Natural Gas for Power Generation

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This is the eighth article in a series by OTC specialists and partners on natural gas (NG) and liquefied natural gas (LNG).

The series comprises the following articles which are scheduled for publication on the dates listed:

1. Overview of the LNG industry – September 2020
2. Traditional gas transport modes – November 2020
3. Safe and clean storage of natural gas – January 2021
4. Alternative modes of natural gas transport – March 2021
5. Overview of LNG technologies – May 2021
6. Comparison of inland NG/LNG and imported LNG – June 2021
7. Outlets and applications for natural gas – August 2021
8. Natural gas for power generation – September 2021
9. Small scale versus large scale LNG – November 2021
10. Gas utilisation in transport – December 2021

These articles are published over a period of 16 months and will be interspersed with articles related to aspects of project management and renewable energy.

Introduction

The world needs an abundant supply of clean and affordable energy to support economic and social progress and build a better quality of life, particularly in developing countries. Until recently, this desire for energy has been met with fossil fuels, primarily coal and oil.

Electricity is perhaps the most versatile form of energy and has a wide range of applications. According to the law of conservation of energy, it is not possible to create or destroy energy. Energy cannot be created from nothing, but fortunately it is possible to convert energy from one form to another. Electrical energy can be obtained from hydrocarbon fuels like coal, oil and gas, and primary energy flows like solar energy, wind energy and geothermal energy. The use of natural gas in the power sector is expected to increase over the next 20 years as it gains share from coal but falls back by 2050 as the use of renewables accelerate. Electrical energy is easy to transport, can be used to generate heat, power electrical motors to produce mechanical energy, and power electronic devices.

In the seventh article in this series, Steyn (2021) discussed outlets and applications for natural gas, including power generation. In this article, we describe the basics of electric power generation in more detail and focus on the different options for generating power from natural gas.

Basics of power generation

Opening remarks

Although sources such as electric batteries can supply electric power, it is mostly produced by electric generators in power stations. The electric power system, often referred to as the electric power grid, is made up of electricity generation, transmission, and distribution. We briefly discuss power generators and primary drivers, and then consider options for natural gas power generation.

Power generators

In 1831, the physicist Michael Faraday discovered that when a magnet is moved inside a coil of wire, an electromotive force is induced which causes electrons to flow inside the wire, generating an electric energy (Beck, 2018). A generator is any machine that converts mechanical energy to electric current. For a generator to convert mechanical energy into electrical energy, three conditions must exist for electromagnetic induction to take place:

- There must be a magnetic field present.
- There must be an electric conductor adjacent to the magnetic field.
- There must be relative motion between the magnetic field and the conductor.

Most generators used in power stations are alternating current (AC) machines or more specifically three phase rotating field synchronous AC generators, also known as alternators. A synchronous generator delivers AC electrical power at a particular voltage, frequency, and power factor. Each generator is coupled to a primary driver (i.e., turbine or engine) and converts the mechanical energy of the driver into electrical energy. In this case, in its simplest form, the magnetic field is provided by a permanent magnet (or electromagnet) which is rotated within a fixed wire loop or coil in the stator. The moving magnetic field due to the rotating magnet of the rotor will then cause a sinusoidal current to flow in the fixed stator coil as the field moves past the stator windings (conductors). If the rotor field is provided by an electromagnet, it will need direct current excitation. If instead of a single coil in the stator, three independent stator coils or windings, spaced 120˚ apart around the periphery of the machine, are used, then the output of these windings can be interconnected and utilised in a three-phase system, or utilised as three independent single-phase systems. The generated electrical voltage is then stepped up with a transformer and then transmitted to where it is required.

Generator efficiency is the ratio of the electrical power output to the mechanical power input. The efficiency of a very large generator can be as high as 98% or 99% but for a 1 000MW generator, an efficiency loss of just 1% means 10MW of losses must be dissipated, mostly in the form of heat. To avoid overheating, special cooling precautions must be taken and two forms of cooling are usually employed simultaneously. Cooling water is circulated through copper bars in the stator windings and hydrogen is passed through the generator casing. Hydrogen has a thermal capacity 10 times that of air, giving it superior heat removal capability.

Electric grids in the world are either 60Hz (e.g., in the USA) or 50Hz (e.g., in Europe and South Africa). When a two-pole generator is synchronized to the grid, it runs either at 3 600 rpm (for a 60Hz grid) or at 3 000 rpm (for 50 Hz).

Primary drivers

Primary drivers provide mechanical energy to the generators which is the converted into electrical energy. For power generation from natural gas, primary drivers comprise turbines and gas-fired reciprocating engines. A cutaway of a Siemens industrial gas turbine is shown in Figure 1.

Figure 1: Cutaway of a Siemens 593MW gas turbine (Siemens, 2021)

Turbines are used to convert the energy in a flowing fluid into mechanical energy using rotor mechanisms. Gas turbines and steam turbines are thermal turbo machinery, where the work is generated from the enthalpy change of the working fluid as it passes through the turbine. Steam turbines are a mature technology and have been used since the 1880s for power generation. Steam turbines use high pressure steam from a boiler as the working fluid. Superheated steam entering the turbine loses its pressure (enthalpy) moving through the blades of the rotors, and the rotors move the shaft to which they are connected.

Gas turbines are internal combustion engines, using air as the working fluid. The thermodynamic operation of the gas turbine is ideally modelled by the Brayton cycle. Air from the inlet is first compressed using an axial compressor, which performs the exact opposite of a simple turbine. The pressurised air is then directed through a diffuser stage, in which the air loses its velocity, but increases the temperature and the pressure further. In the next stage, air enters the combustion chamber, is mixed with natural gas, and is ignited. As a result of the combustion, the temperature and pressure of the resulting fluid rise to an incredibly high level. This fluid then passes through the turbine section and produces rotational motion to the shaft.

Gas-fired engines are simply reciprocating internal combustion engines designed to run on natural gas and which produce rotational motion.

Options for natural gas

The different options for generating power from natural gas all deal with how the chemical energy of the gas is converted to mechanical rotational energy to drive the generator, as shown in Figure 2. Although there are many different types of generators for different applications, we will not elaborate on power generators, transformers, transmission, and distribution.

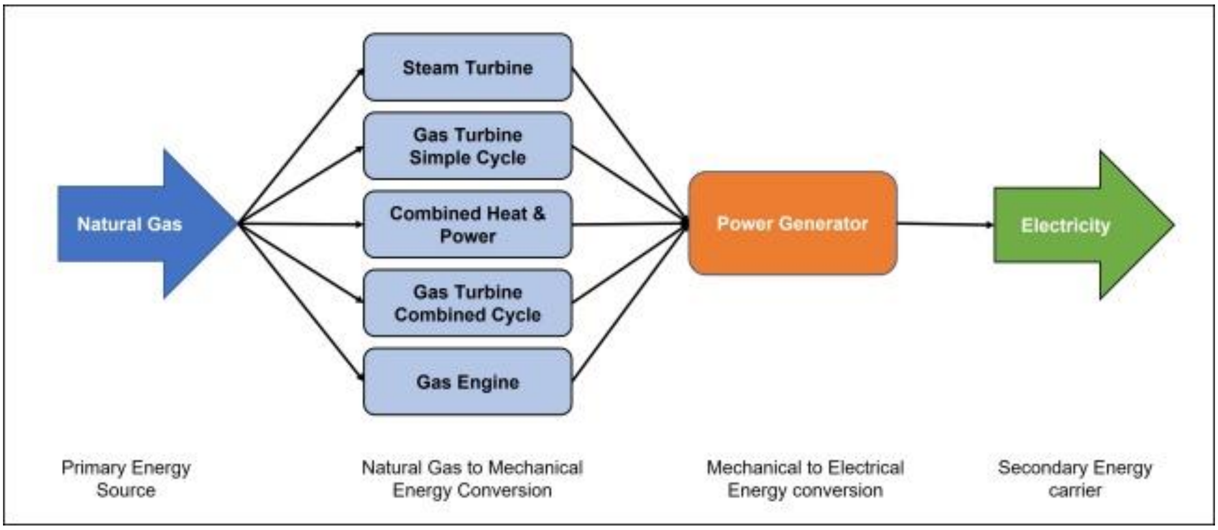

Figure 2: Options for power generation from natural gas

Each of the options for power generation from natural gas is discussed in more detail in the sections that follow.

Steam turbine power plants

Opening remarks

Coal-fired steam turbine or thermal power plants make up most of the power generating facilities in the world. thermal power plants. Electricity demand varies greatly by season and time of day. Because thermal power plants can readily adapt to changes in demand, it plays a central role in maintaining the baseload power supply.

Apart from coal, any other hydrocarbon fuels like oil or natural gas can be used to generate steam for a thermal power plant. Alternatively, nuclear- and geothermal energy can also be used for steam generation.

Technology

In steam turbine power plants, the thermal energy obtained from the fuel source is used to convert water to superheated steam. The steam is used to drive a steam turbine where the thermal energy is converted to mechanical rotational energy. The turbine is connected to a generator where the mechanical energy is converted to electrical energy. A simplified flow diagram of a steam turbine power plant is shown in Figure 3.

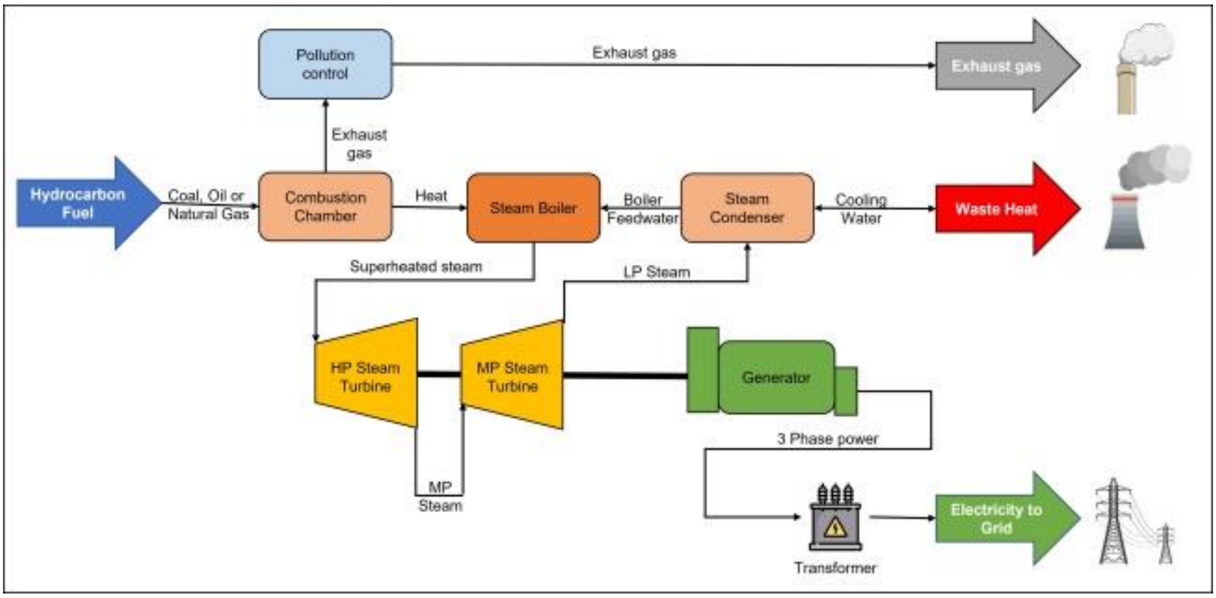

Figure 3: Steam turbine power plant

The pressure and temperature of the steam falls to a lower value and it expands in volume as it passes through the turbine. Depending on the design, the lower pressure steam can be fed to further steam turbines on the same shaft to generate more power. The example shown in Figure 3 has a high pressure (HP) and a medium pressure (MP) turbine.

The expanded low-pressure steam from the final turbine stage is exhausted in the condenser where cooling water is used to condense the steam into water for reuse in the boiler. A boiler feedwater plant is required to supply make up water for steam and condensate lost in the process.

Process efficiency

Considering that three conversion processes, thermal, mechanical, and electrical, are used to extract the energy from fossil fuels, the overall efficiency of a modern hydrocarbon fuelled electrical power generating plant will be about 40% (Lawson, 2020a). This means that 60% of the energy input to the system is wasted. Efficiencies may be <30% in some older plants. Actual efficiencies obtained depend on the fuels used and the technical sophistication of the generating plant and processes.

Applications

Steam turbine power plants produce electrical power for the power grid. Apart from hydrocarbon fuels, other heat sources can also be used to generate steam, i.e., nuclear power, geothermal power, and waste heat from industrial processes.

No new facilities will be built using only natural gas as fuel solely for the purpose of power generation. Better efficiencies can be had by opting for a natural gas-fuelled gas turbine power plant. Natural gas can be used as a fuel in existing steam turbine power plants as a replacement for coal.

Gas Turbine Simple Cycle power plants

Opening remarks

Gas turbine simple cycle power plants are significantly simpler than steam turbine power plants. This is because it does not have the extra equipment (boiler, steam drum, superheater, etc.) or complexity of a steam turbine.

A gas turbine simple cycle power plants comprises an integrated air compressor, combustion chamber, and turbine (together called a gas turbine) and a generator.

Technology

Air is taken from the surroundings, compressed, and fed into the combustion chamber where natural gas is introduced, and the mixture is ignited. The combustion process instantly creates very high pressure and temperature gases. These gases then expand through the turbine section and produce rotational motion (mechanical energy) to the shaft.

With power generation, the gas turbine shaft is coupled to the generator shaft, either directly, with a clutch mechanism, or via a gearbox. A flow diagram of a gas turbine power plant is shown in Figure 4.

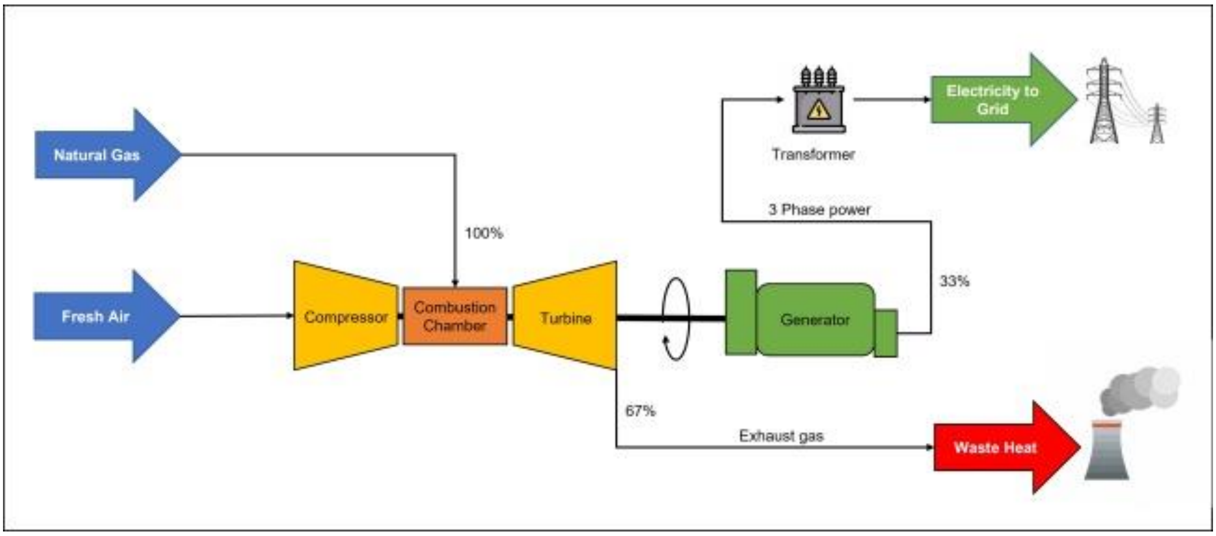

Figure 4: Gas turbine simple cycle power plant

Most of the energy of the natural gas is lost as waste heat in the exhaust gas in a simple cycle power plant. This is not ideal for a baseload power plant.

Process efficiency

Simple cycle plants have great operational flexibility which means they can be started up quickly. However, this comes at a lower efficiency compared to combined cycle plants, as they make less use of the energy in the fuel they are using. The thermodynamic efficiency of these plants is around 33%.

Applications

Gas turbine simple cycle plants are primarily used to provide peak power during periods of very high demand because of their ability to quickly respond to demand fluctuations.

Combined heat and power plants

Opening remarks

Combined heat and power (CHP) plants simultaneous generate usable heat and electric power in a single process. Heat is captured to heat homes or for use in industrial applications. CHP plants enable better overall utilisation of the heat energy supplied to the system. CHP plants are also referred to as cogeneration plants.

Technology

CHP configurations use backpressure steam turbines to generate power and thermal energy. Backpressure steam turbines produce low pressure steam. A typical CHP installation is shown in Figure 5. After the thermal energy in the low pressure steam has been consumed, the resulting condensate is returned to the steam boiler to generate more steam. Heat from the exhaust gases from the combustion chamber can also be used to heat the steam in the low pressure steam drum.

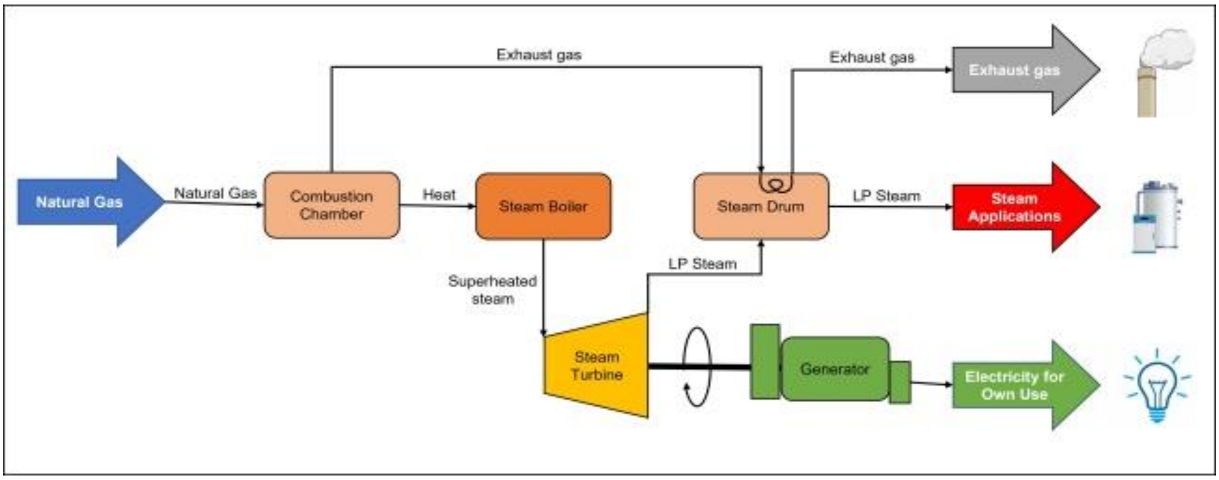

Figure 5: CHP power plants

The primary objective of most steam turbine CHP systems is to deliver relatively large amounts of thermal energy, with electricity being generated as a by-product of heat generation.

According to Lawson (2020b), small-scale or micro-CHP installations are now becoming available for domestic use. The standard domestic heating boiler is replaced by a heating unit which also provides the heat to power a Stirling engine, which in turn drives an electrical generator. The Stirling engine is an external combustion engine and works on the principle that gases expand when heated and contract when cooled.

Process efficiency

Efficiency figures for CHP installations are not comparable to that of other power generation configurations because of the heat energy being used for other purposes than power generation. Overall thermal efficiencies up to about 60% are possible.

Practical Stirling engines with efficiencies of 50% have been produced. This is double the typical efficiency of an internal combustion engine which has greater pumping and air flow losses in the engine and heat losses through the exhaust gases and cooling system (Lawson, 2020b).

Applications

CHP installations are typically much smaller than what is found in power stations tied to the grid and are owned and operated by individual commercial or industrial users. The difficulty of finding a practical use for the surplus heat sets a limit to the size of these systems.

Stirling engine generators with electrical power outputs between 1 kW and 10 kW are available for domestic applications.

Gas turbine combined cycle power plants

Opening remarks

Exhaust gases are discharged to the atmosphere in the gas turbine simple cycle units. In combined cycle power plants, the exhaust gases are used to generate steam in a heat-recovery steam generator (HRSG) before being discharged.

The amount of generating capacity from natural gas-fired combined cycle plants has grown steadily over time, and in 2018, surpassed coal-fired plants as the technology with the most electricity generating capacity in the United States. As of January 2019, U.S. generating capacity at gas-fired combined cycle power plants totalled 264GW, compared with 243GW at coal-fired power plants (EIA, 2019a).

Technology

The first part of a gas-fired combined cycle power plant operates exactly like the gas turbine simple cycle plant described above. However, instead of exhaust gases being discharged to the atmosphere, the exhaust gases are used to generate steam in a HRSG before being discharged. The steam so generated is used to power a steam turbine and drive a second generator to generate more electric power. A simplified flow scheme for a gas-fired combined cycle power plant is shown in Figure 6.

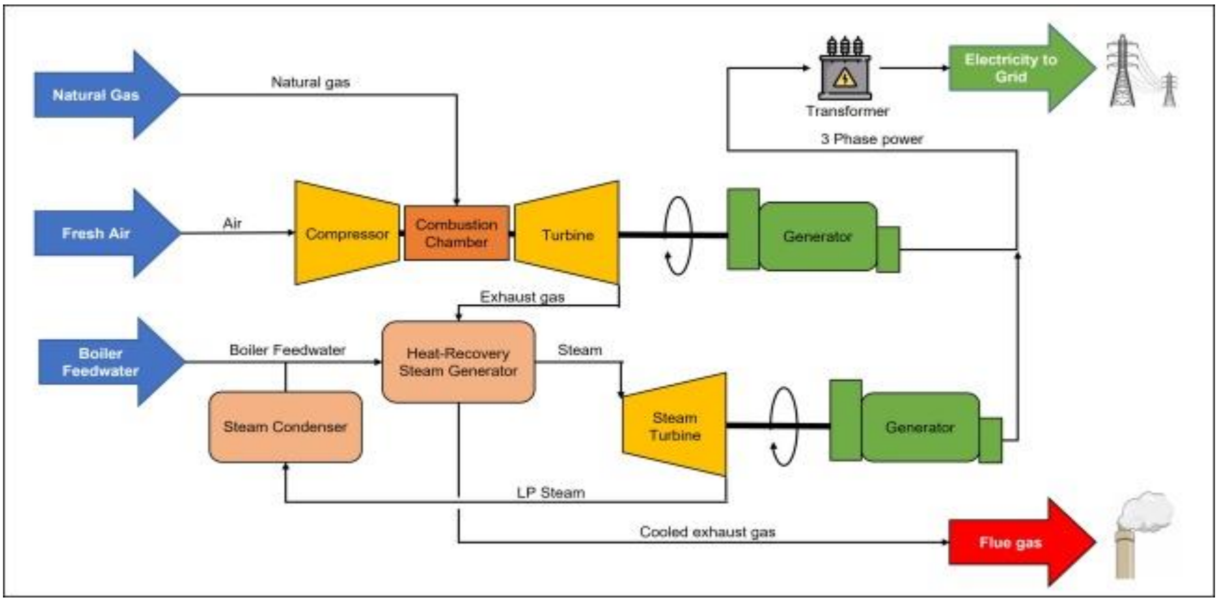

Figure 6: Gas turbine combined cycle power plants

Typically, the hot exhaust gases from several gas turbines will be used to generate steam for a single steam turbine. An alternative arrangement also exists where the steam turbine is mounted on the same shaft as the gas turbine to add additional mechanical energy to drive a single generator.

Process efficiency

Siemens (2021) maintain that the efficiency of their SGT5-9000HL 593 MW gas turbine based combined cycle plants can be as high as 64%. General Electric (2021a) also claim the same efficiency of their 9HA gas 571 MW turbine in combined cycle mode.

Applications

Gas turbine combined cycle plants are not as quick to start as simple cycle plants because of the increased complexity. However, it can nevertheless be put on load in a very short time. Gas turbine combined cycle plants are used as peak load, base lead as well as standby plants.

Gas engine power plants

Opening remarks

Beside gas turbines, another way of utilising natural gas to generate electricity is by using gas-fired internal combustion engines. When used to drive a generator, natural gas engines are efficient and clean and have become popular for small-scale distributed power generation applications. Internal combustion engines present an efficient means of converting gaseous or liquid fuels into mechanical and electrical energy.

Technology

Gas engine power plants are available in standardised designs comprising the gas-fired internal combustion engine and the generator unit. Engines used are typically spark-ignition engines. A flow scheme for a gas-fired internal combustion engine power plant is shown in Figure 7.

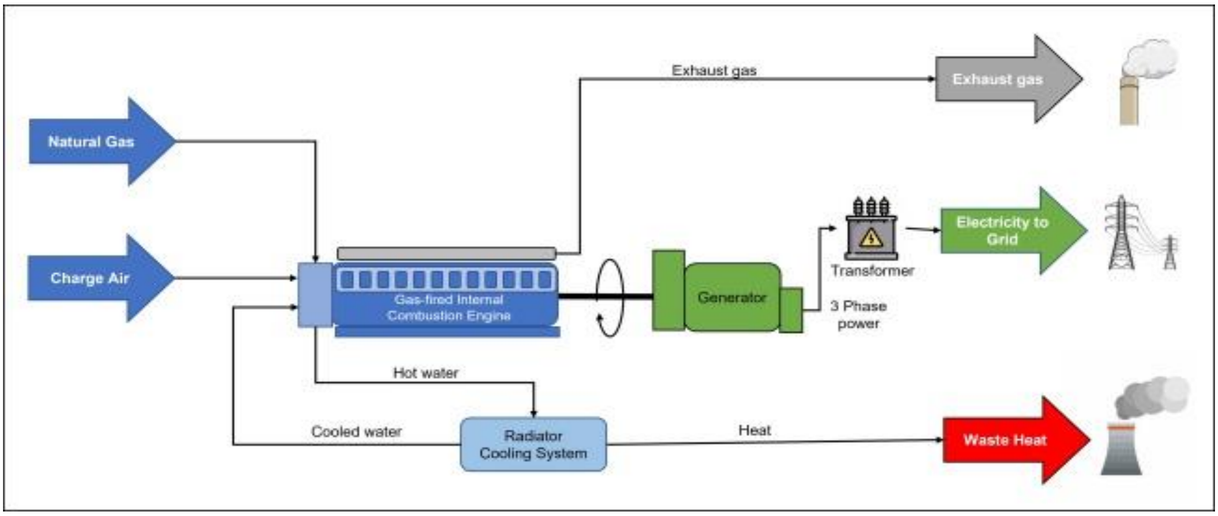

Figure 7: Gas engine power plants

To reduce engine emissions during combustion of natural gas, the combustion temperature is deliberately kept low by introducing more oxygen than is required for complete combustion of the fuel, even though this reduces the efficiency that a reciprocating engine can achieve significantly. Such engines are described as lean-burn engines and can operate with an air to fuel ratio of between 20:1 and 50:1.

The greater proportion of air to fuel lowers the overall combustion temperature which reduces the production of nitrogen oxides from nitrogen in air. More air also provides the conditions for much more complete combustion of the fuel, resulting in reduced carbon monoxide and unburnt hydrocarbons in the exhaust gases.

Process efficiency

Suppliers of gas engine power plants, or generating sets, claim electrical efficiencies of between 48% and 51%, although with lean-burn engines will struggle to meet these high efficiencies in normal operation. With heat recovery from the hot exhaust gases when used in combined cycle mode, this can be pushed up further. High efficiency translates into considerable savings in fuel costs compared to other technologies.

Gas engine power plants can achieve a plant availability of up to 95% and a warm start up time of two minutes.

Applications

Wärtsilä, Jenbacher, Cummins, and Caterpillar, to name a few, provide natural gas-based power generation solutions for baseload, peaking and standby operations. Wärtsilä's gas and multi-fuel power plants are typically based on modular 4MW to 19MW internal combustion engine units. Jenbacher generating sets start at 250kW and go up to 10MW electrical power output. Units from Cummins deliver between 13,5kW and 3 400MW and Caterpillar has a range of 45kW to 10 900MW.

Reciprocating internal combustion engines are now becoming increasingly popular for larger utility-scale power generation applications, especially in areas with high levels of electricity generation from intermittent sources such as wind and solar (EIA, 2019b).

Environmental impacts

Great progress has been made in reducing the environmental impact of coal-fired power stations, especially for pollutants like carbon monoxide, lead, sulphur dioxide (SO_2), nitrogen oxides (NO_x), ground-level ozone and particulate matter. A new pulverized coal-fired power plant can reduce the emission of NO_x by 83%, SO_2 by 98% and particulate matter by 99,8%, as compared with a similar plant having no pollution controls (Institute for Energy Research, 2017). However, coal remains the dirtiest of the fossil fuels and finance for future coal-fired power stations will be difficult to obtain.

Natural gas is composed almost entirely of methane and is considered the most desirable of the fossil fuels for power generation. It is substantially free of particulate matter, combustion is smokeless, and, because it is a gas, it mixes easily and intimately with air to give complete combustion. The combustion of natural gas emits almost 30% less carbon dioxide than oil, and about 45% less carbon dioxide than coal. Its combustion produces negligible amounts of sulphur, mercury, and particulates. The use of natural gas in place of coal or oil will thus contribute to reduced smog formation acid rain, decarbonisation, and lower greenhouse gas emissions. Unfortunately, methane itself is a greenhouse gas with the ability to trap heat almost 23 times more effectively than carbon dioxide.

There are various opportunities to reduce greenhouse gas emissions associated with electricity generation, transmission, and distribution. One way is to increase the efficiency of fossil-fired power plants using advanced technologies and fuel switching. For instance, convert coal-fired boilers to use natural gas and convert simple cycle gas turbine installations to combined cycle facilities. Other options include greater use of renewable energies and carbon capture and sequestration. General Electric (2021b) believes that the world is best served by accelerating renewables deployment, running existing gas plants more, and adding new gas capacity as the industry reduces coal generation. The power sector's journey to lower carbon must be characterised by rapid deployment of renewable energy resources and a rapid reduction in coal usage.

Coal-to-gas switching is a quick way to reduce emissions in many sensitive regions. In addition, the possibility of switching turbines from natural gas to hydrogen, or natural gas/hydrogen blends, when hydrogen becomes more freely available, makes the prospect of a change to natural gas-powered power generation more tenable.

Closing remarks

When it comes to power generation, a switch from coal to gas represents a fast and effective win for emissions reduction in many regions around the world. In future, switching turbines from natural gas to hydrogen fuel, and/or introducing carbon capture and storage solutions, can lead to low or near zero carbon emissions. It is heartening to see that the manufacturers of gas turbines and gas engines are working on prototypes that will be able to switch over from natural gas to 100% hydrogen fuel with minimal modifications.

The competitiveness of natural gas relative to coal in power production is highly dependent on regional market conditions, particularly fuel prices. However, growth prospects for gas are affected not only by the competitiveness of gas prices, but also by recognition of the local air pollution and climate benefits of gas over coal. The introduction of carbon taxes and regulation of plant emissions could encourage coal-to-gas switching.

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