siemens (2008): Siemens Combined Cycle Power Plant. Siemens, Germany, 2008. http://www.powergeneration.siemens.com/products-solutions-services/power-plant-soln/combined-cycle-power-plants/CCPP.htmnetl.doe.gov/coal/refshelf/ncp.pdf.
7. Ishikawa, M. et al (2008): Development of High Efficiency Gas Turbine Combined Cycle Power Plant. Mitsubishi Heavy Industries, Ltd., Technical Review Vol. 45 No. 1 (Mar. 2008). http://www.mhi.co.jp/technology/review/pdf/e451/e451015.pdf.
8. Kehlhofer, R. et al (2009): Combined-cycle gas & steam turbine power plants. PennWell, Tulsa, Oklahoma, USA, 3rd Edition, 2009.
9. King, J. (2008): Proposed Combined-Cycle Power Plant Planning Assumptions. Northwest Power and Conservation Council.
10. Power Committee Portland, OR, USA, October 15, 2008. http://www.nwcouncil.org/energy/grac/meetings/2008/10/Combined-cycle%20planning%20assumptions%20-%206P%20Draft%20101608.ppt#482,1,Sixth Northwest Conservation & Electric Power Plan Proposed Combined-cycle Power Plant Planning Assumptions.
11. McManus, M. et al (2007): Integrated Technologies that Enhance Power Plant Operating Flexibility. POWER-GEN International 2007, New Orleans, LA, USA, December 11-13, 2007. http://www.powergeneration.siemens.com/NR/rdonlyres/97BD3507-B414-44E0-AA97-1CD8AAB5CCAE/0/PowerGen2007PaperFinal_.pdf.
12. Norske Shell (2008): Mid-Norway Power Study. A/S Norske Shell E&P, Norway, June 2008. http://www.regjeringen.no/upload/OED/Rapporter/Shell%20Mid-Norway%20power%20study%20juli%2008.pdf.

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