ATTACHMENT A

Market
Strategy
Department

White Paper

Combined-Cycle Modeling

For discussion only

DRAFT

Author(s):	Robert de Mello
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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
AGC	Automatic generation control
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
RTD	Real-time dispatch
ST	Steam turbine
SCUC	Security-constrained unit commitment

Background Information

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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
Supply of steam to an external process (cogeneration)

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.

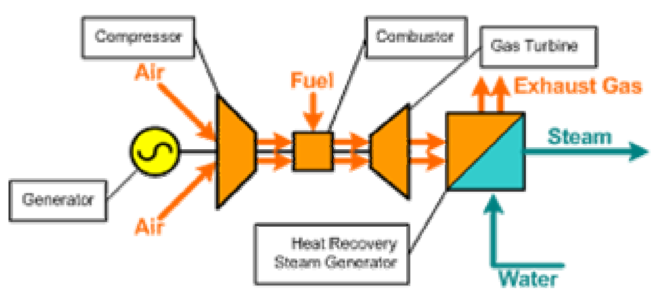

Figure 1. Combustion Turbine & Heat Recovery Steam Generator

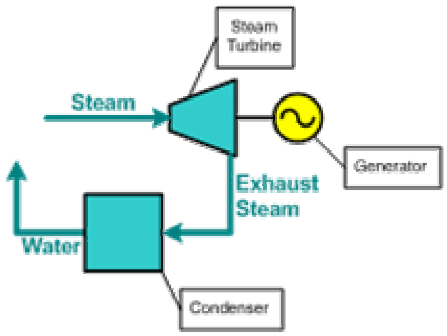

Figure 2. Steam Turbine & Condenser

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.

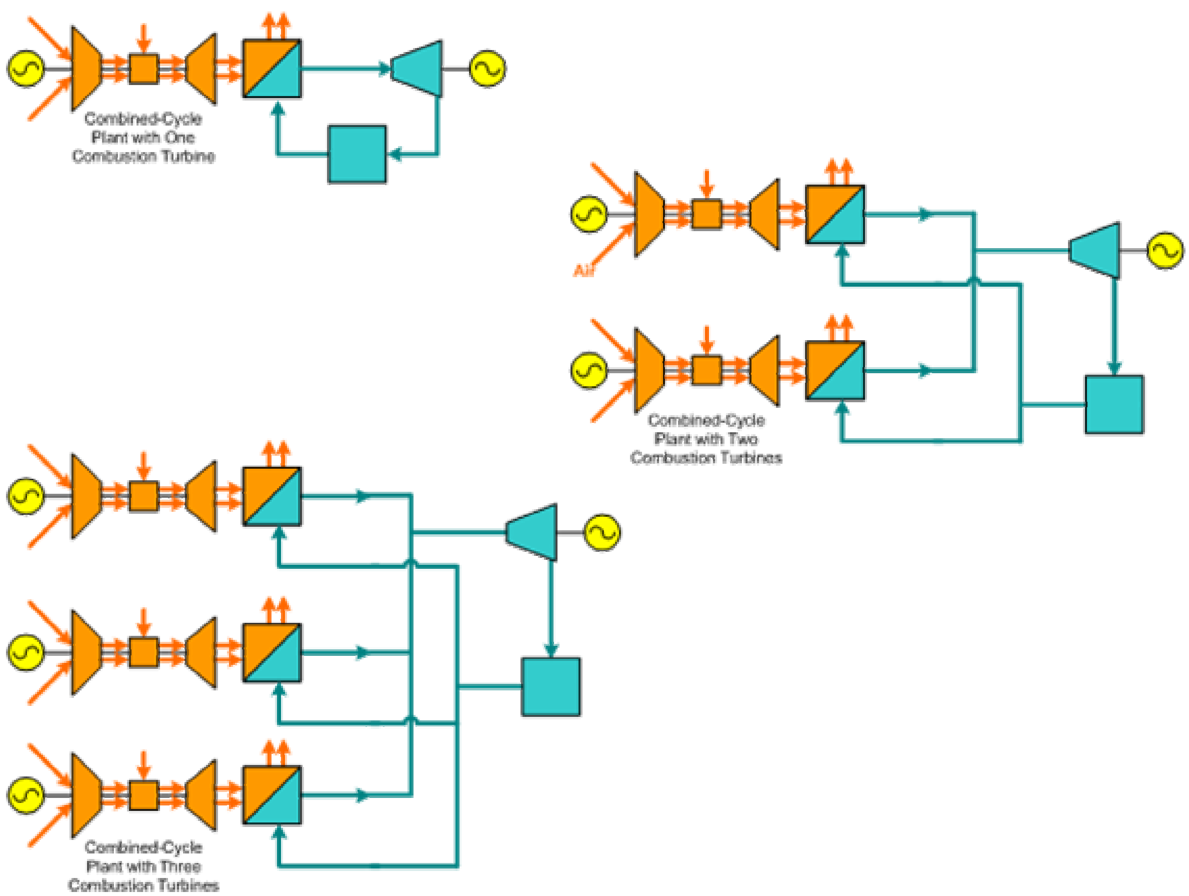

Figure 3. Typical Combined-Cycle Plant Configurations

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 Figure 5. These Figures show component speed and load respectively. The Figures also illustrate the transition from operation with one CT to operation with two CTs. The start-up of a 1-on-1 plant is takes less time; the start-up of a 3-on-1 plant takes more time. Time to full load for a cold plant takes roughly three hours for a 1-on-1 plant, four hours for a 2-on-1 plant, and five hours for a 3-on-1 plant. These times can grow significantly if significant chemical processing of the condensate is required. The start-up of a warm or hot plant takes less time than the start-up of a cold plant. The start up time is also a function of the age and size of the gas turbine. Older, low tech, smaller gas turbines can start faster than newer, high tech, higher efficiency, larger gas turbines. Representative start-up times are tabulated below.

Plant Type	Representative Cold Start	Representative Hot Start
1-on-1	3 Hours	1 hour
2-on-1	4 hours	1½ hours
3-on-1	5 hours	2 hours

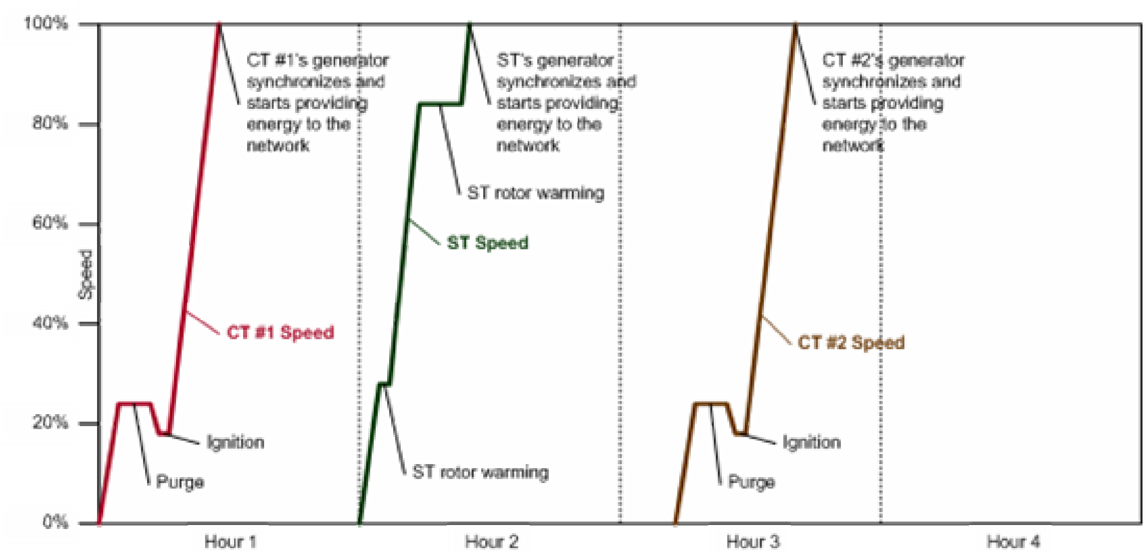

Figure 4. Component Speeds – Representative Cold Start

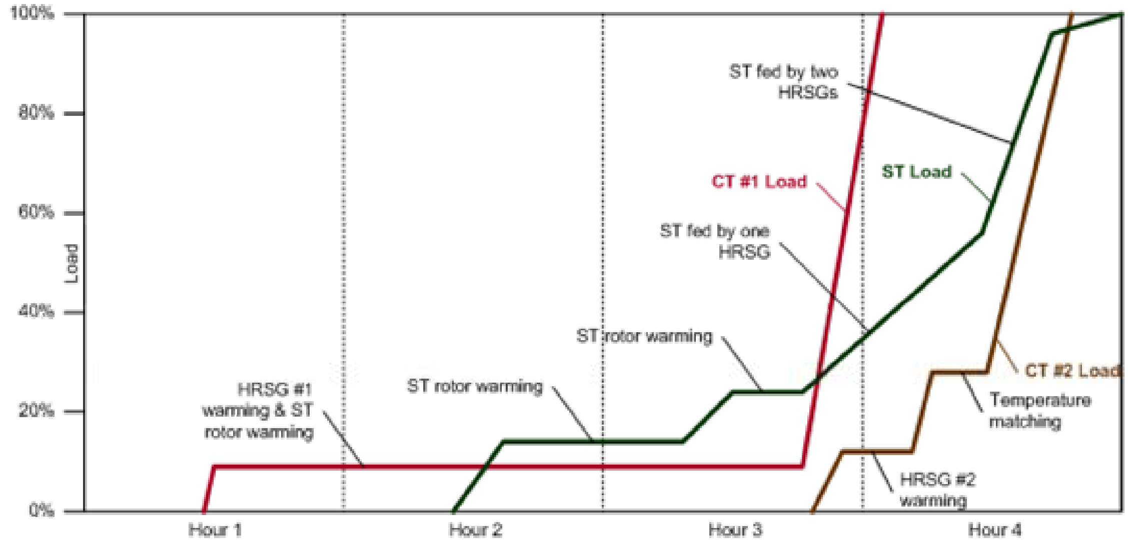

Figure 5. Component Loadings - Representative Cold Start

Typical steps in the start-up of a combined-cycle plant are explained in the sections that follow.

Start-up and Synchronization of First CT

As illustrated in Figure 4, the start-up and synchronization of a CT takes roughly 20-30 minutes. Roughly half of this time is used to purge the HRSG of combustible gases prior to firing the CT. Upon synchronization of the CT's generator, the CT is loaded to approximately 10% of its capacity.

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 Figure 5. It may take an hour or more for a ST to be fully warmed from the time it reaches full speed.

Start-up and Synchronization of the Second CT

The second CT in a combined-cycle plant is started after the ST has been fully warmed. Like the first CT, and as illustrated in Figure 4, the start-up and synchronization of the second CT takes about 20-30 minutes. Roughly half of this time is used to purge the CT and HRSG of combustible gases prior to firing the CT. Upon synchronization of the CT's generator, the CT is loaded to approximately 10% of its capacity.

Warming of the Second HRSG

The HRSG must be warmed to the point of producing steam. This takes approximately half an hour for a cold HRSG and can be seen as the first flat spot in the CT#2 load of Figure 5. Initially steam produced by the HRSG bypasses the ST and is sent directly to the condenser. It takes an additional half hour or so to match steam temperature of the second HRSG with that of the first HRSG and combine their outputs. This can be seen as the second flat spot in the CT#2 load of Figure 5. Once steam temperatures are reasonably matched, steam of the second HRSG is combined with that of the first HRSG and sent through the ST. The second CT is brought up to full load after steam from the two HRSGs is combined.

The third CT, if it exists, is typically started after the second CT is fully loaded. The steps in starting the third CT and the warming of the third CT's HRSG are very much like those of the second CT and its HRSG.

Normal Operation

The normal operating range of a combined-cycle plant is typically 70% to 100% of rated output. In this range the plant usually has excellent control characteristics and should be able to provide spinning reserve or regulation service when natural gas is used as a fuel. 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.

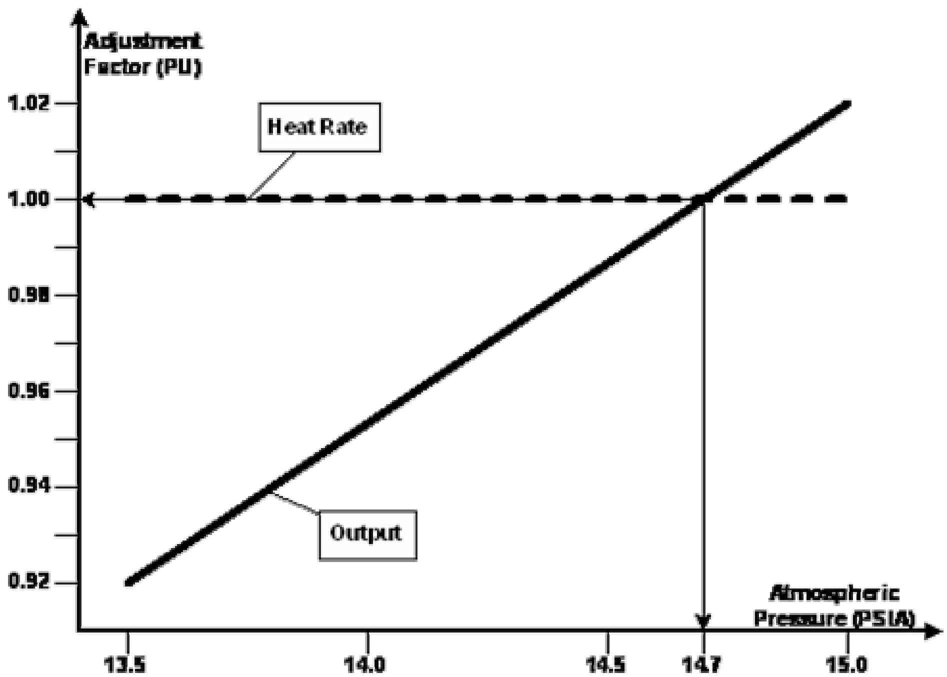

Figure 6. Adjustments for Atmospheric Pressure

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.

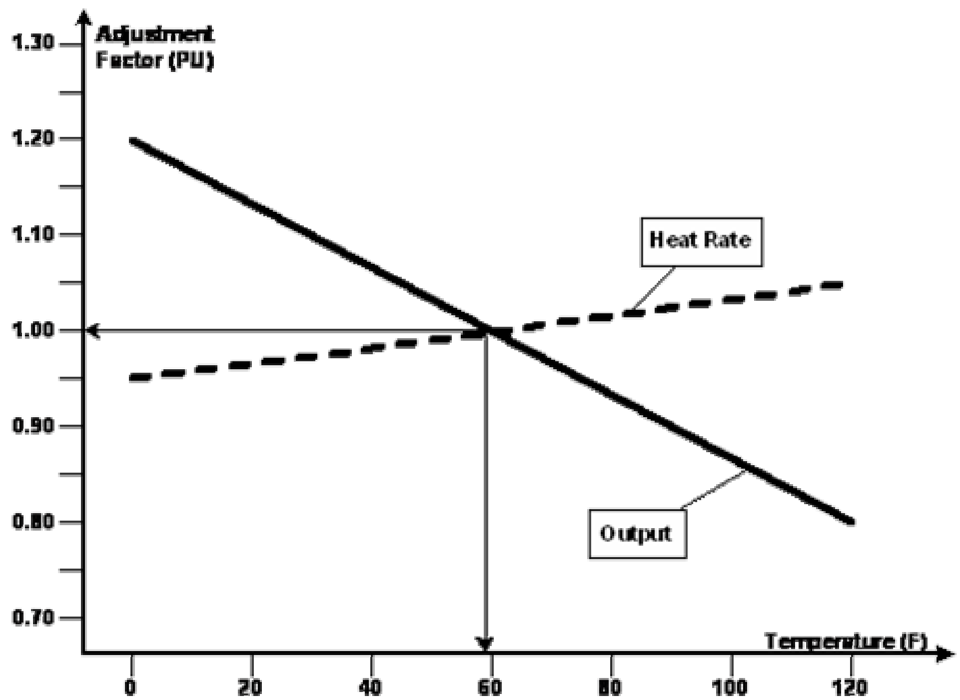

Figure 7. Adjustments for Ambient Temperature

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.

Stage II – Scheduling, Tracking & Modeling

The purpose of Stage II is to document the relevant characteristics and constraints of the scheduling and performance tracking systems and document feasible changes or additions to those systems. Changes to the modeling of combined-cycle plants are described. Two viable approaches suggest themselves:

1. The combined-cycle plant can be modeled in sufficient detail so that transitions between operating states can be scheduled by the ISO. The "mod-and-transition" model, described in later sections of this document, is the most promising way to formulate the unit commitment problem when discrete operating states must be recognized and scheduled. This option would require significant changes to the unit commitment programs currently in use at the ISO.

2. The state of the combined-cycle plant can be monitored to recognize its current operating state and capabilities. With proper monitoring, the combined-cycle plant will not be called on to perform beyond its capabilities. Performance tracking options are also explored in later sections of this document. Since the NYISO real-time processes perform optimizations over a period of time, the mod-and-transition model might have a role in the short-term forecasting of plants' capabilities.

Current System

The current system provides realistic schedules only for the "running" state of combined-cycle plants. The current system has the ability to model a combined-cycle plant as a number of independent units to provide some flexibility in committing individual CTs.

Energy produced during start-up or shutdown can currently be recouped in real-time by participating in the real-time markets, perhaps as a self-scheduled resource. The current system gives all generators the opportunity to advise the ISO of expected generation in 15-minute increments. Such advice, however, requires a lead-time of at least 75 minutes.

The parameters used to describe energy providers, including demand-side resources, in the unit commitment and scheduling functions currently in use at the ISO are shown in the table below. Any enhancement to the unit commitment and scheduling function to recognize multiple operating states must, at the very least, account for the parameters currently in use.

Symbol	Description	Units
FD_g	Flag indicating whether generator "g" is dispatchable	Y/N
FR_g	Flag indicating whether generator "g" is able to supply regulation	Y/N
FS_g	Flag indicating whether generator "g" is able to supply spinning reserve	Y/N

g	Index of generator	-
h	Index of hour of the day (0, 1, 2, 3, …)	0,1,2,…
$IE_{g,h}$	Incremental energy offer curve of generator "g" for the hour beginning "h"	\$/MWH vs MW
$MGC_{g,h}$	Hourly cost for generator "g" to operate at its minimum generation level for the hour beginning "h"	\$/hr
$MGL_{g,h}$	Minimum generation level of generator "g" for the hour beginning "h"	MW
$MNDOWN_g$	Minimum down time of generator "g"	hr
$MNRUN_g$	Minimum run time of generator "g"	hr
$MWS_{g,h}$	Self-scheduled MW of generator "g" for the hour beginning "h"	MW
$MXSTOP_g$	Maximum stops per day of generator "g"	0,1,2,…
RE_g	Emergency ramp rate of generator "g"	MW/min
RN_g	Normal ramp rate of generator "g"	MW/min
RR_g	Regulation ramp rate of generator "g"	MW/min
$SUC_{g,h}$	Start-up cost of "g" for the hour beginning "h." Start-up cost may be defined as a function of hours since the most recent shut down.	\$
$UOLE_{g,h}$	Emergency upper operating limit of generator "g" for the hour beginning "h"	MW
$UOLN_{g,h}$	Normal upper operating limit of generator "g" for the hour beginning "h"	MW

The day-ahead scheduling process performs a security-constrained unit commitment and dispatch for the period of one day. The day-ahead process has a time granularity of one hour and can make binding commitment decisions for any number of hours during the one-day interval. Short duration events, events that are less than one hour in duration, cannot be effectively evaluated in the day-ahead process.

The real-time scheduling process performs a security-constrained unit commitment and dispatch for the period of approximately 2.5 hours. In addition, the real-time scheduling process performs a security-constrained dispatch for the period of approximately one hour. The real-time commitment process has a time granularity of 15 minutes. The real-time process can make binding commitment decisions for at most one hour. Long duration events, events that are more than one hour in duration, cannot be effectively evaluated in the real-time process.

The real-time performance tracking system (PTS) compares the actual output of a plant, or of the units within a plant, to the physical base points sent to the plant. PTS determines various performance metrics that measure whether the plant is responding adequately. Plants that produce energy at a rate less than expected are currently subject to under-generation penalties. Plants that produce energy at a rate more than expected are currently subject to non-payment for excess energies produced.

Day-Ahead Scheduling

Many generating plants, including combined-cycle plants, can operate in a number of configurations. Each configuration is called a "mod" for consistency with the nomenclature in reference 8. Each mod has its own set of parameters, that is, each mod can be modeled as a pseudo-unit. The information associated with a mod is tabulated below.

Information Describing a Mod		
Symbol	**Description**	**Units**
FD_m	Flag indicating whether plant is dispatchable in mod "m"	Y/N
FR_m	Flag indicating whether plant is able to supply regulation in mod "m"	Y/N
FS_m	Flag indicating whether plant is able to supply spinning reserve in mod "m"	Y/N
h	Index of hour of the day (0, 1, 2, 3, …)	0,1,2,…
$IE_{m,h}$	Incremental energy offer curve of plant in mod "m" for the hour beginning "h"	$/MWH vs MW
m	Index of the plant and its mod (operating configuration)	-
$MGC_{m,h}$	Hourly cost for plant in mod "m" to operate at its minimum generation level for the hour beginning "h"	$/hr
$MGL_{m,h}$	Minimum generation level of plant in mod "m" for the hour beginning "h"	MW
$MNRUN_m$	Minimum run time of the plant in mod "m." Perhaps minimum run time can be expressed as a function elapsed time since another transition occurred.	hr
$MXRUN_m$	Maximum run time of the plant in mod "m." Perhaps maximum run time can be expressed as a function elapsed time since another transition occurred.	hr
RE_m	Emergency ramp rate of the plant in mod "m"	MW/min
RN_m	Normal ramp rate of plant in mod "m"	MW/min
RR_m	Regulation ramp rate of plant in mod "m"	MW/min
$UOLE_{m,h}$	Emergency upper operating limit of plant in mod "m" for the hour beginning "h"	MW
$UOLN_{m,h}$	Normal upper operating limit of plant in mod "m" for the hour beginning "h"	MW

The set of allowable transitions between pairs of mods completes the information needed to manage the mod-and-transition model. In this document it is assumed that the transition from one mod to another happens instantaneously. The information associated with a transition is tabulated below.

Information Describing a Transition		
Symbol	**Description**	**Units**
h	Index of hour of the day (0, 1, 2, 3, …)	0,1,2,…
m	Index of the plant and its mod (operating configuration)	-
m1	Prior mod (the configuration prior to the transition)	-
m2	After mod (the configuration after to the transition)	-
$TC_{m1,m2,h}$	Cost of the transition from mod "m1" to mod "m2" for the hour beginning "h." Perhaps cost of a transition can be expressed as a function elapsed time since another transition occurred.	$

Keeping in mind that the day-ahead commitment and scheduling process does not honor operating constraints over midnight, the mod-and-transition model can be used in the day-ahead process when:

> The minimum and maximum run time of each mod must be a whole multiple of hours. Fractional parts of an hour must be rounded up to the next whole hour.

Mindful also that the real-time commitment and scheduling process does not honor operating constraints for more than one hour, the mod-and-transition model can be used in the real-ahead commitment and scheduling process when:

> The minimum and maximum run time of each mod must be a whole multiple of quarter-hour segments (15 minutes, 30 minutes, 45 minutes, etc.). Fractional parts of a quarter-hour segment must be rounded up to a to the next quarter hour; and
>
> The plant can be turned off within an hour. That is, there is a transition, or set of transitions, from any mod to the "off" mod that takes no more than one hour to traverse; or
>
> The plant can be directed back to its day-ahead schedule within an hour. That is, there is a transition, or set of transitions, from the current mod to the mod scheduled day-ahead that takes no more than one hour to traverse;
>
> There may be some other constraints that guarantee enough flexibility to avoid being scheduled "into a corner."

Other information currently used by the unit commitment process is tabulated below. It is unclear how this information will be incorporated into the mod and transition model.

Other Information		
Symbol	**Description**	**Units**
$MXSTOP_p$	Maximum stops per day for plant "p"	0,1,2,…

$MNDOWN_p$	Minimum down time before plant "p" can be started again.	hr
$MNRUN_p$	Minimum run time of the plant "p." A plant's minimum run time can be assured by careful selection of mods and transitions. This is illustrated below for a two-on-one plant.	hr

The "Off" Mod

Every generating plant has an "off" mod. The values assigned to most of the characteristics of the "off" mod cannot be set arbitrarily. Characteristics of the "off" mod are:

FD	No (likely)
FR	No (likely)
FS	No (likely) The plant may supply non-synchronous reserve if transition to an operating mod is sufficiently short.
IE	N/A (likely)
MGC	$0.00 (likely)
MGL	0 MW (likely)
MNRUN	0 hr (likely)
MXRUN	∞ (likely)
RE	0 MW/min (likely)
RN	0 MW/min (likely)
RR	0 MW/min (likely)
UOLE	0 MW (likely)
UOLN	0 MW (likely)

The Two-Mod Plant

It is instructive to apply the mod-and-transition model to the established unit commitment process. As of this writing, the unit commitment model used at the NYISO recognizes only two mods for any generating plant: "off" and "running." As illustrated in Figure 8, this model also allows two transitions. The first transition, from the "off" mod to the "running" mod, is currently called the "start-up." This transition has an associated cost, currently called the start-up cost. The second transition is from the "running" mod to the "off" mod and is currently called the "shutdown."

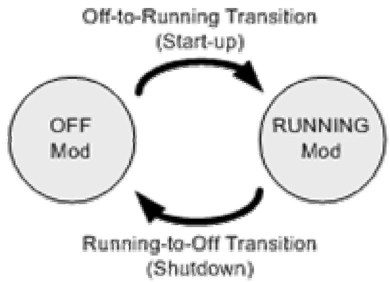

Figure 8. Two Mod Model

Parameters of the "off" mod are given above. The parameters of the "running" mod are those that currently describe the characteristics of the plant, except that start-up cost is part of the "off-to-running" transition. The transition from "running-to-off" has a cost of zero.

One-on-One Combined-Cycle Plant

A one-on-one combined-cycle plant can be represented with three mods and three transitions as shown in Figure 9. The "off" mod is described above. Other mods and transitions for a one-on-one combined-cycle plant are described below. Values assigned to parameters of mods and transitions are representative and used for illustrative purposes only.

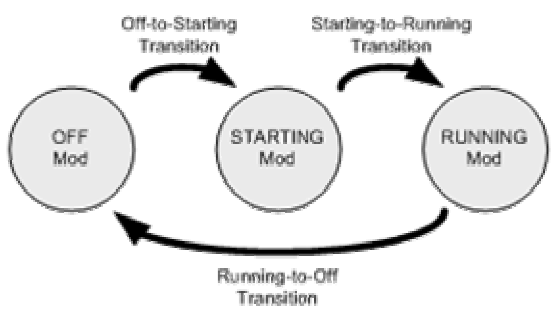

Figure 9. Mod-and-Transition Model for a One-on-One Combined-Cycle Plant

During the "starting" mod the plant is generally operating at a low level while HRSG and ST are warmed. The plant is unable to respond to control signals and is unable to offer spinning reserve or regulation service in the "starting" mod.

Mod: Starting	
FD	No (likely)
FR	No (likely)
FS	No (likely)
IE	Reflects plant's marginal cost
MGC	Reflects plant's cost at the specified minimum generation level
MGL	10% of plant capacity (typical)
MNRUN	Start up takes 1, 2, or 3 hours (typical).

MXRUN	The plant must leave the "starting" mod after 1, 2, or 3 hours (typical).
RE	0.5 MW/min (typical)
RN	0.5 MW/min (typical)
RR	0.5 MW/min (typical)
UOLE	10% of plant capacity (typical)
UOLN	10% of plant capacity (typical)

During the "running" mod the plant is generally operating normally. Both the HRSG and ST are sufficiently warmed for normal operation. The plant is typically able to respond to control signals and is able to offer spinning reserve or regulation service. Typically, the plant must stay in the "running" mod for at least 8 hours, but there is no upper limit on the any period of time that the plant can be in the "running" mod.

Mod: Running	
FD	Yes (typical)
FR	Yes (typical)
FS	Yes (typical)
IE	Reflects plant's marginal cost
MGC	Reflects plant's cost
MGL	70% of plant capacity (typical)
MNRUN	8 hours (typical).
MXRUN	∞ (typical)
RE	1% MW/min (typical)
RN	1% MW/min (typical)
RR	1% MW/min (typical)
UOLE	100% of plant capacity (typical)
UOLN	100% of plant capacity (typical)

The allowable transitions among mods are tabulated below. The "off-to-starting" transition may have an associated transition cost that represents the start-up cost. Other transitions will likely have a cost of zero.

Transition: Off-to-Starting	
m1	"Off" mod
m2	"Starting" mod
TC	Plant's start-up cost. Typically this should not include expected payments for energy produced during the "starting" mod. Start-up cost may depend on the elapsed time since the CT-HRSG was shut down.

Transition: Starting-to-Running	
m1	"Starting" mod
m2	"Running" mod

TC	$0.00 (likely)

Transition: Running-to-Off	
m1	"Running" mod
m2	"Off" mod
TC	$0.00 (likely)

The mod-and-transition model for the one-on-one combined-cycle plant can be applied to the day-ahead commitment and scheduling process, but cannot be used by the real-time commitment process because mandatory durations are typically too long. Bidding parameters must describe each mod and each transition. There are, therefore, significantly more bidding parameters that must be maintained with the mod-and-transition model of a one-on-one combined-cycle plant than must be maintained for a plant that can be represented with a simpler two-mod model. Care must be taken to insure consistency in the data that describe individual mods of the mod-and-transition model. Inconsistent or conflicting data may result in wildly unexpected behavior.

An example of a day-ahead schedule that might be given to a one-on-one combined cycle plant is shown in Figure 10. In this example, the unit is instructed to start at 07:00 with the expectation that the plant's start-up will be complete by 09:00. Thus the plant is scheduled to be in the "starting" mod for these two hours. At 09:00 the plant is scheduled to begin normal operation for a period of five hours. During these five hours the plant is in the "running" mod. In this example the plant is shut down at 14:00. The plant in this example has a minimum run time of five hours or less.

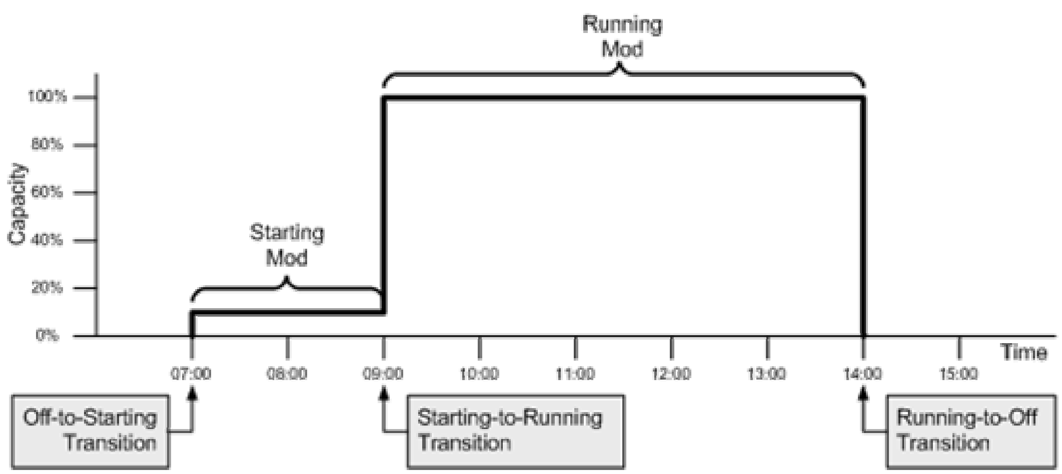

Figure 10. Example Day-Ahead Schedule for One-on-One Plant

Two-on-One Combined-Cycle Plant

A two-on-one combined-cycle plant can be represented with five mods and six transitions as shown in Figure 11. This representation assumes that the plant's two CT-HRSGs are identical, and therefore the order of starting is irrelevant. If the CT-HRSGs differ markedly from one another, the representation of the plant is much more complex.

The "off" mod is described above. Other mods and transitions for a two-on-one combined-cycle plant are described below. Values assigned to parameters of mods and transitions are representative and used for illustrative purposes only.

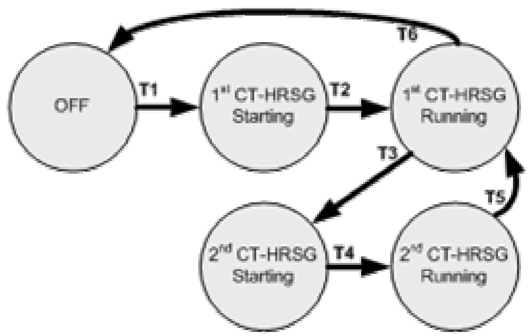

Figure 11. Mod-and-Transition Model for a Two-on-One Combined-Cycle Plant

During the "1st CT-HRSG starting" mod the plant is generally operating at a low level while the first HRSG and the ST are warmed. The plant is unable to respond to control signals and is unable to offer spinning reserve or regulation service in this mod.

Mod: 1st CT-HRSG Starting	
FD	No (likely)
FR	No (likely)
FS	No (likely)
IE	Reflects plant's marginal cost
MGC	Reflects plant's cost at the specified minimum generation level
MGL	5% of plant capacity (typical)
MNRUN	Start up takes 1, 2, or 3 hours (typical).
MXRUN	The plant must leave the "starting" mod after 1, 2, or 3 hours (typical).
RE	0.5 MW/min (typical)
RN	0.5 MW/min (typical)
RR	0.5 MW/min (typical)
UOLE	5% of plant capacity (typical)
UOLN	5% of plant capacity (typical)

During the "1st CT-HRSG running" mod the plant is generally operating normally, but at approximately half of rated capacity. Both the first HRSG and the ST are sufficiently warmed for normal operation. The plant is typically able to respond to control signals and is able to offer spinning reserve or regulation service.

Mod: 1st CT-HRSG Running	
FD	Yes (typical)

FR	Yes (typical)
FS	Yes (typical)
IE	Reflects plant's marginal cost
MGC	Reflects plant's cost
MGL	35% of plant capacity (typical)
MNRUN	0 hours (typical).
MXRUN	∞ (typical)
RE	1% MW/min (typical)
RN	1% MW/min (typical)
RR	1% MW/min (typical)
UOLE	50% of plant capacity (typical)
UOLN	50% of plant capacity (typical)

During the "2nd CT-HRSG starting" mod the plant is generally operating at a low level while the second HRSG is warmed. The ST has already been warmed. At times, the plant is unable to respond to control signals, for example, when temperatures of the two HRSGs are matched. The plant is therefore considered unable to respond to dispatch signals while in this mod. The plant is unable to offer spinning reserve or regulation service in this mod.

Mod: 2nd CT-HRSG Starting	
FD	No (likely)
FR	No (likely)
FS	No (likely)
IE	Reflects plant's marginal cost
MGC	Reflects plant's cost at the specified minimum generation level
MGL	40% of plant capacity (typical)
MNRUN	Start up takes 1 hour (typical).
MXRUN	The plant must leave the "starting" mod after 1 hour (typical).
RE	0.5 MW/min (typical)
RN	0.5 MW/min (typical)
RR	0.5 MW/min (typical)
UOLE	40% of plant capacity (typical)
UOLN	40% of plant capacity (typical)

During the "2nd CT-HRSG running" mod the plant is generally operating normally between 70% and 100% of capacity. All equipment is sufficiently warmed for normal operation. The plant is typically able to respond to control signals and is able to offer spinning reserve or regulation service.

Mod: 2nd CT-HRSG Running	
FD	Yes (typical)
FR	Yes (typical)
FS	Yes (typical)

IE	Reflects plant's marginal cost
MGC	Reflects plant's cost
MGL	70% of plant capacity (typical)
MNRUN	0 hours (typical).
MXRUN	∞ (typical)
RE	1% MW/min (typical)
RN	1% MW/min (typical)
RR	1% MW/min (typical)
UOLE	100% of plant capacity (typical)
UOLN	100% of plant capacity (typical)

The allowable transitions among mods are tabulated below. Any transition that requires a CT to start may have an associated transition cost that represents the start-up cost. Other transitions will likely have a cost of zero.

Transition: T1	
m1	"Off" mod
m2	"1st CT-HRSG Starting" mod
TC	Start-up cost for the first CT-HRSG and ST. Typically this should not include expected payments for energy produced during this mod. Start-up cost may depend on the elapsed time since the 1st CT-HRSG was shut down.

Transition: T2	
m1	"1st CT-HRSG Starting" mod
m2	"1st CT-HRSG Running" mod
TC	$0.00 (likely)

Transition: T3	
m1	"1st CT-HRSG Running" mod
m2	"2nd CT-HRSG Starting" mod
TC	Start-up cost for the second CT-HRSG (the ST is already running). Typically this should not include expected payments for energy produced during this mod. Start-up cost may depend on the elapsed time since the 2nd CT-HRSG was shut down.

Composite Transition: T2+T3 This transition is possible since the minimum run time of the "1st CT-HRSG Running" mod is zero. Presumably composite transitions would not have to be explicitly defined, but could be discovered automatically by the scheduling system.	
m1	"1st CT-HRSG Starting" mod
m2	"2nd CT-HRSG Starting" mod
TC	Combined transition costs of T2 and T3

Transition: T4	
m1	"2nd CT-HRSG Starting" mod
m2	"2nd CT-HRSG Running" mod
TC	$0.00 (likely)

Transition: T5	
m1	"2nd CT-HRSG Running" mod
m2	"1st CT-HRSG Running" mod
TC	$0.00 (likely)

Transition: T6	
m1	"1st CT-HRSG Running" mod
m2	"Off" mod
TC	$0.00 (likely)

Composite Transition: T5+T6 This transition is possible since the minimum run time of the "1st CT-HRSG Running" mod is zero. Presumably composite transitions would not have to be explicitly defined, but could be discovered automatically by the scheduling system.	
m1	"2nd CT-HRSG Running" mod
m2	"Off" mod
TC	Combined transition costs of T2 and T3

The mod-and-transition model for the two-on-one combined-cycle plant can be applied to the day-ahead commitment and scheduling process, but cannot be used by the real-time commitment process because mandatory durations are typically too long. Bidding parameters must describe each mod and each transition. There are, therefore, significantly more bidding parameters that must be maintained with the mod-and-transition model of a two-on-one combined-cycle plant than must be maintained for a plant that can be represented with a simpler two-mod model. Care must be taken to insure consistency in the data that describe individual mods of the mod-and-transition model. Inconsistent or conflicting data may result in wildly unexpected behavior.

An example of a day-ahead schedule that might be given to a two-on-one combined cycle plant is shown in Figure 12. In this example, the unit is instructed to start its first CT-HRSG 07:00 with the expectation that the second CT-HRSG will start at 09:00. Full plant start-up will be complete by 10:00. The plant will be shut down at 15:00.

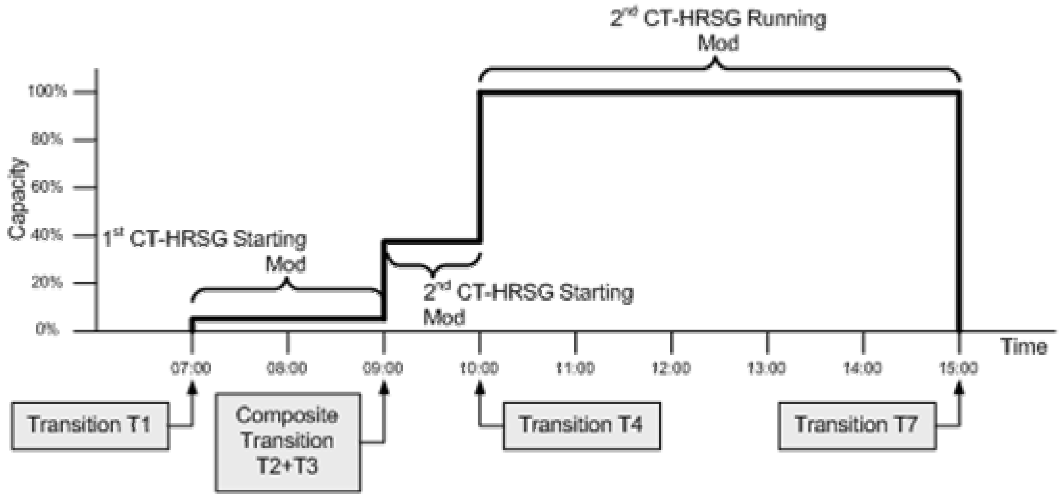

Figure 12. Example Day-Ahead Schedule for Two-on-One Plant

Two-on-One Combined-Cycle Plant with Minimum Run Time

The mod-and-transition model can be constructed to guarantee a minimum run time for a plant. Figure 13 shows an example for a two-on-one combined-cycle plant. The model has seemingly redundant "running" mods, but these are differentiated by the minimum run time parameter: either zero hours or eight hours as noted in the Figure. This model guarantees (except over midnight) that the plant will run for a minimum of eight hours either in the "1st CT-HRSG Running" mod (at approximately half power in a one-on-one configuration), or in the "2nd CT-HRSG Running" mod (at full power in a two-on-one configuration). The model is capable of scheduling the plant to operate in both a one-on-one configuration and a two-on-one configuration, provided that the plant operates for at least eight continuous hours in one of the two configurations.

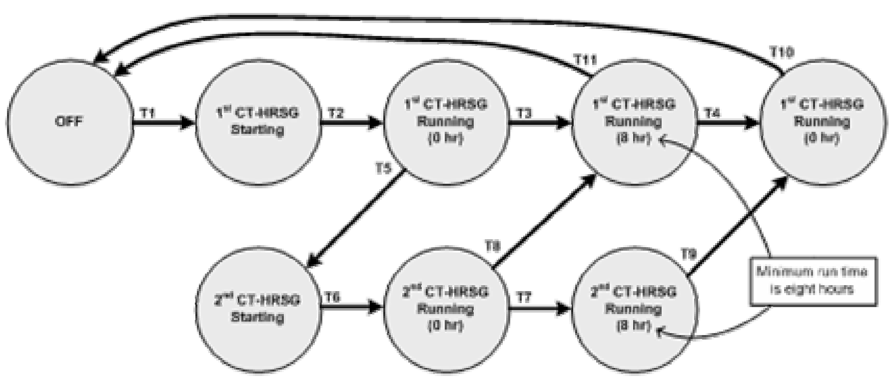

Figure 13. Two-on-One Plant with Minimum Run Time

The formulation above[1] does not directly address the plant's minimum run time. Rather, minimum run times refer to each mod separately. However, modifications can be made in

[1] Correspondence with Art Cohen, ABB, March 30, 2005

the modeling to accommodate an overall minimum run time for the plants operation. This can be done in one of the following ways:

> Modify the dynamic programming algorithm used in the algorithm described in the paper to include such a constraint. This constraint can only be handled suboptimally by dynamic programming and so there may be some loss of optimality -- basically this loss of optimality occurs when there are two possible transitions into the same mod because I can only keep track of the up time corresponding to the least costly cost-from-start transition. Any loss of optimality will probably be small and this change would be fairly easy to implement.
>
> Use Mixed Integer Programming (MIP) to solve the single unit problem currently solved by dynamic programming -- we could model the plant minimum run time constraint using MIP.
>
> Use MIP to solve the overall problem. We currently have a MIP version of our SCUC (actually we can run the same problem with MIP or Lagrangian Relaxation) which has shown good results for NY problems. We had planned to implement the combined cycle modeling in both MIP and LR.

The issue with MIP is run time. The run time for current NY problems is OK for SCUC however we know that the run time is very problem dependent. We cannot guarantee performance without doing some prototyping which would take some time to do. Since the run time is so problem-dependent we would have to implement the algorithm prior to testing. The good part is that we can use the same data setup routines and economic dispatch routines as for LR. This is where much of the work will be in implementing the CC modeling.

Three-on-One Combined-Cycle Plant

A three-on-one combined-cycle plant can be represented with seven mods and nine transitions as shown in Figure 14. This representation assumes that the plant's three CT-HRSGs are identical, and therefore the order of starting is irrelevant. If the CT-HRSGs differ markedly from one another, the representation of the plant is much more complex.

The "off" mod is described above. Other mods, transitions, and composite transitions for a three-on-one combined-cycle plant are left as an exercise for the reader. Enumeration of mods and transitions is straight forward. However, as before, care must be taken to insure consistency in the data that describe individual mods of the mod-and-transition model. Inconsistent or conflicting data may result in wildly unexpected behavior.

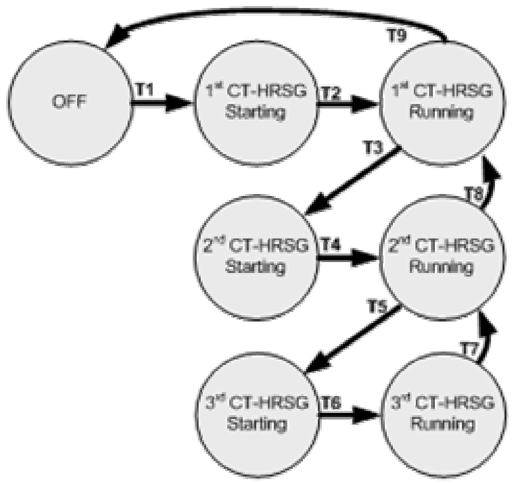

Figure 14. Mod-and-Transition Model for a Three-on-One Combined-Cycle Plant

Plant with Non-Monotonic IHR

Some combined-cycle plants are alleged to have an incremental heat rate that decreases, rather than increases, in the upper portions of their operating ranges. This section illustrates how the mod-and-transition model can be applied to a one-on-one combined-cycle plant with such a characteristic. The plant used for this illustration is assumed to have a minimum generation limit of 70% of capacity. Incremental heat rate for the example plant is higher below 90% of capacity than it is above 90% of capacity. The example plant's marginal cost characteristics are illustrated in Figure 15.

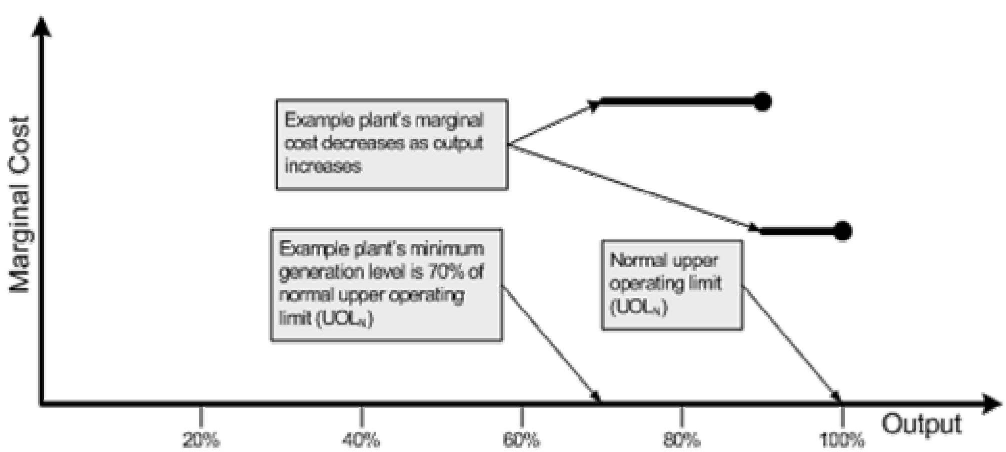

Figure 15. Example of Decreasing Marginal Cost

A possible mod-and-transition model for this plant is shown in Figure 16. By now the reader is sufficiently versed in the mod-and-transition model to assign characteristics to each of the mods and transitions. Suffice it to point out that:

The "Running (low)" mod has a minimum generation level of 70% of capacity and an upper operating limit of 90% of capacity.
The "Running (high)" mod has a minimum generation level of 90% of capacity and an upper operating limit of 100% of capacity.
The marginal cost of the "Running (low)" mod is higher than the marginal cost of the "Running (high)" mod.
The ability of the plant to offer reserve and regulation is limited. This model forces the plant to operate either in the range 70% to 90% of capacity or in the range 90% to 100% of capacity. This model does not recognize that reserve or regulation could be scheduled over the full operating range of the plant.
Minimum run times of the "Running (low)" and "Running (high)" mods might be as short as 15 minutes. Durations this short would permit RTC to schedule transitions between low and high operating states in real-time.
This model does not address the plant's minimum run time. It is unclear how the plant's minimum run time could be accommodated while maintaining real-time scheduling flexibility.

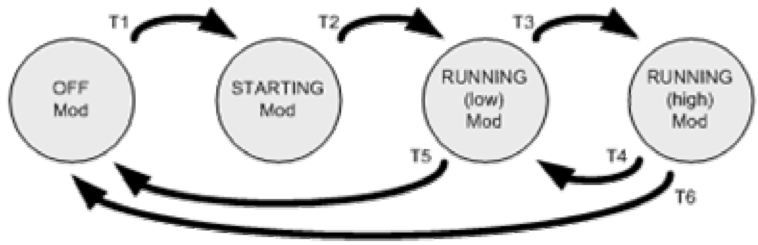

Figure 16. Mod-and-Transition Model for a Non-Monotonic Plant

It may be possible to address the limitations of this formulation with the scheduling spinning reserve. The functionality of the scheduling systems might be modified to provide a second "low limit" to be used in calculating the reserve contribution. If we did this, then we could model reserve more accurately.[2]

Pumped Hydro Plant

The mod-and-transition model can be applied to energy producers other than combined-cycle. The model may be useful for any plant that operates in one of several configurations, where each configuration has unique properties. As an example, the mod-and-transition model is applied to a pumped-hydro plant. The example, shown in Figure 17, illustrates a hydro plant consisting of two identical turbines. The transition from "off" to "pumping" or "off" to "generating" is assumed to be very fast, so no "starting" mod is necessary. Allowable operating states for this example are:

Off
Pumping with one turbine

[2] Correspondence with Art Cohen, ABB, March 30, 2005

Generating with one turbine
Generating with two turbines

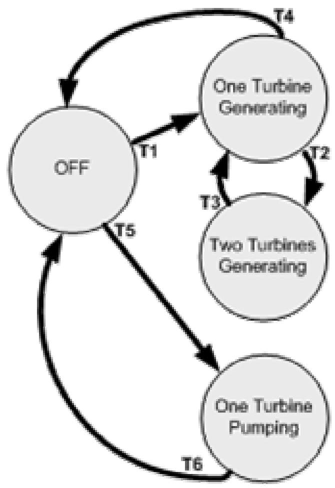

Figure 17. Pumped Hydro Example

The "off" mod is described above. Other mods and transitions for this example pumped-hydro plant are described below. Values assigned to parameters of mods and transitions are representative and used for illustrative purposes only.

During the "One Turbine Generating" mod the plant is generally operating at half of rated capacity The plant is able to respond to control signals and is able to offer spinning reserve and regulation service in this mod.

Mod: One Turbine Generating	
FD	Yes (example)
FR	Yes (example)
FS	Yes (example)
IE	Reflects plant's marginal cost
MGC	Reflects plant's cost at the specified minimum generation level
MGL	25% of plant capacity (example)
MNRUN	0 hours
MXRUN	∞ (example)
RE	5 MW/min (example)
RN	5 MW/min (example)
RR	5 MW/min (example)
UOLE	50% of plant capacity (example)
UOLN	50% of plant capacity (example)

During the "Two Turbines Generating" mod the plant is generally operating at rated capacity The plant is able to respond to control signals and is able to offer spinning reserve and regulation service in this mod.

Mod: Two Turbines Generating	
FD	Yes (example)
FR	Yes (example)
FS	Yes (example)
IE	Reflects plant's marginal cost
MGC	Reflects plant's cost at the specified minimum generation level
MGL	50% of plant capacity (example)
MNRUN	0.25 hours (15 minutes)
MXRUN	∞ (example)
RE	10 MW/min (example)
RN	10 MW/min (example)
RR	10 MW/min (example)
UOLE	100% of plant capacity (example)
UOLN	100% of plant capacity (example)

During the "One Turbine Pumping" mod the plant is generally consuming energy rather than producing energy. Suppose that the plant is able to respond to control signals and is able to offer spinning reserve but is unable to provide regulation service in this mod.

Mod: One Turbine Pumping	
FD	Yes (example)
FR	No (example)
FS	Yes (example)
IE	Reflects plant's marginal cost
MGC	Reflects plant's cost at the specified minimum generation level
MGL	-50% of plant capacity (example)
MNRUN	0.25 hours (15 minutes)
MXRUN	∞ (example)
RE	5 MW/min (example)
RN	5 MW/min (example)
RR	5 MW/min (example)
UOLE	-25% of plant capacity (example)
UOLN	-25% of plant capacity (example)

The allowable transitions among mods are tabulated below. Any transition that requires a hydro turbine to start may have an associated transition cost that represents the start-up cost. Other transitions will likely have a cost of zero.

Transition: T1	
m1	"Off" mod

m2	"One turbine generating" mod
TC	Start-up cost for the first hydro turbine.

Transition: T2	
m1	"One turbine generating" mod
m2	"Two turbines generating" mod
TC	Start-up cost for the second hydro turbine.

Composite Transition: T1+T2 This transition is possible since the minimum run time of the "One turbine generating" mod is zero. Presumably composite transitions would not have to be explicitly defined, but could be discovered automatically by the scheduling system.	
m1	"Off" mod
m2	"Two turbines generating" mod
TC	Combined transition costs of T1 and T2

Transition: T3	
m1	"Two turbines generating" mod
m2	"One turbine generating" mod
TC	$0 (likely)

Transition: T4	
m1	"One turbine generating" mod
m2	"Off" mod
TC	$0 (likely)

Composite Transition: T3+T4 This transition is possible since the minimum run time of the "One turbine generating" mod is zero. Presumably composite transitions would not have to be explicitly defined, but could be discovered automatically by the scheduling system.	
m1	"Two turbines generating" mod
m2	"Off" mod
TC	$0 (likely)

Transition: T5	
m1	"Off" mod
m2	"One turbine pumping" mod
TC	$0 (likely)

Transition: T6	
m1	"One turbine pumping" mod
m2	"Off" mod

TC	$0 (likely)

The mod-and-transition model for a pumped hydro plant can probably be applied to both the day-ahead and real-time commitment and scheduling processes. Start-up of a hydro plant is very quick, and mandatory operating durations are typically quite short. Minimum run times in this example are at most 15 minutes.

Real-Time Tracking

As noted above, the real-time commitment and scheduling system is limited by (i) the duration of the optimization windows used for commitment and dispatch, (ii) the 15-minute granularity of the commitment interval, and (iii) the hour-long period during which bids and offers are binding. These limitations prohibit the real-time processes from optimally scheduling many of the transitions from one operating state of an energy supplier's plant to another. However, it may be possible to infer the actual state of a plant in real-time by measuring its output. If the state of a plant can be determined by the real-time scheduling system, then it can be scheduled to provide only those services for which it is capable.

The real-time scheduling systems perform optimizations over extended periods of time. The duration of the commitment window is approximately 2.5 hours; the duration of the dispatch window is approximately one hour. Not only must the current state of a plant be inferred from instrumentation, but the projected state of the plant must be estimated for the duration of the optimization window. The mod-and-transition model of a plant may play a significant role in making a forward estimate of the plant.

The efficient real-time scheduling of generating units depends, in part, upon the accurate knowledge of each unit's capabilities. For flexible units, this includes an accurate depiction of operating limits and ramp rates. For inflexible units, an accurate forecast of unit output is required. Inaccurate or incomplete information may have substantial market impacts as evidenced by the concern of the NYISO and its market participants over the "persistent dragging" issue. The capabilities of a combined-cycle plant depend upon its current operating state, or mod. When in a "running" mod the plant is able adjust its output in response to control signals from the ISO. These control signals may be either the base points generated every five minutes by RTD or the base points generated every six seconds by the automatic generation control (AGC) process. When in a "starting" mod the plant is unable to respond to control signals. The following sections examine to possibility that RTC and RTD might recognize the changing capabilities of combined-cycle plants and formulate schedules accordingly. That is:

> A plant in a "starting" mod might be considered inflexible. The plant would have to provide the ISO with its best estimate of its energy production rate. The plant might be ineligible to set prices.

A plant in a "running" mod might be considered flexible. The plant would participate in economic dispatch and might provide regulation service. The plant might be eligible to set prices.

Measuring or predicting transitions between flexible and inflexible operation would be required for such transitions to be recognized or scheduled.

Detecting a Plant's Operating State

Suppose that the real power output of each generator in a combined-cycle plant were measured. Suppose further that the output of each CT's generator were compared to a set of threshold values to make an estimate of the plant's state, or mod. For example, Figure 18 shows a one-on-one combined-cycle plant that contains two generators. We have seen previously that this plant can be in one of three mods: "off," "starting," and "running."

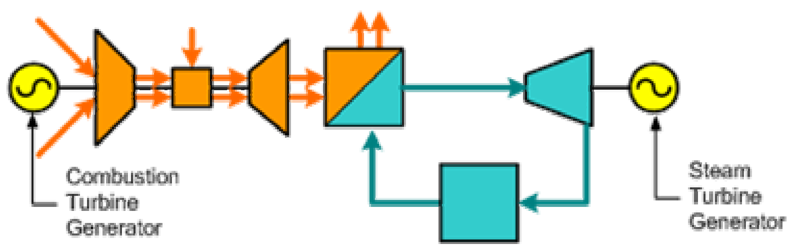

Figure 18. Monitoring a One-on-One Combined-Cycle Plant

Identifying the current mod can be accomplished by comparing the output of the combustion turbine's generator to a set of thresholds as shown below. In this case it is not necessary to measure the ST generator's output. It is assumed that the plant lacks a gas bypass system and cannot operate as a simple-cycle CT.

	Condition	Mod
CT1off	$CTGen < T_1$	"Off" mod. The first threshold represents some minimum generation level, perhaps 2% of the CT's capacity
CT1start	$T_1 \le CTGen \le T_2$	"Starting" mod
CT1run	$CTGen > T_2$	"Running" mod. The second threshold might be 65% or 70% of the CT's capacity, a value that represents the minimum continuous operating level of the CT.

T_1 and T_2 are threshold outputs of the CT's generator. CT1off, CT1start, and CT1run identify the states of the CT's generator and are used to select the mod of the plant. The states of the CT generator must (i) cover the complete output range of the generator, and (ii) must not overlap. That is, the CT's generator must always be in exactly one of the state listed above.

While in the "starting" mod, the combined-cycle plant most likely will not respond to dispatch signals and will not provide reserve or regulation. In the "running" mod the plant will respond to dispatch signals and may also be able to provide reserve and regulation. By identifying the current operating state (mod) of the plant, the real-time system can make informed judgments about where to schedule the production of energy, the supply of reserve, and the source of regulation service.

The real-time performance metrics calculated for the one-on-one combined-cycle plant above might be modified to reflect its current capabilities. That is, when the plant is unable to respond to dispatch signals, the performance tracking system might calculate the performance metrics applicable to "fixed"[3] energy suppliers. When the plant is able to respond to dispatch signals, the performance tracking system might calculate the performance metrics applicable to "flexible"[4] energy suppliers. Performance penalties would then be based on the supplier's actual capabilities. The performance metrics that are currently calculated make little or no distinction between the differing capabilities among suppliers.

It is more complex to identify the current mod of a two-on-one combined-cycle plant, illustrated in Figure 19. Recall that the two-on-one combined-cycle plant can be represented with five mods. Letting CT1 and CT2 represent the two combustion turbines in the plant, each can be "off," "starting," or "running." The nine combinations of states are enumerated below. In each case the relevant mod for the plant is shown, if possible. In this example, the ISO does not care whether CT1 starts before CT2, or CT2 starts before CT1. That flexibility in operation is left to the operators of the plant.

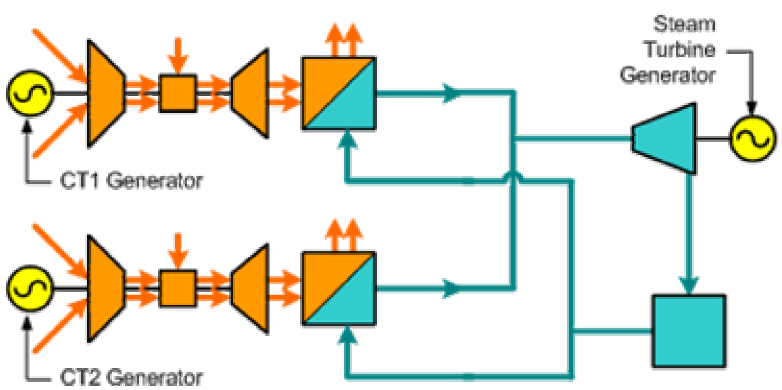

Figure 19. Monitoring a Two-on-One Combined-Cycle Plant

CT1 State	CT2 State	Plant Mod
CT1off	CT2off	"Off"
CT1off	CT2start	"First CT-HRSG starting"
CT1off	CT2run	"First CT-HRSG running"

[3] A "fixed" energy supplier is unable to respond to the dispatch instructions, issued every five-minutes, by the real-time dispatch function. Instead, the "fixed" supplier must give the ISO its best estimate of energy production rate.
[4] A "flexible" energy supplier is able to respond to the dispatch instructions, issued every five-minutes, by the real-time dispatch function.

CT1start	CT2off	"First CT-HRSG starting"
CT1start	CT2start	Impossible state – two CT-HRSGs cannot start simultaneously
CT1start	CT2run	"Second CT-HRSG starting"
CT1run	CT2off	"First CT-HRSG running"
CT1run	CT2start	"Second CT-HRSG starting"
CT1run	CT2run	"Second CT-HRSG running"

As with the simpler case of the one-on-one plant above, the two-on-one combined-cycle plant most likely will not respond to dispatch signals and will not provide reserve or regulation in either of the "starting" mods. In any of the "running" mods the plant will respond to dispatch signals and may also be able to provide reserve and regulation. By identifying the current operating state (mod) of the plant, the real-time system can make informed judgments about where to schedule the production of energy, the supply of reserve, and the source of regulation service.

There are 27 possible combinations of states for the three CT generators in a three-on-one combined-cycle plant. Some of the combinations are feasible, others are not. A three-on-one combined-cycle plant can be represented with seven mods. It is left as an exercise for the reader to enumerate the 27 combinations, identify which combinations are feasible and which are infeasible, and associate feasible combinations with one of the plant's seven mods.

Predicting a Plant's Operating State

Both RTC and RTD must be told, or be presented with enough information to infer, whether a supplier that is currently able to be on dispatch, provide spinning reserve, or provide regulation will still be able to do the same for up to 2.5 hours in the future. Suppliers that are currently unable to offer these services may become able to supply them in the near future. There are many possible combinations that must be considered. Predicting the operating characteristics of combined-cycle plants in the near future is an important function for the efficient short-term commitment of other resources and for the efficient allocation of energy, reserve, and regulation among all suppliers. RTC must know the operating characteristics of each supplier for the next 2.5 hours (or so) to make its best decision about what gets turned on or turned off in the next 15-30 minutes. Similarly, RTD must know the operating characteristics of each supplier for the next hour (or so) to make its best decision about how to allocate the production of energy and supply of reserve and regulation in for the next five minutes.

The day-ahead schedule can be used to define the capabilities of a particular energy supplier for each 15-minute real-time commitment interval in an hour. If the day-ahead schedule determines that a particular supplier is "flexible," able to provide spinning reserve, and able to provide regulation service during a particular hour, the supplier's capabilities could be treated the same way for the same hour in real-time. Using the day-ahead mod in real-time for any particular hour is a fairly straight forward conceptually. Implementation should be feasible. This technique has a few limitations, however:

Actual operation of the plant in real-time may differ markedly from the day-ahead schedule. The plant may actually operate for some hours with no day-ahead schedule. The day-ahead mod for those hours would be unknown. The day-ahead mod for other hours might become out of synch with real-time operation.

The day-ahead mods change only hourly, but the actual capabilities of a supplier might change at any time during the hour. The real-time systems could not take immediate advantage of changing capabilities, but would rather have to wait until the next hourly transition.

Predicting the mod, or operating characteristics, of combined-cycle plant is a very difficult task, particularly if there are multiple possible paths that can be taken from the current mod to other mods. This problem is illustrated in Figure 20 for a two-on-one plant. Recall that the minimum run time of the "1st CT-HRSG Running" mod has previously been set to zero. Hence the transition from "1st CT-HRSG Starting" to "2nd CT-HRSG Starting" is possible. At the end of the "1st CT-HRSG Starting" mod, the plant can remain in the "1st CT-HRSG Running" mod or can bypass that mod and enter the "2nd CT-HRSG Starting" mod. That is, the plant can continue to run at half capacity or proceed to start its other half. In general it takes a unit commitment program to determine the best schedule for a plant. An attempt to approximate the results of a unit commitment program using an ad hoc or heuristic approach may prove unsatisfactory. One should always be wary of tackling a vast problem with methods and techniques that are only half vast.

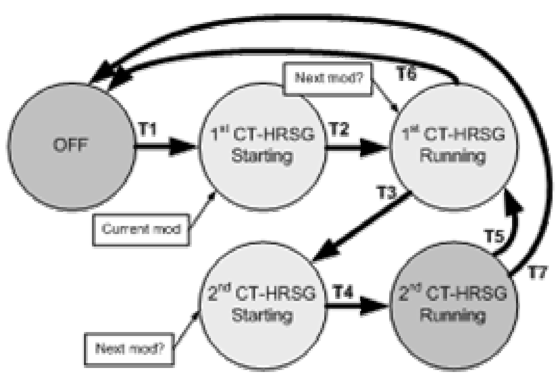

Figure 20. How Can the Next Mod be Predicted?

The information that might be available to make a prediction is illustrated in Figure 21, and includes:

The mod-and-transition model for the plant. The model used in real-time may be identical to the model used day-ahead, even though the day-ahead time granularity is one hour while the real-time time granularity is 15 minutes. Minimum and maximum run times can be rounded up to the next whole time increment.

The current mod, as deduced from measurements made at the plant
The previous mod, as deduced from measurements previously made at the plant.
The day-ahead schedule for the plant
The look-ahead portions of the RTC schedule for the plant
Clocks and timers to keep track of how long the plant has been, or will have been, in a particular mod
Others

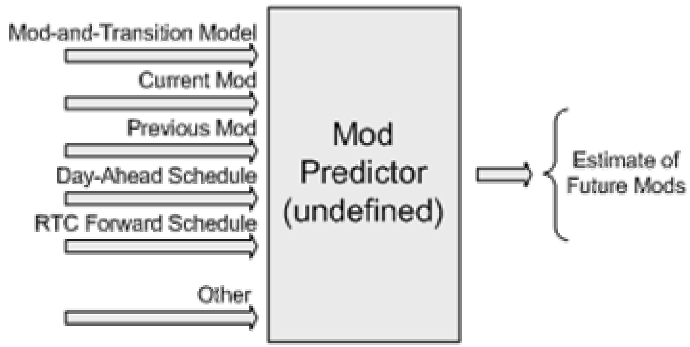

Figure 21. Mod Predictor (as yet undefined)

Real-Time Scheduling

A process that might be viable, albeit a process that would be very difficult and costly to implement, involves an auxiliary unit commitment program. The auxiliary unit commitment would estimate forward schedules by optimizing over an extended time period. That period could include the remainder of the current day and, if the next day's schedules have been determined, the entire next day. The auxiliary commitment process would define the operating state (mod) for each combined-cycle plant at the end of each RTC commitment window. RTC would have the flexibility of reaching that end-state mod as efficiently as possible, perhaps by scheduling transitions during the hour, rather than on the hour. The process is illustrated in Figure 22.

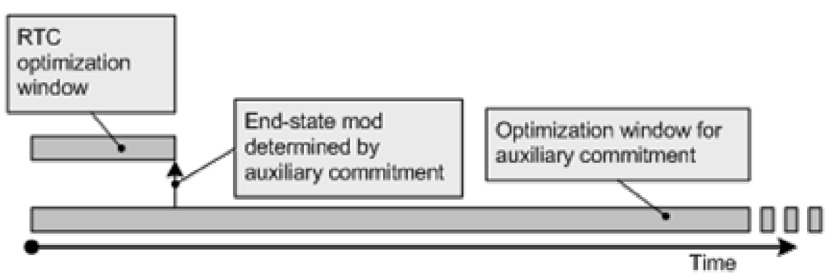

Figure 22. RTC with Auxiliary Commitment Process

As noted above, the day-ahead commitment process (SCUC) might provide a reasonable estimate of the operating state of combined-cycle plants throughout the day. However, without the ability to update its estimate, synchronization between the day-ahead estimate and real-time operation could be lost. An auxiliary commitment process might have the flexibility to be run on demand. Such a process might not have to run continuously, but might have to be run, or rerun, upon detecting a significant real-time deviation from a previous prediction.

Issues and Options

Most of the options that would improve the scheduling and tracking of combined-cycle plants require major enhancements of the NYISO's scheduling and tracking systems. Realistically, these changes cannot be realized before the summer of 2006 at the earliest. However, an interim measure could provide relief from performance penalties incurred by combined-cycle plants during the start-up phase of operation. This interim measure might be in place as early as the summer of 2005 and would remain in effect until more suitable performance tracking measures could be formulated and implemented.

Relief from Performance Penalties (Interim)

The current scheduling systems do not model the various operating states of combined-cycle plants. Hence the limited operating ranges or the limited ability of these plants to respond to control signals, particularly during start-up, is recognized neither by the scheduling systems nor by the performance tracking systems. Because of these modeling limitations, there are cases when a combined-cycle plant is asked to operate in a manner that is not possible, and subsequently penalized for nonperformance. This option would provide relief from performance penalties to combined-cycle plants during start-up phases until modeling and tracking enhancements can be implemented.

This option has the advantage of being relatively easy to implement. It has the disadvantage of not addressing market distortions that arise from unrealistic schedules that may be produced for combined-cycle plants. Further, this option removes incentives that combined-cycle plants might have to accurately advise the ISO of expected generating levels during start-up. Ignorance of actual output also leads to market distortions.

Day-Ahead Scheduling (Long-Term)

The mod-and-transition model is a viable method of producing realistic day-ahead schedules for combined-cycle plants. The mod-and-transition model would also permit combined-cycle plants to provide reserve and regulation services only when able. This option would add the mod-and-transition model to the day-ahead scheduling system.

This option is difficult to implement. Substantial amounts of data are needed to characterize mods and transitions. The models themselves are complicated and may be difficult to understand. Errors in data, whether or not the result of incomplete understanding of the model, are more likely since more data are required. Modifying the mod-and-transition model of a combined-cycle plant to reflect a forced outage is far from straight forward.

Real-Time Performance Tracking (Long-Term)

The performance tracking portion of the real-time system could be modified to recognize the operating state of a combined-cycle plant and calculate performance metrics accordingly. The performance metrics of a flexible (on-dispatch) generator are appropriate for a combined-cycle plant that is in normal operation. The performance metrics of an inflexible (off-dispatch) generator are appropriate for a combined-cycle plant that is in a start-up mode of operation.

Real-Time Scheduling (Long-Term)

There are two options for the real-time scheduling system – a passive and an active option. Implementation of the passive option does not preclude implementation of the active option. One can imagine a phased implementation where the active option would be considered only if the passive option were shown to be inadequate.

The passive option would let the real-time scheduling system know the current operating state of each combined-cycle plant. Combined-cycle plants in a normal operating mode would be considered flexible and receive dispatch instructions from the ISO. Combined-cycle plants in a start-up mode would be required to inform the ISO, through the hourly real-time offer, of their expected output.

The active option would add the mod-and-transition model to the real-time scheduling systems along with a supplementary long-term unit commitment process that would determine an operating configuration for each combined-cycle plant at the end of each RTC evaluation window. The supplementary unit commitment process is needed because the RTC evaluation window is too short to properly use the mod-and-transition model. As with the day-ahead process, modifying the mod-and-transition model of a combined-cycle plant to reflect a forced outage would be far from straight forward. The mod-and-transition model, as noted above, might be too unwieldy due to its complexity. A supplementary unit commitment process that might provide enough look-ahead capability to accommodate the time durations inherent with the operation of combined-cycle plants is, as yet, ill defined.

Summary

Two types of approaches have been presented to deal with the penchant of combined-cycle plants to operate in one of a variety of states: an active approach and a passive approach. The active approach involves changes to the unit commitment processes currently in use at the ISO to determine day-ahead and real-time commitments. The passive approach involves the recognition, in real-time, of a combined-cycle plant's operating mode and its current capabilities and limitations. Improvements in the ISO's scheduling and tracking processes to better accommodate combined-cycle plants may incorporate portions of both approaches.