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## **DESIGN CONSIDERATIONS FOR COMBINED CYCLE PLANTS FOR THE DEREGULATED MARKET—AN EPC CONTRACTOR'S PERSPECTIVE**

**Ram G. Narula**

Principal Vice President and  
Bechtel Fellow

**Martin Massy**

Business Development  
Manager, EAMS Region

**Jyoti Singh**

Mechanical Engineer

Bechtel Power Corporation, Frederick, Maryland USA

### **ABSTRACT**

Deregulation of the power industry in Europe and the attendant pressures to innovate have led to new approaches to financing and construction of power plants. This paper discusses the salient design, procurement, and project execution considerations of a combined cycle (CC) plant for a deregulated market.

### **INTRODUCTION**

While deregulation of the electricity market in Europe started about a decade ago, first in the Scandinavian countries and then in the United Kingdom, it was not until February 1999, when European Union (EU) directive 96/92 took effect, that the deregulation pace picked up. Now, more than 60 percent of the EU energy sector has been liberalized.

Before deregulation, most of the major utilities in Europe and elsewhere were vertically integrated government-owned monopolies. Their primary obligation was to serve their customers with reliable power. Cost minimization and profitability were not necessarily key drivers. The utilities had large research engineering, procurement, construction management, and startup departments and by and large directly procured the equipment and performed detailed designs themselves. Deregulation has resulted in greater competition and brought in new players—the independent power producers (IPPs) that want to develop and own power generation facilities and provide competitive power. The obligation to serve of the monopoly utilities is being replaced by freedom-of-choice for consumers. The IPP projects generally employ non-recourse financing, taking on significant levels of debt. The lending institutions for these projects insist that IPPs use reputable contractors that can provide the performance wrap (cost, schedule, and plant performance). Thus, design and

construction of such plants are driven by “needs” justified on an economic basis and not mere “wants.”

The IPP plant of choice today is most often gas-fired combined cycle, which, for large plants, is highly efficient with relatively low capital cost and time to construct. The paper discusses the unique design, construction, and project execution approach employed for CC IPP plants.

### **FRONT-END PLANNING AND SITE SELECTION**

Well-thought-out front-end planning and site selection are vital to the success of a lump-sum turnkey (LSTK) CC IPP project. The key ingredients of front-end planning include:

- Fuel purchase and power sales strategies that are sufficiently robust to meet lenders' requirements. These are frequently long-term power purchase and fuel supply agreements. However, merchant plants that have neither have also been built and financed. The fuel composition must meet stringent requirements of modern advanced GTs to avoid retrofitting expensive fuel pre-treatment systems.
- Selection of a reputable and experienced EPC contractor with a proven track record in executing LSTK projects. A very well defined and mutually agreed upon project scope book is essential.
- An environmental plan that incorporates local and national requirements.
- Experienced plant operating staff or an operations and maintenance (O&M) contract.

The key ingredients of an ideal site are:

- Proximity to a high pressure gas pipeline and fuel availability at a reasonable price for the life of the plant.
- Proximity to a high voltage transmission line and a load center.

- Availability of sufficient cooling water/makeup water to meet the plant's cooling needs. While air-cooled condenser technology is available for arid sites, it requires higher capital cost and results in somewhat reduced plant output.
- Community acceptance and support. These conditions are vital because the “not-in-my-backyard” syndrome can cause long and very expensive delays in permitting.

The authors believe that the key to a successful project is to have a qualified EPC contractor aboard early that can work hand-in-hand with the Owner to achieve the desired results for all project phases from development to execution.

## DESIGN CONSIDERATIONS FOR A COMBINED CYCLE PLANT

An ideal CC plant would have low capital cost, operate at high efficiency at both full and part load, have high reliability, have a high level of automation, be able to start up quickly, and be easily and inexpensively maintained. Unfortunately, these goals conflict with each other to some extent. For example, the plant can be designed for higher efficiency, but to achieve this higher efficiency, more money must be spent. Similarly, higher levels of redundancy can be employed to achieve higher reliability, but this, too, increases the plant capital cost.

Thus, an IPP must decide or anticipate how it intends to operate the plant. If the plan is to operate at base load, then the plant must be designed for a very high efficiency. However, if the business plan is to primarily satisfy peak seasonal demand, then plant efficiency becomes less important and greater emphasis must be placed on reducing capital cost per kW.

The plant designer's task is to balance the various criteria to achieve the optimum plant for each particular application. This may require detailed design studies, and best results are obtained when plant designer and IPP developer work closely together. Important design features that must be considered in designing the optimum plant are described in the following sections.

### Selection of Gas Turbine(s)

The resurgence of the power market in the United States in the last 3 years and the popularity of the gas-fired CC plant due to its relatively lower fuel price, lower capital cost, higher thermal efficiency, and environmental friendliness have resulted in shortages in the availability of gas turbines (GTs) despite a four-fold increase in the manufacturing capacity. Thus, the utilities and IPPs are signing up for advance purchases or reservation agreements that in some cases have not been thought through sufficiently to determine the optimum characteristics for a particular application. While the GT supply situation may correct itself because of the looming slowdown in the global economy, our experience indicates that owners would still be well advised to involve their EPC contractor in any advance purchase or reservation agreement for GTs or power islands (PIs) to ensure that terms and conditions essential to managing the project design, construction, and commissioning are adequately included in these agreements.

An experienced EPC contractor can work with the equipment supplier and the customer to ensure the scope is complete and all interfaces are well defined. Examples of areas in which the EPC contractor can add value to an owner's reservation agreement are:

- Assuring adequate coverage of performance test tolerances and measurement uncertainty protocol
- Accounting for the temperature drop in main and reheat steam lines
- Optimizing pressure drops in main and reheat steam lines
- Addressing impact of GT performance offsets (between output and exhaust energy) on heat recovery steam generator (HRSG) and steam turbine (ST) sizing
- Ensuring consistency in pollutant levels and units included in the plant permits and those guaranteed by GT suppliers
- Determining appropriate liquidated damage levels

The final selection of the GT(s) should be based on the price, delivery schedule, basic plant objectives, economic selection criteria, and the operating record of the GT fleet with regard to reliability, availability, and emissions.

### Steam Cycle Parameters Selection

Because fuel constitutes 50 to 70 percent of the levelized cost of electricity from a combined cycle plant, cycle efficiency has historically been the single most dominant variable in selecting a plant's thermodynamic configuration. Thus, a triple pressure reheat cycle has become the industry standard for achieving higher efficiency. With the increased firing temperatures and the attendant higher gas exhaust temperatures from the GTs, the main steam pressures have steadily increased over the years. Today, 124 bar (1,800 psig) cycle in the unfired mode is considered the industry norm. Main steam pressures approaching 166 bar (2,400 psig) are being considered and used where the fuel cost is high. Therefore, a detailed project-specific study is recommended for optimizing the thermodynamic cycle to meet the Owner's objectives. For screening purposes, the following rules-of-thumb may be used:

Cycle Parameters	Change in Net Plant Output (%)	Change in Net Plant Heat Rate (%)
Main steam pressure, bar (psig)		
166 (2,400)	+0.30	-0.30
124 (1,800)	Base	Base
100 (1,450)	-0.30	+0.30
86 (1,250)	-0.40	+0.40
*Reheat versus nonreheat (three pressure)	+1.20	-1.20
*Reheat versus nonreheat (two pressure)	+0.90	-0.90
*Three pressure versus two pressure (reheat cycle)	+1.10	-1.10
*Three pressure versus two pressure (nonreheat cycle)	+0.80	-0.80

\*See [1]

A power plant typically does not operate at a single point throughout its operating life. Therefore, the plant must be designed so that it can maintain its efficiency over a wide load range as opposed to picking the highest efficiency at one guaranteed point. This must be considered when selecting the cycle and balance-of-plant (BOP) equipment.

### Power Augmentation Options

In the warm weather months, a CC plant loses as much as 10 to 15 percent of its rated output because of high ambient air temperature. For IPP projects, power output enhancement may offer significant economic benefits. The predominant methods for power output enhancement are:

- Inlet air cooling
  - Evaporative cooling
  - Inlet air fogging
  - Refrigeration cooling
- GT power augmentation with moisture injection
- Supplemental firing of HRSG to increase ST output
- Combination of the above

Each of the foregoing power enhancement methods will achieve a different level of power output enhancement and impact on plant heat rate and capital cost. Depending on the Owner's economic objectives, one or a combination of these methods may be adopted. The following rules-of-thumb can be used for initial planning for advanced GTs using a dry low NO<sub>x</sub> combustor and assuming a warm weather day:

Power Augmentation Option	Change in Net Plant Output (%)	Change in Net Plant Heat Rate (%)
Base (no power enhancement)	Base	Base
Evaporative cooling (5.5 °C, 10 °F)	+3	Negligible
Inlet air fogging (6.7 °C, 12 °F)	+4	Negligible
Refrigeration cooling (11 °C, 20 °F)	+6	+1
Steam injection	+4	+2
Partial supplemental firing (15%)	+3	+1
Full supplemental firing (100%)	+20	+7
Steam injection and partial supplemental firing	+8	+3

It should be noted that output gain from evaporative cooling and inlet air fogging varies considerably with the

ambient relative humidity (RH). These options are generally more cost effective at sites with low ambient RH. The incremental cost for power augmentation can vary from \$50 to \$300 per kW depending on the option(s) selected for a given site.

### Single Versus Multishaft Considerations

The term single shaft combined cycle (SSCC) refers to the configuration where the GT and ST drive a single electrical generator, the various rotors being connected by couplings to form a single continuous shaft and operating at a common speed. The configuration where each GT and ST drives a separate electrical generator is called a multishaft combined cycle (MSCC). Combining GT and ST shafts eliminates one electrical generator and its associated bus duct, transformer, and control and protection equipment. As a result, the electrical equipment related costs are generally lower with SSCC. Conversely, however, the civil costs increase with SSCC because of increased building volume and complex foundation design to facilitate generator removal. Likewise, mechanical costs increase because of increased piping lengths and more BOP equipment associated with multiples of single trains for SSCC.

Refer to [2] for a detailed comparison of SSCC with MSCC for one-, two-, and three-train plants in terms of design, construction, startup, and thermal performance considerations and cost. The authors' experience shows that, on an overall plant basis, the total installed cost for a single GT plant is about the same for SSCC and MSCC. However, for two- and three-GT applications, the SSCC cost is 3 to 5 percent higher than for an MSCC plant with a single ST. Multiple trains of SSCC or MSCC do offer speed-to-market and some operational flexibility.

### Reliability/Availability Considerations

A power plant cannot make money when it is down for maintenance. This is especially true during peak periods when power sales revenues are high. In the private power market, a plant must be available to generate power during any period when its revenues will exceed its operating expenses. Therefore, decisions about factors affecting plant reliability, such as the level of redundancy, must be balanced against the drive to minimize capital cost. To meet an Owner's reliability/availability goal, an availability study is recommended. The technical approach used is to divide the plant into basic subsystems and calculate each subsystem's probability of operation based on the availability of each component in each system. The subsystem availabilities are combined to determine overall plant availability. Key data required to make these calculations are mean time between failures (MTBF) and mean time to restore (MTTR) equipment. The MTTR values must include plant startup and shutdown times in addition to MTTR for the component itself. Data sources include Electric Power Research Institute reports, the North American Electric

Reliability Council (NERC) generating availability data system, the Strategic Power Systems Operational Reliability Analysis Program (ORAP) database, and equipment manufacturer guarantees.

It must be recognized that achieving high reliability/availability is a team effort between the Owner and EPC contractor because both can affect it. The following factors influence availability:

- EPC constructor responsibilities
  - Adequate redundancy
  - Proven equipment and plant designs
  - Quality suppliers with dependable supplier technical support
  - Experienced design, construction, and startup team
- Owner/operator responsibilities
  - Adequate spare parts inventory
  - Qualified, well-trained operators
  - Robust preventive maintenance program
  - Plant management system that rewards performance

Clearly, reliability/availability is a joint concern and responsibility of the Owner and the EPC contractor. Early discussions between the EPC contractor and the Owner on this joint approach to availability are very worthwhile.

### Equipment Redundancy Considerations

If a plant is operating under an agreement that insulates capacity payments from short or intermittent forced outages (e.g., outage bank), then the only cost of downtime is the difference between what the plant would have been paid to generate power and the incremental cost to produce that power (mostly the fuel cost). In a competitive environment, each redundant piece of equipment should be incrementally justified on an economic basis. Thus, if a redundant 100-percent-capacity pump is being considered, the marginal cost of that pump should not exceed the marginal revenue that its installation is expected to produce. When considering marginal cost, it is important to include the total installed cost of the pump, including its maintenance and the additional space it will occupy and the effect of this space on the other bulk quantities in the plant. In addition, the plant capacity factor must be considered because there is obviously no revenue loss due to equipment failure when the plant is already off line due to lack of demand.

One general rule that emerges is that the more costly the component, the harder it is to justify providing redundancy. Conversely, the less reliable the piece of equipment, the more worthwhile redundancy becomes. Finally, the longer the outage caused by a failure, the easier it is to justify the redundancy. For a detailed examination of this subject, the reader is invited to [3], which presents a new methodology for net present value analysis of marginal costs and benefits to optimize equipment redundancy.

### Maintenance Considerations

Adequate access space must be provided to permit disassembly of key operating components. Fork lift access is required for mechanical equipment such as pumps and compressors. Permanent overhead cranes are frequently provided for STs, but sometimes mobile cranes can be used instead. In the United States, mobile cranes are the norm for GTs. Pull space is necessary for condenser and heat exchanger tubes. Access is needed into electrical cabinets. A laydown plan is needed for STs, but this does not necessarily mean that a large operating deck needs to be provided adjacent to the turbine. The fact that access space has an associated cost must always be kept in mind.

Another important maintenance consideration is an adequate supply of spare parts. To provide the lowest total material cost, the spare parts should be purchased at the same time as the original equipment. The EPC contractor must work closely with the Owner to establish the optimum level of on-hand spare parts. Sufficient warehouse space must also be provided. Owners that are planning more than one plant for the same geographic area may want to consider spare parts interchangeability to keep the spare parts cost low. The spare parts philosophy is one aspect of a more general decision regarding reliability.

### Plant Cycling Design Features

In a completely deregulated market, plants will be dispatched by an independent system operator or some equivalent pool, which will determine the forecast for electric power demand and take bids to supply 24-hour ahead power from all available sources. Under such a scenario, the plant could be up producing full power for 1 day, shut down the next day, and up again to some partial load the third day. Regardless of whether it is designed for maximum efficiency or lowest possible capital cost, a CC plant must have some cycling flexibility. The level of desired cycling must be anticipated and specified up front because of its significant impact on selection of the plant thermodynamic cycle and major equipment, and on plant cost. Cycling can be defined as any or all of the following operating conditions:

- Frequent starting and stopping
- Frequent operation at reduced load
- Frequent load changing

A power plant is impacted by cycling operation in three major areas: thermal stress, water chemistry, and operational considerations. Frequent starting and stopping or frequent load changes expose the major power cycle equipment to thermal stress due to heating and cooling cycles. This thermal cycling, especially when rapid, can reduce the life of these components and affect reliability. Cycling operation, including the shutdown period, also affects a plant's water chemistry, most notably the control of dissolved oxygen. Frequent startup and shutdown place greater demands on the plant operators. In addition, a plant's design impacts its startup time, and

minimizing startup time for a plant requiring frequent startups may be an important consideration.

IPP plants may be subject to frequent starts and stops as well as to part-load operation. The various potential operating scenarios must be considered in the design and must be fully understood by the plant designer and the major equipment suppliers. The plant must be able to start up quickly to minimize startup fuel consumption. Design features that improve startup time must be considered, such as a properly sized steam bypass system, remote operation capability for valves used during every startup, and provisions to keep the plant in a hot standby condition (such as HRSG stack damper and auxiliary steam to maintain steam to turbine seals to keep a vacuum). Recommended features for specifying power island equipment and designing major systems are detailed in [4].

### **Steam Bypass System**

An adequately sized bypass system is essential in a plant requiring frequent starting and stopping. This sizing directly influences the plant's startup procedure and the time required to achieve full load. To properly design this system, startup criteria and limitations of the major power cycle equipment (allowable ramp-up rates, required steam/metal temperature differences, etc.) must be fully understood.

The primary objectives of a steam bypass system are:

- Allow steam piping to be warmed earlier and thereby lower thermal stresses
- Bring the steam turbine on line faster by appropriately matching the steam and metal temperatures
- Preclude lifting of safety valves during the transients following a steam turbine trip while the gas turbine is running back
- Provide a means to dump steam during steam turbine load rejection

These objectives can normally be met by using a conventional direct or a cascade turbine bypass system of approximately 75 percent capacity (at design pressure). Under certain circumstances, it would be beneficial to design the bypass system to allow the GT(s) to remain at full load when the ST is tripped. This means that HRSG reheater tubes must be protected from being overheated by the hot gas turbine exhaust by having the steam continue to flow through the reheater tubes even if the steam turbine shuts down. This is accomplished by using a 100-percent-capacity cascade bypass system. The 100-percent bypass system leads to larger piping, control valves, and condensate pumps. The condenser and cooling tower may also be affected. The condenser cooling capacity must be checked to ensure that the maximum exhaust pressure of the steam turbine during coastdown or startup is not exceeded. Inlet water temperature to the cooling tower must not exceed the maximum temperature allowed for the cooling tower fill material. If extended operation in the bypass mode is required, makeup water systems must be checked to ensure that they can handle the higher evaporation rate from the cooling tower under this high load condition. The 100-percent bypass

system increases the plant capital cost. Thus, a project-specific cost/benefit analysis must be performed to select the optimum size and type of bypass system.

### **Noise**

While meeting noise requirements for a power plant located in an urban area is always a challenge, it takes on an additional dimension for plants designed for cycling duty and subjected to a daily startup and shutdown routine. A base load plant that starts only a few times a year is more forgiving. However, if the plant needs to start up daily, for example at 6:00 a.m., noise from steam bypass system valves, drain and vent valves, and cooling tower fans and radiated by stack and various other ducts and steamlines becomes noticeable and could invite complaints from the neighborhood if the plant is not properly designed to mitigate it. Noise mitigation and mitigation costs (that in some cases can add up to \$10 to \$15 per kW) should be properly accounted for at the design stage to preclude severe restrictions being imposed once the plant becomes operational. One of Bechtel's current plants in Europe is being designed with the following features to meet the permitted noise limitations:

- Noise barriers around HRSGs and transformers
- Noise attenuated roof and side walls for the turbine building
- Low noise air-cooled condenser fans and transformers
- Use of drag valves for steam bypass system valves
- Silencers for stack and vents

## **PROCUREMENT CONSIDERATIONS**

### **Multi-Project Acquisition**

Strategic sourcing of materials to achieve significant cost savings has been practiced in the manufacturing industry for some time. In the electric power industry, the common practice has been to competitively bid all equipment and materials on a project-by-project basis. A major EPC contractor that buys billions of dollars worth of equipment and materials every year can achieve significant cost savings by leveraging material quantities, standardizing the products, and minimizing transaction costs.

Equipment and materials typically account for 40 to 60 percent of a new power plant's total installed cost. By keeping a strong focus on acquisition of these materials, an EPC contractor can achieve significant cost savings and pass them on to its customers.

### **Power Island Versus Component Approach**

The term power island is used to include procurement of GT, HRSG, and ST from a single original equipment manufacturer (OEM). It should be noted that many OEMs do not themselves manufacture all three components.

The term component approach is used when each of these three components—GT, HRSG, and ST—is individually procured. Because the GTs come in discrete sizes, makes, and models, the authors believe that the optimal approach to

procurement is to first select the GT(s) and then individually optimize the HRSG and ST for the selected GT based on the GT's exhaust gas conditions. Because EPC contractors have no bias in favor of or against any supplier, they are best equipped to mix and match the equipment that results in optimum selection and lowest overall cost.

Furthermore, in a deregulated market where the projects use non-recourse financing, the lending institutions insist that the EPC contractor provide the performance wrap (cost, schedule, and plant performance) for the entire plant. With the component procurement approach, the EPC contractor has control over delivery of all components and integration of construction activities and is best equipped to manage this wrap risk and add value to the ultimate customer. The authors' company has successfully employed both approaches. Our experience indicates that the power island approach is more suitable for a new technology where an OEM needs to retain more control over the equipment for diagnostics and troubleshooting and retains the majority of the performance risk. For technologies that are mature and considered fully commercial, we have found that the performance and cost benefits of the component procurement approach may outweigh the risk protection available with the power island approach. In such cases, an EPC contractor can better manage its risk through the component procurement approach.

## PROJECT EXECUTION APPROACH

### Overall Execution Approach

An important aspect of the overall project execution approach is to establish the construction and commissioning approach at the very start of a project and then design the plant to facilitate these at the later phases. For example, Bechtel finds it essential to assign construction and startup specialists to the design team to perform constructability reviews. These specialists ensure that design of critical features for commissioning, such as adequate flushing water storage capacity and routing and supports for temporary steam blow piping, receives adequate consideration.

### Construction Approach

The construction approach is site specific and is dictated by a host of variables. Consideration is always given to the area's skilled labor availability, site accessibility for deliveries, including heavy haul (rail and barge, etc.), infrastructure development to support construction activities, construction equipment availability, safety requirements, and local culture, laws, and practices.

A CC plant has a much shorter construction schedule than a conventional coal-fired steam plant of the same MW rating due to the HRSG's modular design. The horizontal construction associated with a CC plant is more conducive to safety and also

tends to reduce construction time. Given the greater amount of major rotating equipment (GTs and ST), the need for specialized skilled labor is greater for a CC than for a conventional steam plant. More heavy haul equipment is also needed for a CC plant because of modular HRSG design and other major equipment assemblies and modules. The CC plant, however, is more compact and for a given output requires less physical area for the plant itself as well as for construction laydown. The CC plant is also more adaptable to outdoor construction unless constraints are posed by noise control requirements or extremely cold weather.

### Project Execution Tools

To succeed in today's competitive environment, the project's plant design and engineering are performed in parallel in a number of global locations, including the EPC contractors' and suppliers' design offices. This requires electronic linkages between the home, field, and satellite offices and use of innovative tools that allow for effective execution and administration of work. The authors' company has developed a suite of integrated tools (*ProjectWorks*®) that is currently being used for tracking schedule, cost, quantities, and other deliverables for both domestic and international projects.

## CONCLUSIONS

Deregulation of European electricity/energy markets has accelerated since the EU directive 96/92 came into effect.

The "obligation to serve" is being replaced by "freedom of choice," with profitability a key driver for IPPs as each power plant has to operate as a separate business unit. In this environment, design, construction, and operating approaches are "need based" and must be justified on an economic basis.

The early involvement of an experienced EPC contractor that provides an overall wrap for the project is essential to ensure success and meet customer objectives of providing competitive power profitably.

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