CTS *Customer Technical Services*

White Paper

Combined-Cycle Modeling

For discussion only

DRAFT

Author(s):	Robert de Mello
Document:	CC_Modeling.doc

Date:	**Revision Comments:**
January 10, 2005	Stage 1 – First draft

Back of Title Page

Table of Contents

Introduction.. 1
Terminology.. 2
Background Information.. 3
Stage I – Combined-Cycle Power Plant.. 4
  Typical Plant Configurations.. 4
  Significant Variations.. 6
  Start-Up.. 7
  Normal Operation.. 9
  Shutdown.. 14
  Summary.. 14

Back of Table of Contents

Introduction

The purpose of this document is to record the various aspects of the modeling, performance tracking, operating characteristics, scheduling, and compensation of combined-cycle generating units in the New York wholesale electric markets. A second purpose of this document is to record possible changes to unit commitment functions or market rules that will better enable New York's wholesale electric markets to accommodate combined cycle generating units. This document is restricted to energy and ancillary service markets.

This document is being written in three stages. Initially the characteristics and constraints of combined-cycle generating units will be documented. These are the characteristics and constraints that improvements in modeling or changes in market rules, if any, must address. Subsequent stages in the evolution of the document will address the characteristics and constraints of the unit commitment functions used in New York. Feasible extensions of the modeling capabilities of New York's unit commitment functions will be recorded. Characteristics, constraints, and feasible changes or additions to the system used to track generator performance will also be recorded. Finally, after a reasonable consensus has been reached among all parties involved, this document will record the steps that will be taken, if any, to change the way combined-cycle units are committed, scheduled, tracked, or compensated.

As noted above, a complete view of combined-cycle generating units include three parts: (i) their characteristics, (ii) their scheduling, and (iii) their performance tracking and compensation. Briefly:

- Combined-cycle generating stations are becoming a significant portion of the electrical supply in New York and in other regions as well. A combined-cycle generating station consists of one or more combustion turbines (CT), each with a heat recovery steam generator (HRSG). Steam produced by each HRSG is used to drive a steam turbine (ST). The steam turbine and each combustion turbine have an electrical generator that produces electricity. Typical configurations contain one, two, or three combustion turbines, each with a HRSG, and a single steam turbine. The combined-cycle generating station can be operated in one of several states. The station's characteristics differ from one state to another, and the transition from one state to another may have a significant cost. The single-shaft plant is much less common. It has a CT and ST on a single shaft driving a common generator.

- The unit commitment function makes commitment (including decommitment) decisions and determines a schedule for generating resources. In the day-ahead market, the Security Constrained Unit Commitment (SCUC) function makes commitment decisions hourly for a day's duration. In real-time, the Real-Time Commitment (RTC) function makes commitment decisions every 15 minutes. In addition to starts and stops, these unit commitment functions determine an operating level, or schedule, for each committed resource (dispatch). The unit commitment function used in New York (and elsewhere) models a generator's transition from off-to-on or from on-to-off, but does not model transitions between operating states.

- All generators in New York are expected to follow instructions issued by the NY-ISO. The reason is twofold: (i) uninstructed deviations from NYISO schedules may put the security of the network at risk, and (ii) uninstructed deviations from NYISO schedules may adversely impact the energy or ancillary service markets. The performance of all generators is measured, and uninstructed deviations from schedules established by the NYISO are penalized.

The remainder of this document contains a summary of terminology and acronyms, a list of reference material, and sections for stages I, II and III described above. Stage I, II, and III of the document are to be prepared sequentially. Briefly:

- Stage I will document the characteristics and constraints of combined-cycle units.

- Stage II will document the relevant characteristics and constraints of the scheduling, performance tracking, and market systems and documents feasible changes or additions to those systems.

- Stage III will document the steps that will be taken, if any, to improve the way combined-cycle plants are handled in New York's wholesale electric markets.

Terminology

Term	**Description**
1-on-1	Combined-cycle plant with one CT-HRSG and one ST-COND
2-on-1	Combined-cycle plant with two CT-HRSGs and one ST-COND
3-on-1	Combined-cycle plant with three CT-HRSGs and one ST-COND
COND	Condenser
CT	Combustion turbine, also referred to as a gas turbine
HRSG	Heat recovery steam generator
MW	Megawatt – energy production rate, also used to describe capacity of a generator, which is its maximum or rated energy production rate
MWH	Megawatt Hour – unit of energy
PTS	Performance tracking system
RTC	Real-time unit commitment
ST	Steam turbine
SCUC	Security-constrained unit commitment

Background Information

1. Kehlhofer, R. H., Warner, J., Nielsen, H., Bachmann, R., Combined-Cycle Gas & Steam Turbine Power Plants, PennWell Publishing Company, Tulsa, Oklahoma, 1999.
2. Polimeros, G., Energy Cogeneration Handbook, Industrial Press, Inc., New York City, New York, 1981.
3. Wood, A. J., Wollenberg, B. F., Power Generation Operation and Control, John Wiley & Sons, Inc. New,York City, New York, 1984.
4. de Mello, R. W., Westcott, J. C., "Economic Characterization of Power Plants," Institute of Electrical and Electronics Engineers, 86-JPGC-PTC-8, 1986.
5. Brooks, F. J., "GE Gas Turbine Performance Characteristics," General Electric Company, GER-3567H, 2000.
6. Chase, D. L., Kehoe, P. T., "GE Combined-Cycle Product Line and Performance," General Electric Company, GER-3574G, 2000.
7. Jones, C., Jacobs, J. A., "Economic and Technical Considerations for Combined-Cycle Performance-Enhancement Options," General Electric Company, GER-4200, 2000.
8. Cohen, A. I., Ostrowski, G., "Scheduling Units with Multiple Operating Modes in Unit Commitment," Institute of Electrical and Electronics Engineers, 0885-8950/96, 1995.

Stage I – Combined-Cycle Power Plant

The purpose of preparing stage I of this document is to record relevant characteristics and constraints of combined-cycle generating units. These are the characteristics and constraints that improvements in modeling or changes in market rules, if any, must address. Characteristics and constraints are recorded here for all interested parties to review for accuracy and completeness.

A review of combined-cycle characteristics and constraints, including a review of pertinent literature and discussions with several owners of combined-cycle plants, has highlighted the following areas where the operation of the combined-cycle plant differs markedly from traditional steam generating plant or simple-cycle CTs:

- Start-up of a CT, warming of its HRSG, and possible warming of the ST
- Transitions among operating states with one, two, or three CTs

In many instances this document provides characteristics and constraints typical of combined cycle plants. Significant variations can exist among the components of a combined-cycle plant. These variations may be a result of design, size, age, manufacturer, state of repair, etc. While these variations may be important in determining marginal costs, duration of heat-soak periods, etc., they are not important in identifying the characteristics and constraints are relevant to improved modeling, commitment, and performance tracking of combined-cycle plants.

Typical Plant Configurations

The two building blocks of most combined-cycle power plants are (i) the combustion turbine (CT) combined with a heat recovery steam generator (HRSG) shown in Figure 1, and (ii) the steam turbine (ST) combined with a condenser (COND) shown in Figure 2. The typical combined-cycle power plant is made up of one or more of the CT-HRSG blocks and a single ST-COND block.

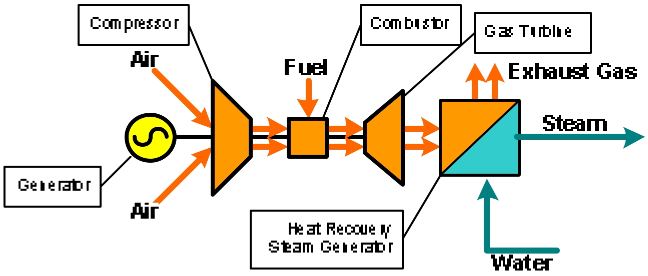


Figure 1. Combustion Turbine & Heat Recovery Steam Generator

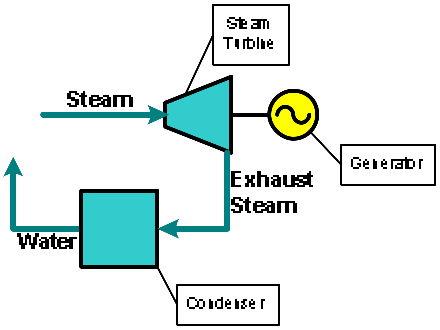


Figure 2. Steam Turbine & Condenser

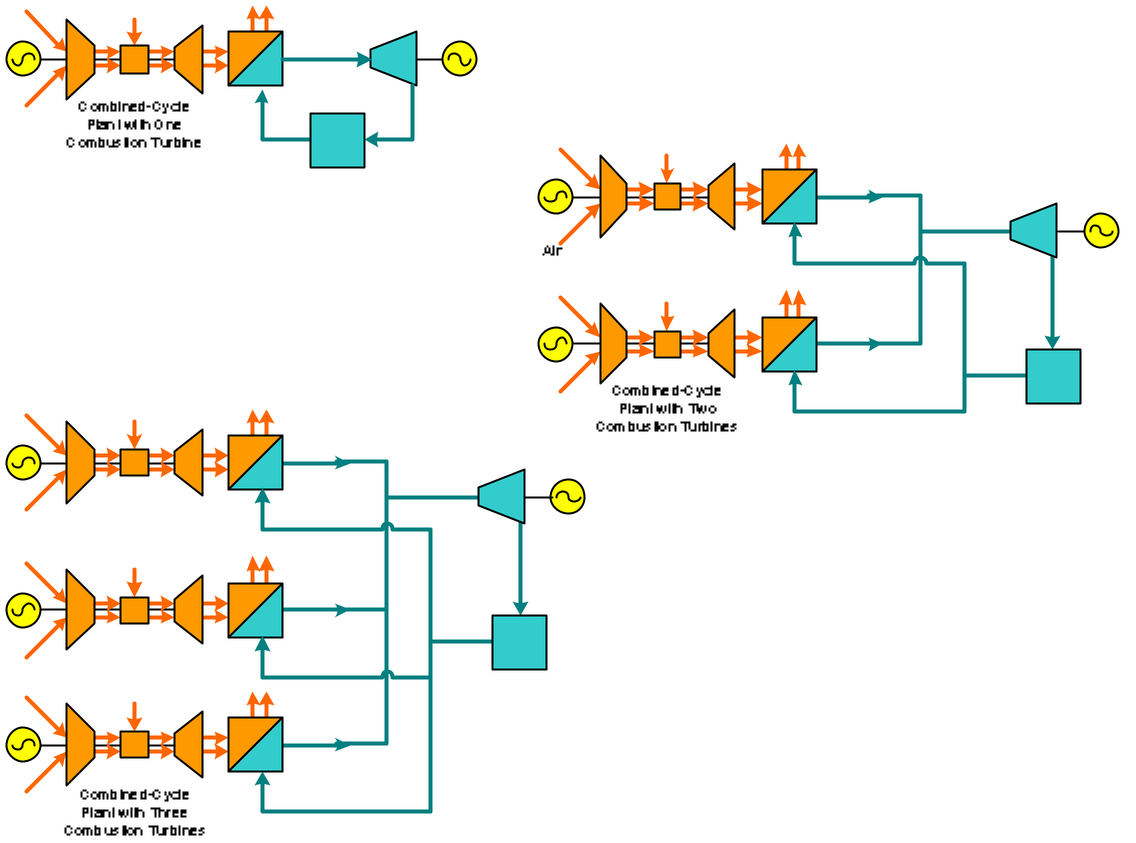


Figure 3 illustrates the configurations of combined-cycle plants found in New York. These contain one, two, or three CT-HRSG blocks and a single ST-COND block. Respectively, these plants are referred to as 1-on-1, 2-on-1, and 3-on-1 and have two, three, or four electrical generators.

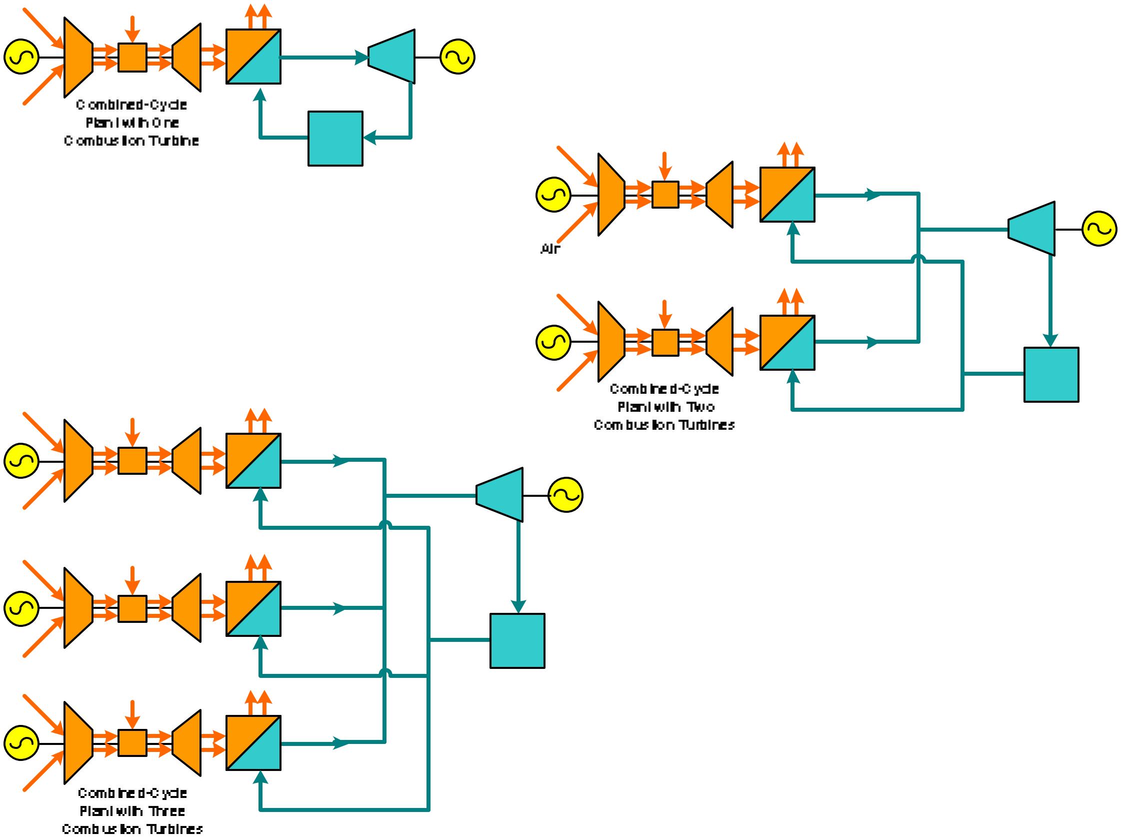


Figure 3. Typical Combined-Cycle Plant Configurations

The capacity of a plant's ST is roughly half that of the plant's CTs. That is a 1-on-1 plant with an 80 MW CT will support a 40 MW ST with a full-load plant output of 120 MW. The same sized CTs in a 2-on-1 plant will support an 80 MW ST for a full-load plant output of 240 MW. Similarly, a 3-on-1 plant with three 80 MW CTs will support a 120 MW ST with a full-load plant output of 360 MW.

Significant Variations

There are many variations in the components of a combined-cycle plant. Many of these variations impact only the efficiency of the plant but have little impact on the capacity or responsiveness of the plant. The four variations that have an impact on the plant's participation in the wholesale electric markets are:

- Presence of a gas bypass system
- Ability to duct fire
- Dual fuel capability
- Cogeneration

Gas Bypass

Gas bypass gives a combined-cycle plant the ability to divert the hot CT exhaust to atmosphere rather than to the HRSG. This provides extra operating flexibility by permitting the CT to operate in simple-cycle mode, albeit at a greatly reduced efficiency. Very few of the combined-cycle plants in New York have a gas bypass.

Duct Firing

Duct firing, or supplemental firing, is a way of increasing plant output by injecting and burning fuel in the HRSG. With duct firing, both the hot exhaust of the CT and heat from additional fuel is used to make steam in the HRSG. Overall plant efficiency descreases when duct firing is used. Many, but not all, of the combined-cycle plants in New York have duct firing capability. One plant reported an increased output of 10%.

Dual Fuel

Some combined-cycle plants may be fired with natural gas or with a high-quality fuel oil such as kerosene or jet fuel. Some plants can be fired using a mix of gas and oil. As of this writing natural gas is the preferred fuel for all of the combined-cycle plants in New York as fuel oil is more costly than natural gas. Many plants report a reduced ability to follow a control signal when burning fuel oil. One plant has reported that it is impossible to follow a control signal when a mix of fuels is burned.

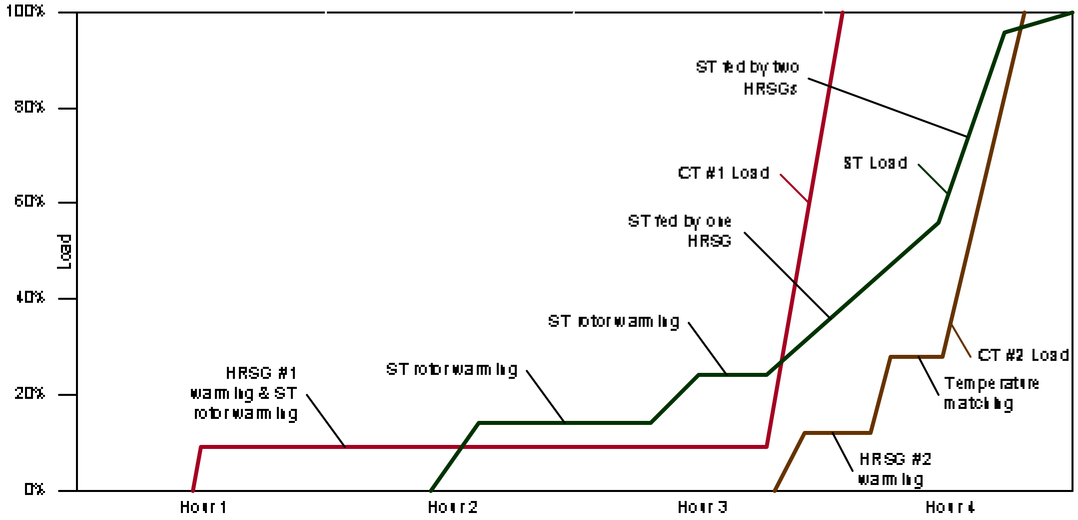
Cogeneration

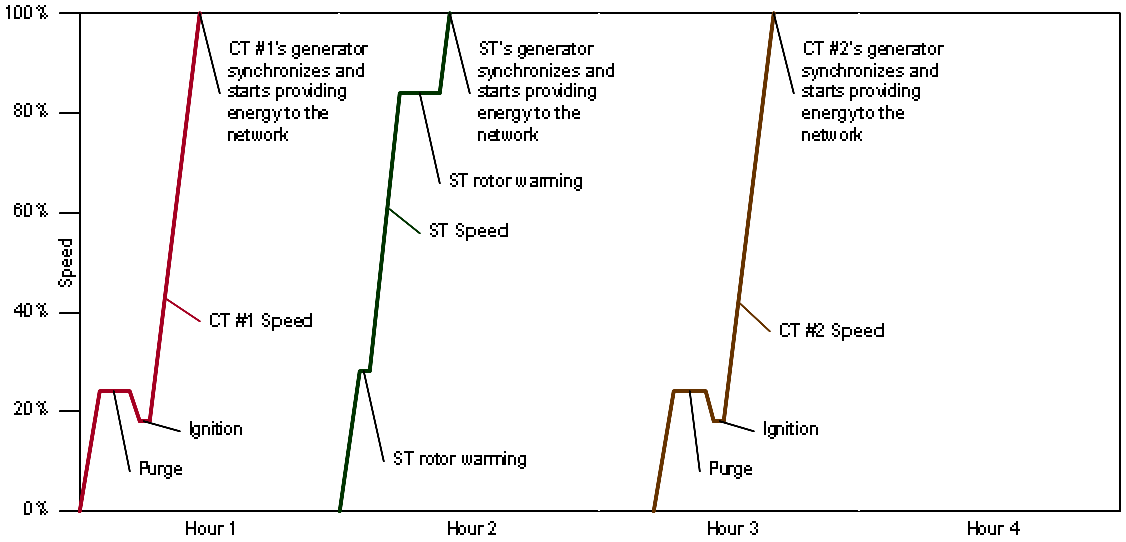
Cogeneration means the simultaneous production of electrical and thermal energy in the same power plant. The thermal energy is usually in the form of steam or hot water that is used for an industrial process, district heating, or some other purpose. Most often, the thermal needs of the external process determine the plant's operating point and the electrical output of the plant.

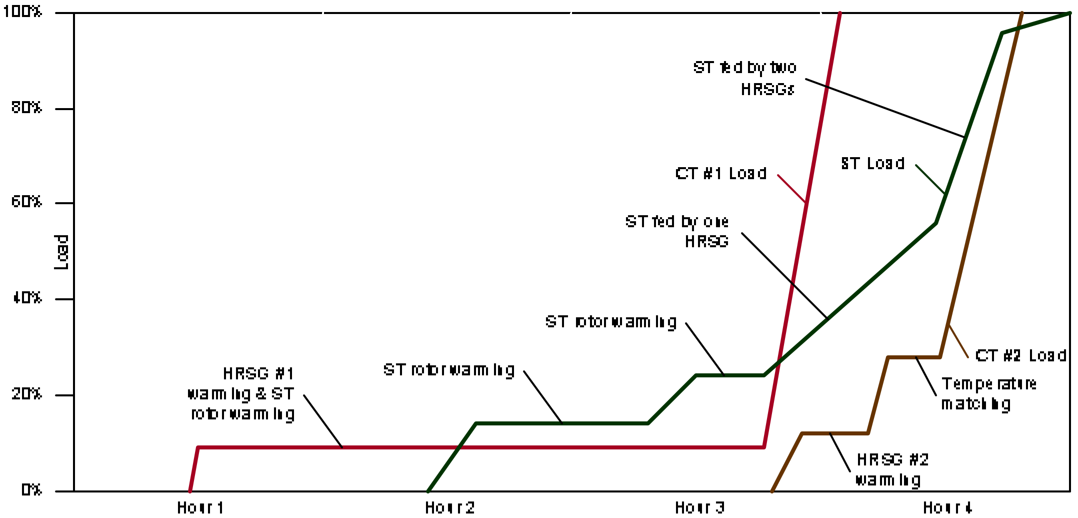
Start-Up

During start-up the combined cycle plant has little ability to follow an external control signal. Plant output, while fairly predictable, does not increase smoothly from minimum load to maximum load. Instead, output during start-up is characterized by extended holds, where plant output does not change, periods where plant output increases slowly, and periods where plant output increases rapidly.

The cold start-up of a typical 2-on-1 combined-cycle plant is illustrated in Figure 4 and




100 %
80 %
60 %
40 %
20 %
0 %
Speed
CT #1's generator synchronizes and starts providing energy to the network
ST's generator synchronizes and starts providing energy to the network
CT #2's generator synchronizes and starts providing energy to the network
ST rotor warming
ST Speed
CT #1 Speed
CT #2 Speed
Ignition
Purge
ST rotor warming
Ignition
Purge
Hour 1
Hour 2
Hour 3
Hour 4


100%
80%
60%
40%
20%
0%
Load
ST fed by two HRSGs
ST Load
CT #1 Load
ST fed by one HRSG
ST rotor warming
ST rotor warming
HRSG #1 warming & ST rotor warming
CT #2 Load
Temperature matching
HRSG #2 warming
Hour 1
Hour 2
Hour 3
Hour 4

Warming of HRSG

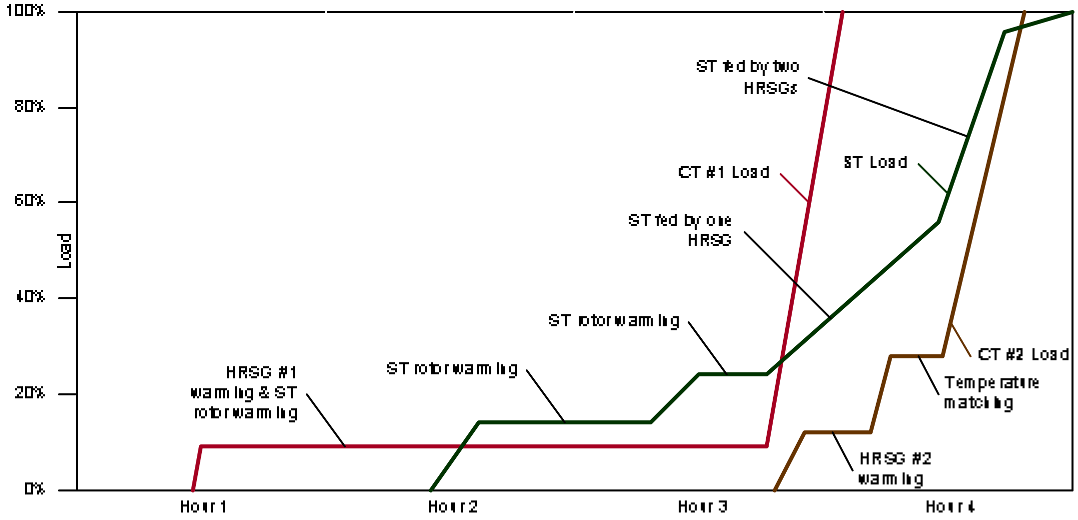
The HRSG must be warmed to the point of producing steam. This takes approximately half an hour for a cold HRSG. Initially steam produced by the HRSG bypasses the ST and is sent directly to the condenser.

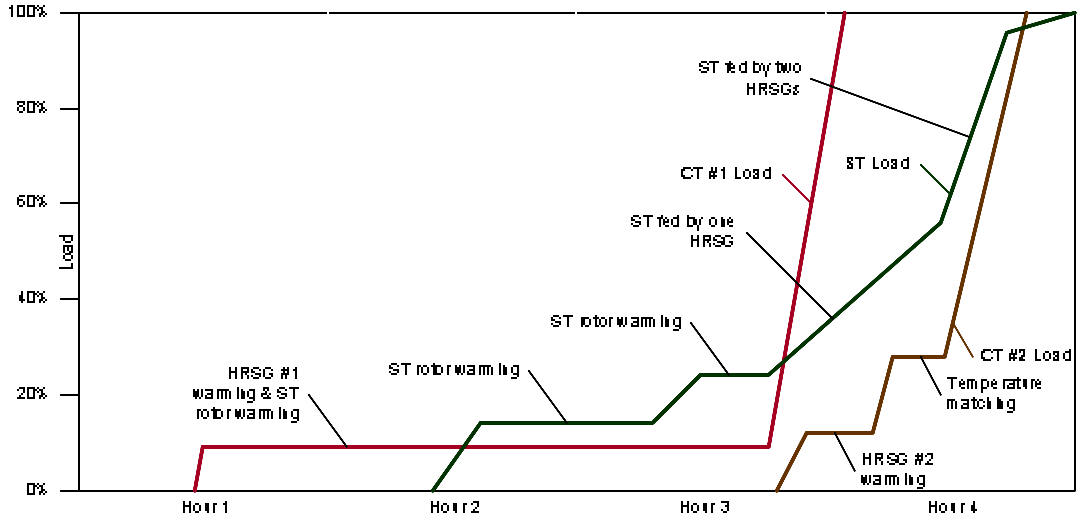
Start-up, Warming, and Synchronization of ST

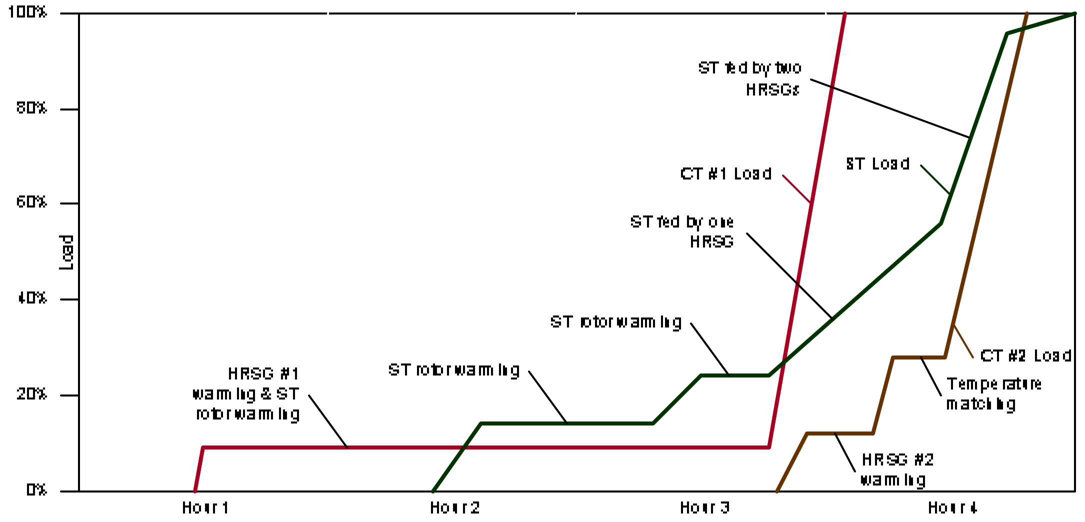
Before steam can be introduced into the ST, the turbine's steam seals must be put into operation and the condenser must be evacuated. The ST, like the HRSG, must be warmed slowly. Steam from the steam seals warms the ST before it rolls. Warming continues while the ST is being brought up to speed. At several points, the ST is held at constant speed (typically 1000 rpm, 3000 rpm, and 3600 rpm) for additional warming. These hold periods can be seen as flat spots in the ST speed of Figure 4. Duration of the holds for warming are longer for a cold ST than for a hot ST. A cold ST takes approximately half an hour to get to full speed. Once at full speed (3600 rpm), the ST's generator is synchronized to the network.

Loading of ST

Warming of the ST continues after it is a full speed and its generator has been synchronized to the network. At several points, the ST is held at a constant load for additional warming. These hold periods can be seen as flat spots in the ST load of




100%
80%
60%
40%
20%
0%
Load
ST fed by two HRSGs
CT #1 Load
ST Load
ST fed by one HRSG
ST rotor warming
HRSG #1 warming & ST rotor warming
ST rotor warming
CT #2 Load
Temperature matching
HRSG #2 warming
Hour 1
Hour 2
Hour 3
Hour 4


100%
80%
60%
40%
20%
0%
Load
ST fed by two HRSGs
CT #1 Load
ST Load
ST fed by one HRSG
ST rotor warming
HRSG #1 warming & ST rotor warming
ST rotor warming
CT #2 Load
Temperature matching
HRSG #2 warming
Hour 1
Hour 2
Hour 3
Hour 4

Some combined-cycle owners report reduced flexibility when a combined-cycle plant is fired with a petroleum fuel. Such reduced flexibility can be reflected in a lower ramp rate. Some combined-cycle owners report that all load following capability is lost when a combination of natural gas and petroleum fuels are burned simultaneously.

A 2-on-1 plant can also be operated in a 1-on-1 configuration with a corresponding decrease in capacity and response rate. A 3-on-1 plant can also be operated in a 2-on-1 or 1-on-1 configuration, also with a corresponding decrease in capacity and response rate. Capacity and control ranges for combined-cycle plants operating in various configurations are tabulated below.

Plant Type	Operating Mode	Capacity	Control Range
1-on-1	1-on-1	100%	70% - 100%
2-on-1	2-on-1	100%	70% - 100%
	1-on-1	50%	35% - 50%
3-on-1	3-on-1	100%	70% - 100%
	2-on-1	67%	47% - 67%
	1-on-1	33%	23% - 33%

CTs can typically be controlled down to approximately 80% of rated capacity without significant loss of efficiency; there are environmental consequences however. Above 80% of rated load both fuel and inlet air flows are controlled together to achieve a proper mix and to maintain temperatures in the CT. Air flow cannot be reduced below about 80% and temperatures are depressed by excess air at low operating levels. This results in a decrease in efficiency of the CT at low operating levels. While the efficiency effects of low-load operation become noticeable below about 80% of rated load, for environmental reasons most CTs in combined cycle plants are normally not permitted to operate below 70% of rated output, except during start-up and shut-down.

Nitrogen oxides (NOx) are reduced through the use of Dry Low NOx combustors, water or steam injection, and/or the use of an Selective Catalytic Reduction in the HRSG. For NOx control water up to 3% or steam up to 5% of the air flow is used. One plant reported using a combination of DLN combustors and SCR to attain 2ppm. The SCR requires a gas inlet temperature of approximately 700F which may not be at-tained at lower CT loads.

The efficiency of the HRSG is largely a function of inlet gas temperature. CT exhaust temperature, which is also HRSG inlet temperature, varies little above 80% load, hence the efficiency of the HRSG varies little in the permissible operating range. The efficiency of the ST is also relatively constant. ST efficiency is impacted by a control stage that regulates steam flow and by exhaust (condenser) pressure. The ST used in combined-cycle applications rarely has a control stage and condensers are often sized large enough that the ST exhaust pressure remains relatively constant. Efficiency of the overall plant, neglecting auxiliary devices such as pumps and fans, is fairly constant from 80% to 100% load.

Output and, to a lesser extent, heat rate of a gas turbine are affected by ambient conditions: air temperature, humidity, and atmospheric pressure. Absent duct firing, the performance of the combined-cycle plant follows the performance of its CTs. Reference conditions for gas turbine are typically 59 F (15 C), 14.7 PSIA (1.013 bar, 29.92 inHg), and 60% relative humidity. These reference conditions are established by the International Standards Organization (ISO) and are also referred to as ISO conditions. Both output and heat rate are taken to be 1.0 at standard conditions. The exact characteristics of any particular gas turbine depend on its cycle parameters and component efficiencies and will vary slightly from the typical results presented here. In summary, the output of a gas turbine may change by ±15% due to ambient conditions. Change in heat rate due to ambient conditions will be in the range of ±5%.

Under unusual (emergency) circumstances the output of some gas turbines can be increased through the use of steam injection, inlet cooling, or peak firing.

- Five percent steam injection can increase output by 16 percentage points. At standard conditions this would be an increase from 100% to 116%. Lower levels of steam injection have a correspondingly lower impact on output. Steam injection can only be used on gas turbines with a wide surge margin in the compressor, typically found in aeroderivative gas turbines.
- The impact of inlet cooling by means of an evaporative cooler or inlet chiller is reflected in the adjustment curve for ambient temperature below. At most a gas turbine could increase its output by 10 percentage points (from 90% of standard to 100% of standard, for example) with the use of inlet cooling. Inlet cooling is employed in an attempt to recover the capacity lost to high ambient temperatures.
- Peak firing is operation at a higher firing temperature than normal, putting the “pedal to the metal” so to speak. An increase output is the result. Peak firing requires no peripheral equipment as do steam injection or inlet cooling, however operation at peak conditions shortens the normal maintenance interval for the turbine. Peak firing can increase output by approximately 10%. Not all gas turbines have the ability to peak fire.

CT Ambient Pressure Adjustments

Air flow to the turbine is reduced in direct proportion to a reduction in atmospheric pressure. There is a corresponding, and linear, reduction in output. Heat rate is not affected. Atmospheric pressure is commonly expressed as inches of Mercury (inHg). Atmospheric pressure at sea level is generally in the range 28.0 inHg (13.76 PSIA) to 31.0 inHg (15.23 PSIA) which means that gas turbine output may be as low as 93% of standard during hurricane conditions or as high as 103.5% of standard during the spectacular weather associated with a Bermuda high.

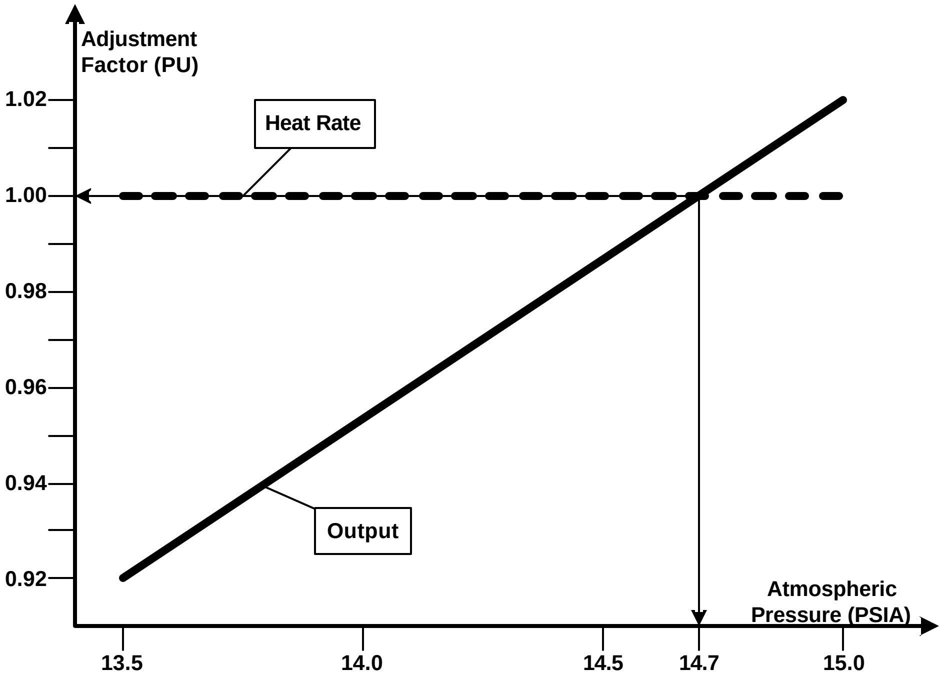


Figure 6. Adjustments for Atmospheric Pressure

CT Ambient Temperature Adjustments

The output of a gas turbine is quite sensitive to ambient air temperature. Output can be as high as 120% of standard on an extremely cold (0 F) day or as low as 86% of standard on an extremely hot (100 F) day. Ambient temperature has a smaller affect on heat rate. Heat rate increases slightly (net efficiency decreases) as temperature increases and decreases slightly (efficiency increases) as temperature decreases.

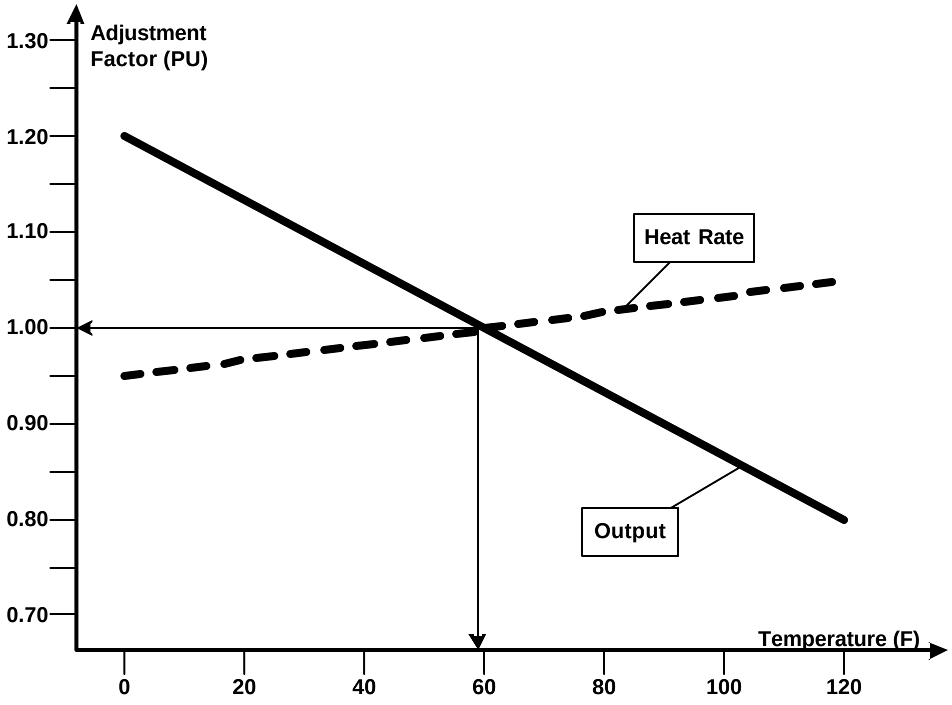


Figure 7. Adjustments for Ambient Temperature

CT Humidity Adjustments

Compared to adjustments for pressure and temperature, the adjustments for relative humidity are small; and the adjustment for humidity can be ignored for all practical purposes. Output of a gas turbine will increase slightly as relative humidity decreases. Output increases to approximately 100.1% of standard during periods of very low humidity and decreases to approximately 99.7% of standard at very high levels of humidity. Heat rate decreases (better efficiency) to approximately 99.7% of standard during periods of very low humidity and increases (poorer efficiency) to approximately 100.8% of standard at very high levels of humidity.

CT Combined Adjustment

An overall adjustment factor is obtained by multiplying the individual adjustment factors. For example, consider a day with an atmospheric pressure of 28.5 inHg (14.0 PSIA) and temperature of 90 F. Humidity is ignored. Output adjustment factors for pressure and temperature are 0.95 and 0.91 respectively. Expected output of the gas turbine will be

$(0.95 \times 0.91) = 0.8645$ of standard, about 86.45% of standard. Under these conditions, a gas turbine that produces energy at a rate of 50 MW under standard conditions will produce energy at a rate of only 43.2 MW.

Shutdown

A combined-cycle plant can typically be shut down within 20 to 30 minutes when all CTs at the plant are unloaded and shut down simultaneously. The shut down ramp rate is much larger than the ramp rate used during start-up or normal operation. The shutdown can be extended for plants that have multiple CTs by making a transition from operation with three to operation with two CTs, or from two CTs to one CT.

Summary

Combined-cycle plants are built in a variety of configurations. Operation of a combined-cycle plant can be divided into three categories: start-up, normal operation, and shutdown.

- Start-up of a combined cycle plant can take many hours. During most of this time at least one of the plant's generators is synchronized to the network and delivering electrical energy to the network. The plant's electrical output is reasonably predictable during start-up but the plant cannot arbitrarily adjust its output. A combined-cycle plant cannot respond to 5-minute dispatch signals during start-up.

- During normal operation, the combined-cycle plant can be quite responsive to external control signals and may, within a limited range, provide dispatch capability, reserve service, or regulation service.

- Shutdown of a combined-cycle plant can be accomplished quickly.