& Combined-Cycle Gas Steam Turbine Power Plants

3rd Edition

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1 Introduction

This third edition of the book *Combined-Cycle Gas & Steam Turbine Power Plants* has been updated and extended to give an accurate picture of today's state of this interesting technology for power generation. It also includes chapters on actual themes such as CO_2 capture and storage, as well as integrated gasification combined-cycle plants (IGCC). These topics have gained a lot of attention as part of the discussion around global warming as potential solutions to this issue.

In substance, the book gives a comprehensive overview about the combined-cycle power plant from a thermodynamic, technical, and economical point of view. It is intended to provide material for lectures and provide an excellent understanding of the potential of this technology. Thanks to practical examples, it offers a real help for professional work. It is equally well suited for students interested in power generation.

The book strives to answer to the following two questions:

- What is a combined-cycle power plant?
- Why are combined-cycle plants among the leading technologies for large power plants?

Combined cycle can be defined as a combination of two thermal cycles in one plant. When two cycles are combined, the efficiency that can be achieved is higher than that of one cycle alone. Thermal cycles with

The risks remaining are mostly related to the plant itself: cost, efficiency and reliability.

The extreme case of this type of project is the **Tolling Agreement**. The investor has an agreement with a client, who supplies him with the fuel and takes off the electricity to convert the fuel into electricity at an agreed-upon fee, based on expected efficiency and availability.

The normal power plant project is, however, fully exposed to the market, which leads to a much higher risk profile. In this case, it is important to make a thorough market analysis in order to develop a solid market scenario. This analysis should include sensitivity analyses and worst-case scenarios.

In fossil fuel plants, both electricity and fuel markets have to be analyzed; however, both markets are coupled to a certain extent. For example, if in a given market most of the players are using gas as fuel, the price of electricity will go up if the gas prices are going up and vice versa.

The **interest and amortization cost** has a direct impact on the production cost of electricity produced. The main factors are:

- Debt-to-equity ratio
- Terms of the debt, such as interest and amortization

The debt-to-equity ratio depends mostly on the risk profile of the project. An IPP project with little market risk can be highly leveraged, which means a high percentage of the project financing can be provided in the form of debt. In good projects up to 80% of the capital required can be borrowed, and the equity share is only 20%.

In risky projects, a much lower leverage is possible. Typically, up to 50% of the capital required has to be provided as equity. The normal utility project falls in this category.

Normally, these merchant projects are realized by large utilities with a strong balance sheet. Financing is done based on the balance sheet of the investor (on-balance sheet financing). In this case, the borrower has the balance sheet of the owner of the power plant (the utility) as a guarantee.

So reliability is the percentage of the time between planned overhauls where the plant is generating or is ready to generate electricity, whereas the availability is the percentage of total time where power could be produced.

Availability and reliability have a big impact on plant economy. When a unit is down, power must be generated in another power station or purchased from another producer. In each case, replacement power is generally more expensive. The power station's fixed costs are incurred whether the plant is running or not.

In deregulated markets, reliability is crucial. At peak tariff hours, a major portion of the income is generated and the plant must be reliable. Scheduled outages can be planned for off-peak periods when tariffs are close to or even below variable costs. Then only a small income loss results from the planned outages.

Typical average figures for the availability and reliability of well designed and maintained plants are indicated in table 3–6.

Table 3–6 Availability and reliability of various power plants

Type of Plant	Availability	Reliability
Combined cycle plant	90–94%	95–98%
Gas turbine plant (gas fired)	90–95%	97–99%
Steam turbine plant (coal fired)	88–92%	94–98%
Nuclear power plant	88–92%	94–98%

These figures are valid for plants operated at base load. They would be lower for peak- or intermediate-load operation because frequent startups and shutdowns reduce the lifetime of critical components and increase the scheduled maintenance and forced outage rates.

The major factors determining plant availability and reliability are:

- Design of the major components
- Engineering of the plant as whole, especially of the interfaces between the systems

considerations, it is generally better to burn the fuel directly in a modern gas turbine rather than in the HRSG because the temperature level at which heat is supplied to the process is higher (GT versus ST process in table 4–1). For that reason, the utilization of supplementary firing is decreasing.

The factors involved in combined-cycle installations with supplementary firing are discussed in more detailed in chapter 5.

Efficiency of combined cycles without supplementary firing in the HRSG

The most common and straightforward type of combined cycle is one in which fuel is supplied in the gas turbine combustion chamber without additional heat supplied in the HRSG. By substituting equations (4–4) and (4–7) into equation (4–2):

$$\eta_{CC} = \frac{\eta_{GT}\cdot\dot{Q}_{GT} + \eta_{ST}\cdot\dot{Q}_{GT}(1-\eta_{GT})}{\dot{Q}_{GT}}$$

$$= \eta_{GT} + \eta_{ST}\,(1-\eta_{GT}) \qquad \textbf{(4–8)}$$

Differentiation makes it possible to estimate the effect that a change in efficiency of the gas turbine has on overall efficiency:

$$\frac{\partial\eta_{CC}}{\partial\eta_{GT}} = 1 + \frac{\partial\eta_{ST}}{\partial\eta_{GT}}\,(1-\eta_{GT}) - \eta_{ST} \qquad \textbf{(4–9)}$$

Increasing the gas turbine efficiency improves the overall efficiency only if:

$$\frac{\partial\eta_{CC}}{\partial\eta_{GT}} > 0 \qquad \textbf{(4–10)}$$

From equation (4–9):

$$-\frac{\partial\eta_{ST}}{\partial\eta_{GT}} < \frac{1-\eta_{ST}}{1-\eta_{GT}} \qquad \textbf{(4–11)}$$

Improving the gas turbine efficiency is helpful only if it does not cause too great a drop in the efficiency of the steam process.

To ease the permitting process where water is not available, a direct air-cooling system with an air-cooled condenser (or a dry cooling tower as indirect system) is used. The disadvantages of this method include higher costs and higher exhaust steam (condenser) pressure, mainly in the off-design points with high ambient temperatures (therefore less power output of the steam turbine) leading to lower plant efficiency. In combined-cycle plants with a direct air-cooling system (ACC) the ambient air temperature directly influences the ST output and consequently the efficiency, which is not (or to a less extent) the case for the other cooling system (see table 5–1).

Table 5–1 Comparison of combined cycle performance data for different cooling systems and ambient temperatures

	Design: ambient temperature = 6°C (43°F)		**Off-design:** Summer ambient temp = 30°C (88°F)	
	P MW	**Efficiency η %**	**P MW**	**η%**
Cooling tower	411.7 100%	57.5 100%	363.5 100%	56.1 100%
ACC	408.1 99.1%	57.0 99.1%	345.4 95%	53.3 95%

In special cases where only a limited amount of water is available, and an evaporation system could be used with restrictions regarding visible plumes, a combination of a dry and wet system with hybrid cooler cells (consisting of a dry and a wet section) could be the optimal solution. Design parameters/performance data are similar to the wet cell cooling tower, but would result in slightly higher costs.

The temperature of the cooling medium has a major effect on the efficiency of the thermal process. The lower the temperature the higher the efficiency that can be attained, because the pressure in the condenser is lower, producing a greater useful enthalpy drop in the steam turbine and hence an increase in steam turbine output and in plant efficiency. This is illustrated in figure 5–10.

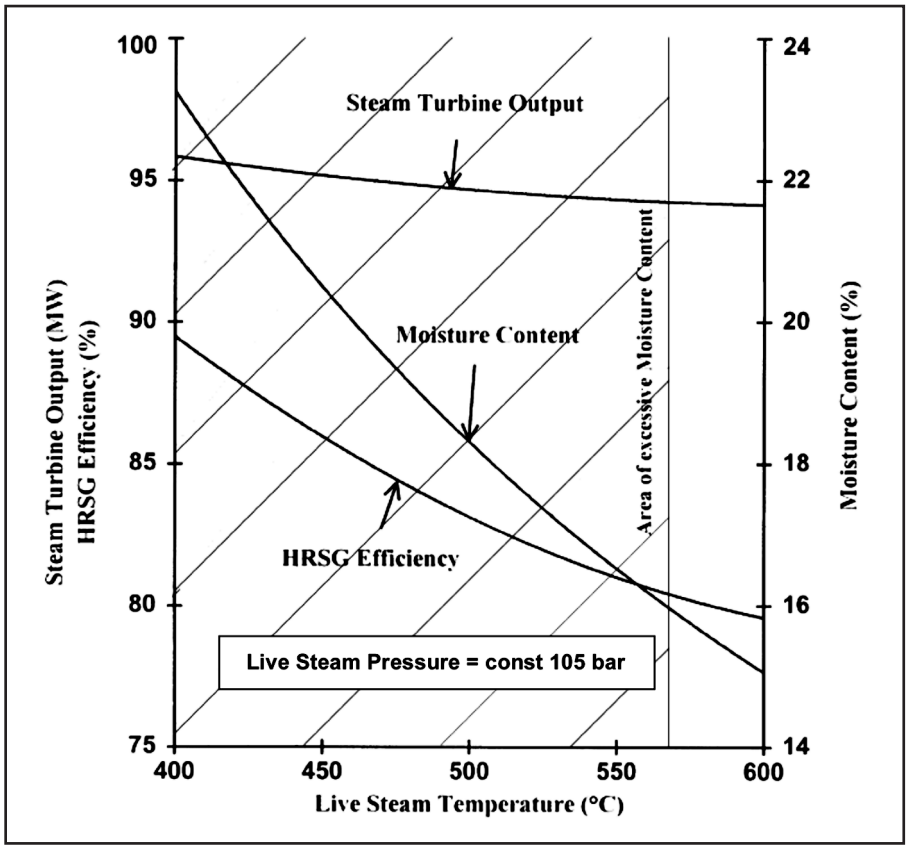

Figure 5–23 Effect of live-steam temperature on steam turbine output for a single-pressure cycle with 105 bar (1508 psig) live-steam pressure (including HRSG efficiency and steam turbine exhaust moisture content)

For gas turbines with lower exhaust gas temperatures than the one in the example, a lower live-steam pressure level would have to be chosen for the reasons previously discussed.