IMM Opportunity Cost Calculator
Technical Reference

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1 Introduction

The opportunity cost is the marginal value of the foregone opportunity to earn higher profits for an environmentally or operationally constrained unit that results from PJM's operation of the unit on a cost based offer. The Opportunity Cost Calculator selects the hours of operation and level of dispatch that maximizes a generator's energy market revenue net of the short run marginal cost of producing energy, subject to the generator's operating parameters and environmental or operational limits. The opportunity cost is defined as the value of the marginal decrease in the net revenue due to a one hour equivalent decrease in the binding environmental or operational limit.

Opportunity cost due to the imposition of environmental limits may be included in the cost based offers to the PJM energy market. Generators with duct or peak firing capability may have distinct environmental limits applicable to only the operation of the duct or peak firing capability. In this document, limits applicable to the plant or generator are referred to as the base unit limits.[1] Depending on the type of environmental limit, the opportunity cost may be included in the cost based energy offer, cost based no load offer or the cost based start up offer.

The process for calculating the opportunity cost adder begins and ends with the Market Monitor's Member Information Reporting Application (MIRA). Figure 1-1 provides an overview. To begin, the generator owner loads the resource parameter data and environmental limit data into MIRA. The optimization problem is modeled using the Generalized Algebraic Modeling System (GAMS). The Opportunity Cost Calculator uses SAS to download the MIRA data and prepare the input data for GAMS. After the optimization is complete, SAS is used to load the results to MIRA.

Figure 1-2 provides an overview of the optimization model in GAMS. The optimal net revenue is first found with no environmental constraints in place. The optimal net revenue is denoted by Z_1. The environmental limits are then imposed and a second optimization produces the optimal net revenue Z_2. If there is no change in the optimal net revenue then the opportunity cost is $0. In the case that the environmental limits reduced the optimal net revenue, the calculator proceeds by determining the earliest binding compliance period, denoted by C in Figure 1-2. A third optimization is run, limited to period C, with the environmental limits imposed. For the fourth and final optimization, each environmental limit is reduced by an hour equivalent amount. For example, the CO_2 limit would be reduced by 50 tons for a 100 MW unit with a CO_2 emission rate of 0.5 tons per MWh. Net revenue is optimized once again over the period C subject to the

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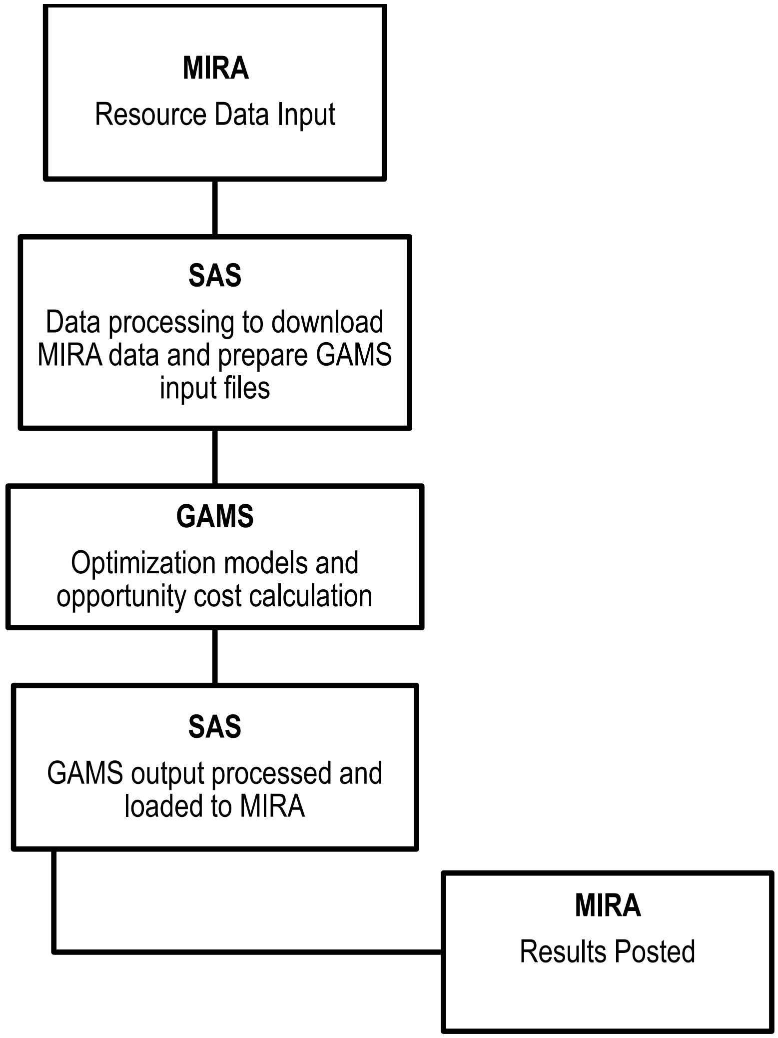
1 Some environmental limits apply to the generation plant and the total of emissions or operations from multiple generation units cannot exceed the plant limit. Other environmental limits apply to a single generation unit. This document refers to both of these as a resource. A resource may be a single unit or a generation plant with multiple units and duct or peak firing capability.

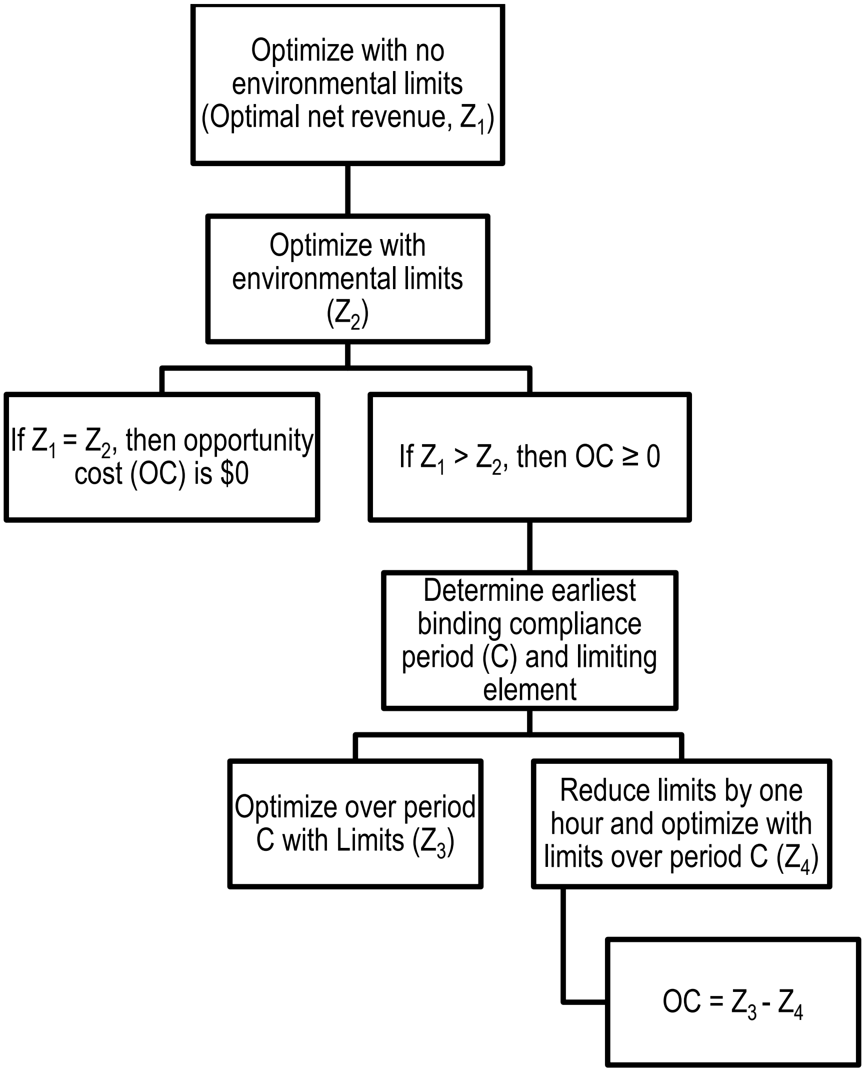
adjusted limits. The opportunity cost is equal to the reduction in the optimal net revenue, denoted by $Z_3 - Z_4$ in Figure 1-2.

Figure 1-1 Overview of the opportunity cost calculator process



The calculation in Figure 1-2 is repeated for three scenarios. Each scenario is based on a different set of estimated forward LMP and forward operating costs for the generator. The forward LMP estimates are PJM Western Hub forward prices with adjustments, calculated using historical LMP, to reflect historical differences between the generator bus LMP and the PJM Western Hub LMP and the historical hourly volatility of the generator bus LMP. The forward operating cost estimates include three different estimates of the delivered fuel price for the forward year based on monthly fuel forward prices, historical fuel prices and fuel delivery charges. A volatility adjustment factor, calculated using historical delivered fuel prices, is included to reflect the historical daily volatility of the delivered fuel price.

Figure 1-2 Optimization Model



2 Inputs

Inputs into the optimization model consists of generator operating parameters, planned outages, expected fuel availability, emission rates, emission histories, environmental limit details and hourly margins for the forward year. Generator parameters, planned outages, expected fuel availability, emission rates, emission histories and environmental limit details are supplied by the generation owner or operator and are loaded into the Market Monitor's Member Information Reporting Application (MIRA).[2] Hourly margins are based on forward and historical prices for LMP and fuel, and are calculated by the Market Monitor, following Manual 15.

2 In some circumstances, the parameters are populated in MIRA by the Market Monitor and then reviewed by the generation owner.

2.1 Operating Parameters

Generation owners provide the following unit parameter data by loading the data into MIRA.

Primary and secondary fuel total heat rates at the economic maximum, and if applicable the heat rate for the duct or peak firing component.

Economic minimum and maximum capability for the primary and secondary fuel schedules, and if applicable the duct or peak firing maximum capability.

Variable operating and maintenance cost (VOM) for generation on the primary and secondary fuel schedules, and if applicable variable operating and maintenance cost for the duct or peak firing component.

Planned generation outage hours and percent of outage during the forward year for the base unit and the duct or peak firing component.

Expected availability of primary fuel in the forward year by month, expressed as percent.

Minimum downtime for the base unit primary and secondary fuel schedules.

Minimum runtime for the base unit primary and secondary fuel schedules.

Start up cost for the primary and secondary fuel schedules.

All parameter data except for the heat rates and VOM are direct inputs into the optimization model. The heat rates and VOM are inputs into the margin calculations.

2.2 Environmental Limit Data

Generation owners provide the following environmental limit data by loading the data into MIRA.

The structure of the compliance period as defined by the relevant permit(s): calendar year, 12 month rolling or 365 day rolling.

Limit types. The Opportunity Cost Calculator models seven pollutant limits (NO_x, SO_2, CO_2, CO, PB, PM, O_3), fuel throughput limits, operating hour limits, start limits and duct or peak firing operating hour limits.

Limiting quantity for each limit type.

Primary and secondary fuel average emission rates for each monitored pollutant, and if applicable, average emission rates for the duct or peak firing component.

Primary and secondary fuel average start up emission rates for each monitored pollutant.

Emission histories for each monitored pollutant, by month for the 13 month period ending with the current month.

Fuel throughput history for units with a fuel throughput limit, by month for the 13 month period ending with the current month.

Operating hours history for units with an operating hours limit, by month for the 13 month period ending with the current month.

Start up history for units with a starts per period limit, by month for the 13 month period ending with the current month.

Duct or peak firing operating hours history for units with a duct or peak firing operating hours limit, by month for the 13 month period ending with the current month.

The emission limits and the start emission rates are direct inputs into the optimization model. The emission rates, entered as lbs per MMBtu in MIRA, are converted to tons per MWh for input into the optimization model by multiplying by the heat rate and dividing by 2,000.

$$\textbf{Emission Rate (tons per MWh)} = \textbf{Emission Rate (lbs per MMBtu)} \cdot \textbf{HeatRate}/\textbf{2,000}$$

The monthly emission histories are used to create emission histories by compliance period for input into the optimization model. Table 2-1 is an example of a 13 month emission history submission in MIRA assuming the calculation date is December 4, 2025. The submitted emissions are assumed to include emissions through December 3, 2025, and the forward year begins on the calculation date, December 4, 2025. If the corresponding limit is a calendar year limit, then there is a single compliance period and the emission history for the compliance period is the sum of emissions beginning with January 1, 2025, or 72.0 tons. In the case of a 12 month rolling limit, there are 12 compliance periods, one for each 12 month rolling period ending in the forward year.

Table 2-1 Thirteen month emission history in submitted to MIRA

MIRA Data	
Month	Emissions (tons)
12/2024	4.0
1/2025	9.0
2/2025	7.0
3/2025	3.0
4/2025	4.0
5/2025	5.0
6/2025	8.0
7/2025	10.0
8/2025	12.0
9/2025	8.0
10/2025	4.0
11/2025	2.0
12/2025	0.0

Table 2-2 shows the emissions history by compliance period corresponding to the emissions history in Table 2-2 for a 12 month rolling limit. The historical emissions entry for the first compliance period C_1 is the sum of emissions that occur between January 1, 2025, and December 31, 2025. The historical emission entry for compliance period C_2 is the sum all emissions since February 1, 2025.

Table 2-3 shows the emissions history by compliance period corresponding to the emissions history in Table 2-1 for a 365 day rolling limit. The first day of the forward year is December 4, 2025 and first compliance period, C_1, begins on December 5, 2024 and ends with the last hour of December 4, 2025. The partial month emissions are prorated by generation during the month. For example, Table 2-3 shows the proration assuming the total generation for December 2024 was 1,000 MWh with 100 MWh occurring on December 5, 2024, and the remaining 900 MWh occurring in the latter half of the month. Compliance period $C_{1,}$ which begins on December 5, 2024, includes all of the December 2024 generation and therefore C_1 includes all emissions in Table 2-1 or 76.0 tons. Compliance period C_2 begins on December 6, 2024, and the December 2024 emissions are prorated based on 900 of the 1,000 MWh occurring in the compliance period. The March 2025 proration in Table 2-3 assumes 500 MWh of generation in March 2025, with 100 MWh occurring on March 1, 2025 and remaining 400 MWh occurring in the latter half of the month.

Table 2-2 Emissions by compliance period, 12 month rolling limit

Opportunity Cost Calculator Input Data			
Compliance Period	Period Begins	Period Ends	Emissions (tons)
C_1	1/1/2025	12/31/2025	72.0
C_2	2/1/2025	1/31/2026	63.0
C_3	3/1/2025	2/28/2026	56.0
C_4	4/1/2025	3/31/2026	53.0
C_5	5/1/2025	4/30/2026	49.0
C_6	6/1/2025	5/31/2026	44.0
C_7	7/1/2025	6/30/2026	36.0
C_8	8/1/2025	7/31/2026	26.0
C_9	9/1/2025	8/31/2026	14.0
C_{10}	10/1/2025	9/30/2026	6.0
C_{11}	11/1/2025	10/31/2026	2.0
C_{12}	12/1/2025	11/30/2026	0.0

Table 2-3 Emissions by compliance period, 365 day rolling limit

Opportunity Cost Calculator Input Data			
Compliance Period	Period Begins	Period Ends	Emissions (tons)
C_1	12/5/2024	12/4/2025	76.0
C_2	12/6/2024	12/5/2025	75.6
C_3	12/7/2024	12/6/2025	75.6
.	.	.	.
.	.	.	.
.	.	.	.
C_{87}	3/1/2025	2/28/2026	56.0
C_{88}	3/2/2025	3/1/2026	55.4
C_{89}	3/3/2025	3/2/2026	55.4
.	.	.	.
.	.	.	.
.	.	.	.
C_{363}	12/2/2025	12/1/2026	0.0
C_{364}	12/3/2025	12/2/2026	0.0
C_{365}	12/4/2025	12/3/2026	0.0

Monthly histories for fuel throughput, operating hours, starts and duct or peak firing operating hours are treated in an analogous manner.

2.3 Forward Margins

The Opportunity Cost Calculator optimizes a resource's forward net revenue over the forward year. The optimization requires hourly estimates of the LMP and daily estimates of resource operating cost in the forward year. The hourly margins, equal to forward LMP net of operating cost, are an input into the optimization model. The Market Monitor calculates three estimates of the hourly forward LMP and daily operating cost based on LMP forward prices, fuel forward prices, and historical LMP and fuel prices from the three most recent years, following the method defined in Manual 15.

2.3.1 Future Hour Map

To obtain three estimates of the forward margins, the forward year is mapped to three different historical periods. The first historical period is the 365 day period that begins one year prior to the forward year. The second historical period is the 365 day period that begins two years prior to the start of the forward year. The third historical period is the 365 day period that begins three years prior to the start of the forward year. The forward year is mapped to the historical period such that week days in the forward period are mapped to historical week days, weekend days are mapped to historical weekend days, and holidays in the forward period are mapped to historical holidays. The mapping also ensures the on peak hours in the forward period are mapped to on peak hours in the historical period, and off peak hours are mapped to off peak hours.

Representing the first day in the forward year by month m, day d, and year y, or concisely as $m/d/y$, the first step is to map $m/d/y$ to the nearest date with the same day of week on or before $m/d/(y-1)$. For example, if the first day of the forward period is 11/18/2025, which is a Tuesday, then 11/18/2025 is mapped to 11/12/2024, the nearest Tuesday occurring on or before 11/18/2024. Initially, each subsequent day is mapped following the calendar order. Future day 11/19/2025 is mapped to 11/13/2024; 11/20/2025 is mapped to 11/14/2024. This results in a map of future days to historical days where the future day of the week matches the historical day of the week. The next step is to check each holiday to ensure holidays are mapped to holidays. In the case where the holidays do not align, an adjustment is made to map future holidays to historical holidays. The resulting map, after the holiday adjustments, maintains the on peak future hour to on peak historical hour criteria, and the same is true for off peak hours. This process is repeated for years $y-2$ and $y-3$.

The future hour to historical hour map is denoted by $M^{(s)}$, where s represents the three scenarios, $s=1, 2, 3$. For each future hour, h, $M^{(s)}(h)$ is the historical hour to which h is mapped in scenario s. In the previous example, the first future hour is hour ending 11/18/2025 01:00 and $M^{(1)}(11/18/2025\ 01{:}00)$ is hour ending 11/12/2024 01:00.

2.3.2 Forward LMP

The calculation of the forward LMP uses on and off peak forward prices for the PJM Western Hub. Forward prices for thirteen months, beginning with the current month, are used in the calculation. For the current month, the balance of month forward price is used. The forward price for each month in the forward year is multiplied by a basis adjustment factor and volatility scalar. The basis adjustment factor is included to capture historical differences between the generator bus LMP and the PJM Western Hub LMP. The volatility scalar is included to capture the historical hourly volatility of the generator bus LMP.

$$Forward\ LMP\ =\ (Forward\ Price)\ \cdot (Basis\ Adjustment\ Factor) \cdot (Volatility\ Scalar)$$

The following variable definitions are used in the description of the forward LMP calculation.

s – Scenario value (equal to 1, 2 or 3) corresponding to the three mappings of the forward year to a historical year.

m/y – Month and year in the forward year.

p – Peak hour indicator, equal to 1 for an on peak hour, 0 for off peak.

$F_{m/y}^{(p)}$ – On or off peak PJM Western Hub forward price with m/y term date.

$M^{(s)}$ – Scenario s mapping function that maps future hours to historical hours.

$M^{(s)}(h)$ – the historical hour to which future hour h is mapped in scenario s.

$H_m^{(p)}$ – set of all on peak hours ($p = 1$) in month m of the forward year; set of all off peak hours ($p = 0$) in month m of the forward year.[3]

$LMP(h)$ – Historical generator LMP for historical hour h.

$HUB\_LMP(h)$ – Historical LMP at the PJM Western hub for historical hour h.

$AVG\_LMP_m^{(s,p)}$ – Scenario s average on or off peak historical generator LMP for future month m.

$B_m^{(s,p)}$ – Scenario s basis adjustment factor for future month m.

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3 The forward year (unless the calculation is done on the first day of a month) includes partial months at the start and end of the year. The hours in the partial months have the same month number and, for purposes of calculating the monthly basis adjustment factor and hourly volatility scalar, are treated as being in the same month. For example, if the calculation date is December 4, 2025, then $H_{12}^{(1)}$ includes the on peak hours for December 4, 2025 through December 31, 2025, and the on peak hours for December 1, 2026 through December 3, 2026.

$V^{(s)}(h)$ – Scenario s volatility scalar for future hour h.

$FLMP^{(s)}(h)$ – Scenario s forward LMP for future hour h.

For future hour h, $M^{(s)}(h)$ is the historical hour to which hour h is mapped. The scenario s basis ratio corresponding to future hour h is

$$\frac{LMP\left(M^{(s)}(h)\right)}{HUB\_LMP\left(M^{(s)}(h)\right)}.$$

The on peak basis adjustment factor for month m is the average basis ratio over all on peak hours in month m. The off peak basis adjustment factor for month m is the average basis ratio over all off peak hours in month m. In terms of the defined variables,

$$B_m^{(s,p)} = \frac{1}{Card\left(H_m^{(p)}\right)} \sum_{h \in H_m^{(p)}} \frac{LMP\left(M^{(s)}(h)\right)}{HUBLMP\left(M^{(s)}(h)\right)}.$$ [4] [5]

The volatility scalar for each future hour is equal to the historical generator LMP corresponding to the mapped historical hour, divided by the average historical on or off peak monthly average LMP. In terms of the defined variables, the scenario s average historical on and off peak LMP for future month m, are given by

$$AVG\_LMP_m^{(s,p)} = \frac{1}{Card\left(H_m^{(p)}\right)} \sum_{h \in H_m^{(p)}} LMP\left(M^{(s)}(h)\right).$$

The scenario s volatility scalar for future hour h is

$$V^{(s)}(h) = \frac{LMP\left(M^{(s)}(h)\right)}{AVG\_LMP_m^{(p)}}$$

where h is in $H_m^{(p)}$.

[4] $Card\left(H_m^{(p)}\right)$ is the number of hours in set $H_m^{(p)}$, where $H_m^{(1)}$ is the set of all on peak hours in future month m and $H_m^{(0)}$ is the set of all off peak hours in future month m.

[5] The notation $h \in H_m^{(p)}$ means "h element of set $H_m^{(p)}$". For $p = 1$, the summation is taken over all on peak hours in month m of the future year. For $p = 0$, the summation is taken over all off peak hours in month m of the future year.

The forward LMP is the product of the PJM Western Hub LMP forward price, the basis adjustment and the volatility scalar. In terms of the defined variables, the scenario s forward LMP for future hour h is

$$FLMP^{(s)}(h) = F_{m/y}^{(p)} \cdot B_m^{(s,p)} \cdot V^{(s)}(h)$$

where h is in future month m/y.

2.3.3 Forward Delivered Fuel Price

Three estimates of the hourly operating cost for the forward year are needed to calculate margins for input into the optimization model. The operating cost estimates are based on the generator's cost parameters and three estimates of the delivered fuel price for the forward year. The operating cost consists of the cost of the delivered fuel, the variable operating and maintenance cost and if applicable the emissions cost.

Three estimates of the delivered fuel price for the forward year are calculated based on monthly fuel forward prices, historical fuel prices and fuel delivery charges.[6] Each generator has been mapped to a fuel index based on the generator's fuel cost policy. Forward prices for thirteen months, beginning with the current month, are used in the calculation. For the current month, the balance of month forward price is used. The sum of the monthly fuel forward price and delivery charge is multiplied by a daily fuel volatility scalar. The fuel volatility scalar is included to capture the historical daily volatility of the delivered fuel price.

The following variable definitions are used in the description of the forward delivered fuel calculation.

s – Scenario value (equal to 1, 2 or 3) corresponding to the three mappings of the forward year to a historical year.

m/y – Month and year in the forward year.

$M^{(s)}$ – Scenario s mapping function that maps future hours to historical hours.

$M^{(s)}(h)$ – the historical hour to which future hour h is mapped in scenario s.

H_m – Set of all hours in month m of the forward year.[7]

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6 If available, a contract price for fuel is used rather than a forward estimate.

7 The forward year (unless the calculation is done on the first day of a month) includes partial months at the start and end of the year. The hours in the partial months have the same month number and, for purposes of calculating the hourly fuel volatility scalar, are treated as being in the same month. For

d – Fuel delivery charge submitted to MIRA.

$FF_{m/y}$ – Fuel forward price with m/y term date.

$HFP(h)$ – Historical fuel price for historical hour h.

$AVG\_HFP_m^{(s)}$ – Average historical delivered fuel price for month m in scenario s.

$FV^{(s)}(h)$ – Scenario s fuel volatility scalar for future hour h.

$FDFP^{(s)}(h)$ – Scenario s forward delivered fuel price for future hour h.

The daily fuel volatility scalar is equal to the ratio of the delivered fuel price divided by the monthly average delivered fuel price. In terms of the defined variables, the scenario s average delivered fuel price for month m is

$$AVG\_HFP_m^{(s)} = \frac{1}{Card(H_m)} \sum_{h \in H_m} \left(HFP\left(M^{(s)}(h)\right) + d \right).$$ [8] [9]

The scenario s fuel volatility scalar for future hour h is

$$FV^{(s)}(h) = \frac{HFP\left(M^{(s)}(h)\right) + d}{AVG\_HFP_m^{(s)}}$$

where $h \in H_m$.

The scenario s forward delivered fuel price for future hour h is the product of the fuel forward price plus the delivery charge, and the fuel volatility scalar

$$FDFP^{(s)}(h) = \left(FF_{m/y} + d\right) \cdot FV^{(s)}(h)$$

where h is in future month m/y.

2.3.4 Forward Emissions Cost

Forward emissions cost values are calculated using emission allowance forward prices. Forward prices for thirteen months, beginning with the current month, are used in the calculation.

example, if the calculation date is December 4, 2025, then H_{12} includes the hours for December 4, 2025 through December 31, 2025, and the hours December 1, 2026 through December 3, 2026.

8 $Card(H_m)$ is the number of hours in set H_m, where H_m is the set of all hours in future month m.

9 The notation $h \in H_m$ means "h element of set H_m". The summation is taken over all hours in month m of the future year.

Emissions cost for three pollutants (NO_x, SO_2, CO_2) are modeled for inclusion in the forward emissions cost.

The following variable definitions are used in the description of the forward emissions cost calculation.

m/y – Month and year in the forward year.

$MIRA\_ER_i$ – emission rate submitted to MIRA for pollutant i (lbs per MMBTU).

EC_IND_i – Binary variable indicating whether or not emissions cost is included for pollutant i.[10]

HR – Heat rate submitted to MIRA .

$EF_{m,y}(i)$ – Emissions allowance forward price for pollutant i with m/y term date.

$FEC_{m/y}$ – Forward emissions cost for future month m/y ($ per MWh).

The forward emissions cost is the product of the emissions allowance forward price and the resource's emission rate. In terms of the defined variables,

$$FEC_{m/y} = \sum_{i=1}^{3} EF_{m/y}(i) \cdot HR \cdot (MIRA\_ER_i/2000) \cdot EC\_IND_i.$$

2.3.5 Forward Operating Cost

The following variable definitions are needed to finalize the forward hourly operating cost.

$VOM1$ – Variable operating and maintenance cost submitted to MIRA in $ per MMBtu.

$VOM2$ – Variable operating and maintenance cost submitted to MIRA in $ per MWh.[11]

CBA – Cost based adder equal to 1.1 if the resources uses the adder in its cost based offer; otherwise equal to 1.0;

$FOC^{(s)}(h)$ – Scenario s forward operating cost for future hour h.

The scenario s forward operating cost estimate for future hour h is

$$FOC^s(h) = \left(HR \cdot \left(FDFP^{(s)}(h) + VOM1\right) + VOM2 + +FEC_{m/y}\right) \cdot CBA$$

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10 An emission cost is included if the resource's cost based offer includes emission cost.

11 MIRA also includes an option for submitting variable operating and maintenance cost in $ per hour. In this case, the value is a direct input into the optimization model.

where h is in future month m/y.

The forward operating cost for the duct fire component is defined in the same way. The heat rate and variable operating and maintenance cost are the only differences. The following variable definitions are needed.

DF_HR – Duct or peak firing heat rate submitted to MIRA .

DF_$VOM1$ – Duct or peak firing variable operating and maintenance cost submitted to MIRA in $ per MMBtu.

DF_$VOM2$ – Duct or peak firing variable operating and maintenance cost submitted to MIRA in $ per MWh.[12]

DF_$FOC^{(s)}(h)$ – Duct or peak firing scenario s forward operating cost for future hour h.

The scenario s forward operating cost estimate, applicable to the duct or peak firing component, for future hour h is

$$FOC\_DF^{s}(h) = \left(DF\_HR \cdot \left(FDFP^{(s)}(h) + DF\_VOM1\right) + DF\_VOM2 + +FEC_{m/y}\right) \cdot CBA$$

where is in future month m/y.

2.3.6 Forward Margins

The hourly forward margins are equal to the forward LMPs net of the forward operating cost. In terms of the defined variables, the scenario s forward margin applicable to the base unit, for future hour h is

$$margin^{(s)}(h) = FLMP^{(s)}(h) - FOC^{s}(h).$$

The duct or peak firing scenario s forward margin for future hour h is

$$DF\_margin^{(s)}(h) = FLMP^{(s)}(h) - DF\_FOC^{s}(h).$$

The forward margins, $margin^{(s)}(h)$ and $DF\_margin^{(s)}(h)$, $s = 1, 2, 3$, are inputs to the optimization model.

3 Optimization Model

The optimization model uses a series of constrained optimizations to determine the opportunity cost. Each constrained optimization is formulated as a mixed integer programming application. The Generalized Algebraic Modeling System (GAMS) is used to set up the optimization problem,

12 MIRA also includes an option for submitting variable operating and maintenance cost in $ per hour. In this case, the value is a direct input into the optimization model.

which includes the specification of the objective function, operating parameter constraints and environmental constraints. Once the optimization is formulated in GAMS, the IBM CPLEX solver is called upon to find the commitment and dispatch that maximizes net revenue. The duct firing or peak capability, if it exists, is modeled as a separate component. In the descriptions below the base unit refers to the resource as a whole.[13]

3.1 Model Parameters

C_k – Compliance period k where k ranges from 1 to 12 for 12 month rolling constraints and 1 to 365 for 365 day rolling. For a calendar year constraint, there is a single compliance period with $k = 1$.

h – Hour in the forward year.

i – Index representing the seven pollutants (NO_x, SO_2, CO_2, CO, PB, PM, O_3).

$FUEL\_AVAIL(h)$ – expected availability of primary fuel in forward year (value between 0 and 1).

$DFEMISS\_RATE_i$ – duct or peak firing primary fuel emission rate for pollutant i (tons per MWh).

$DFMARGIN(h)$ – forward LMP net the duct or peak firing forward energy and variable operating and maintenance cost for hour h ($ per MWh).

$DFMW$ – duct or peak firing maximum capability (MW).

$DFOP\_HIST(C_k)$– duct or peak firing operating hours history during compliance period C_k.

$DFOP\_LIMIT(C_k)$– duct or peak firing operating hours limit (hours per compliance period).

$DFOUTAGE(h)$ – planned duct or peak firing outages in forward year (value between 0 and 1).

$ECOMAX$ – economic maximum for the base unit primary fuel schedule (MW).[14]

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13 Some environmental limits apply to the generation plant and the total of emissions or operations from multiple generation units cannot exceed the plant limit. Other environmental limits apply to a single generation unit. This document refers to both of these as a resource. A resource may be a single unit or a generation plant with multiple units and duct or peak firing capability.

14 In the case that a duct or peak firing component is modeled, $ECOMAX$ represents the maximum capability of the resource independent of the duct or peak firing component.

$ECOMAX$_SF – economic maximum for the base unit secondary fuel schedule (MW).[15]

$ECOMIN$ – economic minimum for the base unit primary fuel schedule (MW).

$EMISS\_HIST(i, C_k)$ – historical emissions for pollutant i during compliance period C_k (tons).

$EMISS\_LIMIT_i$ – emission limit for pollutant i (tons per compliance period).[16]

$EMISS\_MRSF_i$ – emissions of pollutant i from a commitment, equal in duration to the minimum runtime, on the secondary fuel schedule (tons).

$EMISS\_RATE_i$ – base unit primary fuel emission rate for pollutant i (tons per MWh).

$EMISS\_RATE\_SF_i$ – base unit secondary fuel emission rate for pollutant i (tons per MWh).

$HEATRATE$ – primary fuel summer total heat rate at the economic maximum (MMBtu per MWh).

$HEATRATE\_SF$ – secondary fuel summer total heat rate at the economic maximum (MMBtu per MWh).

$LAR1(h)$ – a look ahead restriction parameter that is greater than or equal to 1 and less than 2 if a commitment beginning in hour h, of duration equal to the minimum runtime, has a nonnegative net revenue; is greater than 0 and less than 1 otherwise (value between 0 and 2).[17]

$LAR2(h)$ – a look ahead restriction parameter, applicable to a resource with a one hour minimum runtime, that is greater than or equal to 1 and less than 2 if a one hour commitment beginning in hour h has a nonnegative net revenue; is greater than or equal to 0 and less than 1 otherwise (value between 0 and 2).

$LAR(h)$ – for resources with a one hour minimum runtime, $LAR(h)$ is equal to the larger of $LAR1(h)$ and $LAR2(h)$. For all other resources, $LAR(h)$ is equal to $LAR1(h)$.

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15 In the case that a duct or peak firing component is modeled, $ECOMAX\_SF$ represents the maximum capability of the resource independent of the duct or peak firing component.

16 The current design models seven pollutants: NO_x, SO_2, CO_2, CO, PB, PM, O_3. In this document, the pollutant is referred to by its order as given above. For example, pollutant 1 is NO_x, pollutant 2 is SO_2, and proceeding in this manner, pollutant 7 is O_3.

17 The look ahead restriction parameters all have the same basic calculation, $1 + {}^{x}/_{1+|x|}$, where x is the net revenue value. To calculate the value of the look ahead parameters, the output level is equal to the economic maximum output if the margin is nonnegative and is equal to the economic minimum output if the margin is negative.

$LARX1(h)$ – a look ahead restriction parameter that is greater than or equal to 1 and less than 2 if the revenue net the operating cost for hour h is nonnegative; is greater than 0 and less than 1 otherwise (value between 0 and 2).

$LARX2(h)$ – a look ahead restriction parameter that is greater than or equal to 1 and less than 2 if the revenue net the operating cost for hours h and $h + 1$ is nonnegative; is greater than 0 and less than 1 otherwise (value between 0 and 2).

$LARX(h)$ – equal to the larger of $LARX1(h)$ and $LARX2(h)$.

$MARGIN(h)$ – forward LMP net the base unit forward energy and variable operating and maintenance cost for hour h ($ per MWh).

$MINDOWN$ – minimum downtime for the base unit primary fuel schedule (hours).

$MINRUN$ – minimum runtime for the base unit primary fuel schedule (hours).

$MINRUN$_SF – secondary fuel schedule minimum runtime for the base unit (hours).

$MRG\_OPP\_COST(s)$ – the base unit marginal opportunity cost for scenario s.

$MRG\_OPP\_COST\_DF(s)$ – the duct or peak firing marginal opportunity cost for scenario s.

$MRG\_OPP\_COST\_SF(s)$ – the secondary fuel marginal opportunity cost for scenario s.

$MWH\_HIST(C_k)$ – historical MWh during compliance period C_k.

MWH_LIMIT – MWh limit (MWh per compliance period).[18]

MWH_MRSF – MWh of generation on the primary fuel that is equivalent to a commitment, equal in duration to the minimum runtime, on the secondary fuel schedule.[19]

$OPHOUR\_HIST(C_k)$ – historical operating hours during compliance period C_k.

$OPHOUR\_LIMIT$ – operating hours limit (hours per compliance period).

OPP_COST_ADDER – the base unit opportunity cost adder.

$OPP\_COST\_DF\_ADDER$ – the duct or peak firing opportunity cost adder.

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18 Fuel throughput limits are typically stated in MMBtu terms and are converted to MWh limits by dividing MMBtu limit by the base unit heat rate.

19 This value is limited to few cases where the Title V permits includes a conversion factor.

$OPP\_COST\_SF\_ADDER$ – the secondary fuel opportunity cost adder.

$OPTCR$ – GAMS system parameter that controls the relative error tolerance. $OPTCR$ is set to 10^{-7}.

$OUTAGE(h)$ – planned base unit outages in forward year (value between 0 and 1).

$RESLIM$ – GAMS system parameter that defines the computational time for each optimization. $RESLIM$ ranges from 6 to 90 minutes.

$SFPF\_CONV$ – a conversion factor used to covert secondary fuel usage to primary fuel usage for a fuel throughput limit.

$STARTCOST$ – start up cost ($ per start).

$START\_EMISS_i$ – emissions per start for pollutant i (tons per start).

$START\_EMISS\_SF_i$ – secondary fuel emissions per start for pollutant i (tons per start).

$START\_HIST(C_k)$– start up history during compliance period C_k.

$START\_LIMIT(C_k)$– start up limit (starts per compliance period).

$TOT\_DFHOUR(C_k, n)$ – equal to the total amount of duct or peak operating hours accounted for in the optimal solution for optimization n, during compliance period C_k. This amount includes historical duct or peak firing operating hours as well as additions from the commitment and dispatch in the optimal solution for the forward year.

$TOT\_EMISS(i, C_k, n)$ – equal to the total amount of pollutant i accounted for in the optimal solution for optimization n, during compliance period C_k. This amount includes historical emissions as well as additions from the commitment and dispatch in the optimal solution for the forward year.

$TOT\_MWH(C_k, n)$ – equal to total amount of MWh accounted for in the optimal solution for optimization n, during compliance period C_k. The total amount includes historical MWh as well as additions from the commitment and dispatch of the optimization in the forward year.

$TOT\_OPHOUR(C_k, n)$ – equal to total amount of operating horus accounted for in the optimal solution for optimization n, during compliance period C_k. The total amount includes historical operating hours as well as additions from the commitment and dispatch in the optimal solution for the forward year.

$TOT\_START(C_k, n)$ – equal to total number of starts accounted for in the optimal solution for optimization n, during compliance period C_k. The total amount includes historical starts as well as additions from the commitment and dispatch in the optimal solution for the forward year.

VOM_HRLY – base unit variable operating and maintenance cost ($ per hour).

3.2 Decision Variables

Decision variables are variables whose values are determined by the optimization engine. Decision variables may have a prescribed range but otherwise the optimization assigns values that maximize net revenue while satisfying all constraints. The optimization model uses the following decision variables.

$HOURON(h)$ – a binary variable that equals 1 if the unit is operating during hour h; otherwise equals 0.

$START(h)$ – a binary variable that equals 1 if the unit starts during hour h; otherwise equals 0.

$XTRAHR(h)$ – a binary variable that equals 1 if the unit is to remain on for hour h, surpassing the minimum runtime; equals 0 otherwise.

$DFON(h)$– a binary variable that equals 1 if the duct or peak firing component is on for hour h; otherwise equals 0.

$OUTPUT(h)$ – a nonnegative variable representing the MWh output during hour h.

3.3 Objective Function

Each optimization in the optimization model finds the commitment and dispatch that maximizes the net revenue. Net revenue is the total energy revenue less the start up and operating cost over the forward period. The following equation states the objective function in terms of the decision variables and model parameters.

$$\mathbf{Z} = \sum_{\mathbf{h}} \mathbf{OUTPUT(h) \cdot MARGIN(h) + DFMW \cdot \left(1 - DFOUTAGE(h)\right) \cdot DFMARGIN(h) \cdot DFON(h)} \\ \mathbf{- STARTCOST \cdot START(h) - VOM\_HRLY \cdot HOURON(h)}$$

3.4 Operating Constraints

Operating constraints ensure that the commitment and dispatch of the unit adheres to the operating parameters. The optimization model also includes logic that limits the look ahead period for the start up and shut down decisions.

The economic maximum constraint restricts the $OUTPUT(h)$ decision variable to be at or below the economic maximum when the unit is operating.[20]

$$\mathbf{OUTPUT(h) \le HOURON(h) \cdot ECOMAX \cdot min\{FUEL\_AVAIL(h), 1 - OUTAGE(h)\}}$$

20 The $ECOMAX$ parameter is adjusted to reflect derates due to outages or lack of fuel.

The economic minimum constraint restricts the $OUTPUT(h)$ decision variable to be at or above the economic minimum when the unit is operating.[21]

$$\mathbf{OUTPUT(h) \geq HOURON(h) \cdot min\{ECOMIN, ECOMAX \cdot min\{FUEL\_AVAIL(h), 1 - OUTAGE(h)\}\}}$$

The minimum runtime constraint prevents shutdown of the unit prior to the completion of the minimum runtime period.

$$\sum_{\mathbf{t=1}}^{\mathbf{MINRUN}} \mathbf{HOURON(h + t - 1) \geq MINRUN \cdot \big(HOURON(h) - HOURON(h - 1)\big)}$$

The minimum downtime constraint prevents the start up of the unit prior to the completion of the minimum downtime period.

$$\sum_{\mathbf{t=1}}^{\mathbf{MINDOWN}} \mathbf{\big(1 - HOURON(h + t - 1)\big) \geq MINDOWN \cdot \big(HOURON(h - 1) - HOURON(h)\big)}$$

The start up constraints require the $START(h)$ decision variable to equal 1 in an hour the resource starts up and to equal 0 in all other hours.

$$\mathbf{START(h) \geq HOURON(h) - HOURON(h - 1)}$$

$$\mathbf{START(h) \leq 0.5 \cdot \big(HOURON(h) - HOURON(h - 1)\big) + 0.5}$$

The start up look ahead constraint requires the $LAR(h)$ parameter to be greater than or equal to 1 in order for the resource to start up in hour h.

$$\mathbf{START(h) \leq LAR(h)}$$

The extra hour constraints specify conditions that must hold for the $XTRAHR(h)$ decision variable.

$$\mathbf{XTRAHR(h) \leq LARX(h)}$$

$$\mathbf{XTRAHR(h) \leq HOURON(h - 1)}$$

$$\mathbf{XTRAHR(h) = HOURON(h) - \sum_{t=1}^{MINRUN} START(h - t + 1)}$$

The duct or peak firing constraint requires the base unit to be operating in any hour the duct or peak firing capability is dispatched.

$$\mathbf{DFON(h) \leq HOURON(h)}$$

21 The $ECOMIN$ parameter is restricted to be no higher than the ECOMAX after adjustment for derates.

3.5 Environmental Constraints

Environmental limits are typically imposed on a calendar year, 12 month rolling or 365 day rolling basis. A constraint for each compliance period ending within the forward year must be modeled. A calendar year limit is modeled with a single constraint. A 12 month rolling limit is modeled with 12 constraints, one for each 12 month period ending in the forward year. A 365 day rolling limit is modeled with 365 constraints, one for each 365 day period ending in the forward year.

Resources may have several distinct environmental limits. The Opportunity Cost Calculator models seven pollutants (NO_2, SO_2, CO, CO_2, PB, PM, O_3), fuel throughput, operating hours, starts and duct or peak firing operating hours.[22] Environmental constraints in the optimization model have the following general format.

$$(\textbf{Historical level during } \mathbf{C_k}) + (\textbf{Additions from model dispatch during } \mathbf{C_k}) \leq \textbf{Limit}$$

For the seven pollutants, the environmental constraints in terms of model parameters and decision variables for pollutant i and compliance period C_k are

$$\mathbf{EMISS\_HIST(i, C_k)} + \sum_{\mathbf{h \in C_k}} \mathbf{EMISS\_RATE_i \cdot OUTPUT(h)} + \sum_{\mathbf{h \in C_k}} \mathbf{START\_EMISS_i \cdot START(h)}$$
$$+ \sum_{\mathbf{h \in C_k}} \mathbf{DFEMISS\_RATE_i \cdot DFMW \cdot DFON(h)} \leq \mathbf{EMISS\_LIMIT_i} .$$

Constraints for an operating hours limit, MWh limit, starts limit and duct or peak firing hours limit are modeled in a similar manner.

$$\mathbf{OPHOUR\_HIST(C_k)} + \sum_{\mathbf{h \in C_k}} \mathbf{HOURON(h)} \leq \mathbf{OPHOUR\_LIMIT}$$

$$\mathbf{MWH\_HIST(C_k)} + \sum_{\mathbf{h \in C_k}} \mathbf{OUTPUT(h)} + \sum_{\mathbf{h \in C_k}} \mathbf{DFMW \cdot DFON(h)} \leq \mathbf{MWH\_LIMIT}$$

$$\mathbf{START\_HIST(C_k)} + \sum_{\mathbf{h \in C_k}} \mathbf{START(h)} \leq \mathbf{START\_LIMIT}$$

$$\mathbf{DFOP\_HIST(C_k)} + \sum_{\mathbf{h \in C_k}} \mathbf{DFON(h)} \leq \mathbf{DFOP\_LIMIT}$$

22 Fuel through limits are converted to MWh limits.

3.6 Opportunity Cost for the Base Unit

The first step is to find the maximum net revenue without imposing the environmental limits.

Optimization 1: Maximize Z subject to the operating constraints in Sections 3.4 where

$$\mathbf{Z} = \sum_{h=1}^{H_0} \mathbf{OUTPUT(h) \cdot MARGIN(h) + DFMW \cdot \big(1 - DFOUTAGE(h)\big) \cdot DFMARGIN(h) \cdot DFON(h)}$$
$$\mathbf{- STARTCOST \cdot START(h) - VOM\_HRLY \cdot HOURON(h)}.$$ [23]

The next step is to maximize the same expression for Z subject to the operating constraints in Section 3.4 and the environmental constraints in Section 3.5.

Optimization 2: Maximize Z subject to the operating constraints in Sections 3.4 and the environmental constraints in Section 3.5 where

$$\mathbf{Z} = \sum_{h=1}^{H_0} \mathbf{OUTPUT(h) \cdot MARGIN(h) + DFMW \cdot \big(1 - DFOUTAGE(h)\big) \cdot DFMARGIN(h) \cdot DFON(h)}$$
$$\mathbf{- STARTCOST \cdot START(h) - VOM\_HRLY \cdot HOURON(h)}.$$

Denoting the first optimal net revenue value as Z_1 and the second as Z_2, it must be true that $Z_1 \geq Z_2$. If $Z_1 = Z_2$ then the environmental constraints do not affect the net revenue and the opportunity cost is $0. If $Z_1 > Z_2$ then the environmental constraints do affect the net revenue and the opportunity cost is nonzero. The opportunity cost calculator then proceeds, as in Figure 1-2, to determine the marginal opportunity cost by determining the earliest binding constraint.

A base unit environmental constraint is binding if applying the environmental limit reduced the total emissions or dispatch of the resource and the unit cannot operate for an additional hour at its maximum output during the compliance period without exceeding the limit.[24] The total emissions for pollutant i accounted for in the optimal solution of Optimization 1, in compliance period C_k is given by

23 For a calendar year constraint, H_0 is the last hour of the calendar year. For a 12 month rolling period, H_0 is the last hour of the 12th rolling compliance period, C_{12} . For a 365 day rolling period, H_0 is the last hour of the forward year.

24 The base unit environmental constraints are the seven pollutant constraints, the MWh constraint, the operating hours constraint and the start ups constraint.

$$\mathbf{TOT\_EMISS(i, C_k, 1)}$$

$$= \mathbf{EMISS\_HIST(i, C_k)} + \sum_{\mathbf{h \in C_k}} \mathbf{EMISS\_RATE_i} \cdot \mathbf{OUTPUT(h)}$$

$$+ \sum_{\mathbf{h \in C_k}} \mathbf{START\_EMISS_i} \cdot \mathbf{START(h)} + \sum_{\mathbf{h \in C_k}} \mathbf{DFEMISS\_RATE_i} \cdot \mathbf{DFMW} \cdot \mathbf{DFON(h)}$$

where the values for decision variables $OUTPUT(h)$, $START(h)$ and $DFON(h)$ are from the optimal solution for optimization 1. Total emissions for pollutant i accounted for in the optimal solution of Optimization 2, in compliance period C_k are calculated in the same manner and denoted by $TOT\_EMISS(i, C_k, 2)$. The corresponding environmental constraint for pollutant i and compliance period C_k is binding if the total emissions were reduced by applying the environmental limits and the difference between the emission limit and the total emissions is less than the product of the economic maximum and the emission rate. The following two conditions must hold for the constraint to be binding.

$$\mathbf{TOT\_EMISS(i, C_k, 2)} < \mathbf{TOT\_EMISS(i, C_k, 1)}$$

$$\mathbf{EMISS\_LIMIT_i} - \mathbf{TOT\_EMISS(i, C_k, 2)} < \mathbf{ECOMAX} \cdot \mathbf{EMISS\_RATE_i}$$

The total operating hours accounted for compliance period C_k in the optimal solution of Optimization 2 is

$$\mathbf{TOT\_OPHOURS(C_k, 2)} = \mathbf{OPHOUR\_HIST(C_k)} + \sum_{\mathbf{h \in C_k}} \mathbf{HOURON(h)}$$

where the values for the decision variable $HOUR(h)$ are from the optimal solution for optimization 2. The operating hour constraint for compliance period C_k is binding if

$$\mathbf{TOT\_OPHOURS(C_k, 2)} < \mathbf{TOT\_OPHOURS(C_k, 1)}$$

$$\mathbf{OPHOUR\_LIMIT} - \mathbf{TOT\_OPHOURS(C_k, 2)} < 1\,.$$

The total MWh accounted for in the optimal solution of Optimization 2 is

$$\mathbf{TOT\_MWH(C_k, 2)} = \mathbf{MWH\_HIST(C_k)} + \sum_{\mathbf{h \in C_k}} \mathbf{OUTPUT(h)} + \sum_{\mathbf{h \in C_k}} \mathbf{DFMW} \cdot \mathbf{DFON(h)}$$

where the values for decision variables $OUTPUT(h)$ and $DFON(h)$ are from the optimal solution for optimization 2. The MWh constraint for compliance period C_k is binding if

$$\mathbf{TOT\_MWH(C_k, 2)} < \mathbf{TOT\_MWH(C_k, 1)}$$

$$\mathbf{MWH\_LIMIT} - \mathbf{TOT\_MWH(C_k, 2)} < \mathbf{ECOMAX}\,.$$

The total starts accounted for in the optimal solution of Optimization 2 is

$$\mathbf{TOT\_START}(C_k, \mathbf{2}) = \mathbf{START\_HIST}(\mathbf{C_k}) + \sum_{\mathbf{h} \in \mathbf{C_k}} \mathbf{START}(\mathbf{h})$$

where the values for the decision variable $START(h)$ are from the optimal solution for optimization 2. The start constraint for compliance period C_k is binding if

$$\mathbf{TOT\_START}(C_k, \mathbf{2}) < \mathbf{TOT\_START}(C_k, \mathbf{1})$$

$$\mathbf{START\_LIMIT} - \mathbf{TOT\_START}(C_k, \mathbf{2}) < 1\ .$$

The earliest binding compliance period, equal to the binding compliance period with the smallest value of k, is denoted by C_b.[25]

After establishing the earliest binding compliance period and binding monitored element, a third optimization over compliance period C_b is solved. The objective function remains the same with the exception that the calculator optimizes over compliance period C_b.[26]

Optimization 3: Maximize Z subject to the constraints in Sections 3.4 and 3.5 where

$$\mathbf{Z} = \sum_{h \in C_b} \mathbf{OUTPUT}(\mathbf{h}) \cdot \mathbf{MARGIN}(\mathbf{h}) + \mathbf{DFMW} \cdot \big(\mathbf{1} - \mathbf{DFOUTAGE}(\mathbf{h})\big) \cdot \mathbf{DFMARGIN}(\mathbf{h}) \cdot \mathbf{DFON}(\mathbf{h}) - \mathbf{STARTCOST} \cdot \mathbf{START}(\mathbf{h}) - \mathbf{VOM\_HRLY} \cdot \mathbf{HOURON}(\mathbf{h})$$

For the fourth and final optimization to determine the base unit marginal opportunity cost, the environmental constraints in Section 3.5, with the exception of the duct or peak firing hours constraint, are replaced with the following constraints that reflect a reduction to the limit equal to a one hour equivalent of the monitored element.[27] For pollutant i, the new environmental constraint is

25 In cases where there are multiple binding elements, the base unit binding monitored element is chosen as the first binding element encountered in list of monitored elements: NO_x, SO_2, CO, CO_2, PB, PM, O_3, MWH, Operating Hours.

26 All environmental constraints with compliance periods ending within compliance period C_b are active for Optimization 3. For example, if the binding compliance period is C_6, then all of the environmental constraints for compliance periods C_k, $k = 1, \ldots, 6$, are included in the optimization.

27 The duct or peak firing limit still applies in Optimization 4 but the limit is not adjusted to reflect one less hour of operation.

$$\mathbf{EMISS\_HIST}(\boldsymbol{i}, \boldsymbol{C_k}) + \sum_{\mathbf{h} \in \mathbf{C_k}} \mathbf{EMISSION\_RATE}_{\boldsymbol{i}} \cdot \mathbf{OUTPUT}(\mathbf{h})$$

$$+ \sum_{\mathbf{h} \in \mathbf{C_k}} \mathbf{START\_EMISSIONS_i} \cdot \mathbf{START}(\mathbf{h})$$

$$+ \sum_{\mathbf{h} \in \mathbf{C_k}} \mathbf{DFEMISSION\_RATE_i} \cdot \mathbf{DFMW} \cdot \mathbf{DFON}(\mathbf{h})$$

$$\leq \mathbf{EMISSION\_LIMIT_i} - \boldsymbol{ECOMAX} \cdot \boldsymbol{EMISSION\_RATE_i} \,.$$

The operating hour and start constraints in Section 3.5 are restated by reducing the limit by one.

$$\mathbf{OPERATING\_HOURS}(\mathbf{C_k}) + \sum_{\mathbf{h} \in \mathbf{C_k}} \mathbf{HOURON}(\mathbf{h}) \leq \mathbf{OPHOURS\_LIMIT} - \mathbf{1}$$

$$\mathbf{STARTS\_HISTORY}(\mathbf{C_k}) + \sum_{\mathbf{h} \in \mathbf{C_k}} \mathbf{START}(\mathbf{h}) \leq \mathbf{STARTS\_LIMIT} - \mathbf{1}$$

The MWh constraint in Section 3.5 is restated by reducing the limit by the economic maximum.

$$\mathbf{MWH\_HIST}(\mathbf{C_k}) + \sum_{\mathbf{h} \in \mathbf{C_k}} \mathbf{OUTPUT}(\mathbf{h}) + \sum_{\mathbf{h} \in \mathbf{C_k}} \mathbf{DFMW} \cdot \mathbf{DFON}(\mathbf{h}) \leq \mathbf{MWH\_LIMIT} - \mathbf{ECOMAX}$$

Optimization 4: Maximize Z subject to the operating constraints in Sections 3.4, the duct or peak firing hours constraint in Section 3.5 and the updated environment constraints in Section 3.6 where

$$\mathbf{Z} = \sum_{\boldsymbol{h} \in \boldsymbol{C_b}} \mathbf{OUTPUT}(\mathbf{h}) \cdot \mathbf{MARGIN}(\mathbf{h}) + \mathbf{DFMW} \cdot \big(\mathbf{1} - \mathbf{DFOUTAGE}(\mathbf{h})\big) \cdot \mathbf{DFMARGIN}(\mathbf{h}) \cdot \mathbf{DFON}(\mathbf{h})$$
$$- \mathbf{STARTCOST} \cdot \mathbf{START}(\mathbf{h}) - \mathbf{VOM\_HRLY} \cdot \mathbf{HOURON}(\mathbf{h}) \,.$$

Denoting the optimal net revenue from Optimization 3 by Z_3 and the optimal net revenue from Optimization 4 by Z_4 , the marginal opportunity cost is equal to $Z_3 - Z_4$. If the binding monitored element is pollutant i, the marginal opportunity cost is converted to $ per MWh by dividing by the reduction in emissions between Optimization 3 and Optimization 4, and multiplying by the binding pollutant emission rate.

$$\mathbf{MRG\_OPP\_COST}(\mathbf{s}) \; = \frac{\mathbf{Z_3} - \mathbf{Z_4}}{\mathbf{TOT\_EMISS}(\mathbf{i}, \mathbf{C_b}, \mathbf{3}) - \mathbf{TOT\_EMISS}(\mathbf{i}, \mathbf{C_b}, \mathbf{4})} \cdot \mathbf{EMISSION\_RATE_i}$$

If the binding monitored element is operating hours, the marginal opportunity cost is converted to $ per hour by dividing by the reduction in operating hours between optimization 3 and optimization 4. Similarly, if the binding monitored element is starts, the marginal opportunity cost is converted to $ per start by dividing by the reduction in starts between optimization 3 and optimization 4.[28]

$$\mathbf{MRG\_OPP\_COST(s)} \ = \frac{\mathbf{Z_3 - Z_4}}{\mathbf{TOT\_OPHOUR(C_b, 3) - TOT\_OPHOUR(C_b, 4)}}$$

$$\mathbf{MRG\_OPP\_COST(s)} \ = \frac{\mathbf{Z_3 - Z_4}}{\mathbf{TOT\_START(C_b, 3) - TOT\_START(C_b, 4)}}$$

If the binding monitored element is MWh, the marginal opportunity cost is converted to $ per MWh by dividing by the reduction in MWh between optimization 3 and optimization 4.

$$\mathbf{MRG\_OPP\_COST(s)} \ = \frac{\mathbf{Z_3 - Z_4}}{\mathbf{TOT\_MWH(C_b, 3) - TOT\_MWH(C_b, 4)}}$$

The base unit opportunity cost adder is the average of the three scenarios.

$$\mathbf{OPP\_COST\_ADDER} = \frac{\mathbf{1}}{\mathbf{3}}\sum_{\mathbf{s=1}}^{\mathbf{3}} \mathbf{MRG\_OPP\_COST(s)}$$

3.7 Opportunity Cost for the Duct or Peak Firing Component

The solution to Optimization 2 is used to determine if a duct or peak firing environmental constraint is binding. The total operating hours of the duct or peak firing component accounted for compliance period C_k in the optimal solution for Optimization 2 is

$$\mathbf{TOT\_DFHOURS(C_k, 2) = DFHOUR\_HIST(C_k)} + \sum_{\mathbf{h \in C_k}} \mathbf{DFON(h)}$$

where the values for the decision variable $DFON(h)$ are from the optimal solution for optimization 2. The duct or peak firing operating hours constraint for compliance period C_k is binding if applying the environmental limits reduced the dispatch hours of the duct or peak firing component and the duct or peak firing component cannot operate for an additional hour during the compliance period without exceeding the limit.

$$\mathbf{TOT\_DFHOURS(C_k, 2) < TOT\_DFHOURS(C_k, 1)}$$

$$\mathbf{DFHOUR\_LIMIT - TOT\_DFHOURS(C_k, 2)} < 1$$

[28] To date the opportunity cost adders corresponding to an operating hours constraint have been converted to a $ per MWh by dividing the $ per hour number by the economic maximum.

If no duct or peak firing operating hour constraints are binding then the marginal opportunity cost for the duct or peak firing component is \$0. If a duct or peak firing constraint is binding then the earliest binding constraint is established and denoted by C_d. A fifth optimization over the duct or peak firing binding compliance period is solved.[29]

Optimization 5: Maximize Z subject to the constraints in Sections 3.4 and 3.5 where

$$\mathbf{Z} = \sum_{h \in C_d} \mathbf{OUTPUT(h) \cdot MARGIN(h) + DFMW \cdot \left(1 - DFOUTAGE(h)\right) \cdot DFMARGIN(h) \cdot DFON(h)} \\ \mathbf{- STARTCOST \cdot START(h) - NOLOAD \cdot HOURON(h)}\,.$$

A sixth optimization is solved to determine the impact of reducing the duct or peak firing hours constraint by one hour. The duct or peak firing hours constraint in Section 3.5 is replaced by

$$\mathbf{DFOP\_HIST(C_k)} + \sum_{\mathbf{h \in C_k}} \mathbf{DFON(h) \leq DFOP\_LIMIT - 1}\,.$$

Optimization 6: Maximize Z subject to the operating constraints in Sections 3.4, the environmental constraints, except for the duct or peak firing hours constraint, in Section 3.5 and the updated duct or peak firing constraint in Section 3.7 where

$$\mathbf{Z} = \sum_{h \in C_d} \mathbf{OUTPUT(h) \cdot MARGIN(h) + DFMW \cdot \left(1 - DFOUTAGE(h)\right) \cdot DFMARGIN(h) \cdot DFON(h)} \\ \mathbf{- STARTCOST \cdot START(h) - VOM\_HRLY \cdot HOURON(h)}\,.$$

The marginal opportunity cost for the duct or peak firing component is the difference in the optimal net revenue values for Optimization 5 and Optimization 6, $Z_5 - Z_6$. This value is converted to \$ per MWh by dividing by the change in the number of hours of duct or peak firing dispatch in the optimal solutions of Optimization 5 and Optimization 6, and then dividing by dispatch capability of the duct or peak firing component.

$$\mathbf{MRG\_OPP\_COST\_DF(s)} = \frac{\mathbf{Z_5 - Z_6}}{\mathbf{TOT\_DFHOUR(C_d, 5) - TOT\_DFHOUR(C_d, 6)}} \cdot \frac{\mathbf{1}}{\mathbf{DFMAX}}\,.$$

The duct or peak firing opportunity cost is the average over the three scenarios

$$\frac{\mathbf{1}}{\mathbf{3}} \sum_{\mathbf{s=1}}^{\mathbf{3}} \mathbf{MRG\_OPP\_COST\_DF(s)}\,.$$

The duct or peak firing opportunity cost may be included in the duct or peak firing portion of the cost based energy offer. Since the duct or peak firing occurs in addition to the base unit

[29] If the base unit earliest binding compliance period is the same as the duct or peak firing earliest binding compliance period, $C_b = C_d$, then Optimization 3 and Optimization 5 are identical problems.

generation, the duct or peak firing opportunity cost adder is the sum of the base unit opportunity cost and the duct or peak firing opportunity cost.

$$\mathbf{OPP\_COST\_DF\_ADDER} = \mathbf{OPP\_COST\_ADDER} + \frac{\mathbf{1}}{\mathbf{3}}\sum_{\mathbf{s=1}}^{\mathbf{3}}\mathbf{MRG\_OPP\_COST\_DF(s)}$$

3.8 Secondary Fuel Opportunity Cost

The secondary fuel opportunity cost is applicable to dual fuel generators with an environmental limitation that applies regardless of the fuel type. The secondary fuel opportunity cost is intended to address the possibility that a generator is picked up out of merit on its secondary fuel schedule due to a reliability issue that is not reflected in the real time LMP. If this were to happen there could be an opportunity cost since generation on the secondary fuel schedule reduces the maximum level of generation on the primary fuel schedule in the forward year.

The optimization model assumes the generator is committed on its secondary fuel schedule for a duration equal to the minimum runtime on the first day of the forward year. The environmental limits are reduced to reflect the commitment on the secondary fuel schedule. For pollutant i, the emissions from the commitment on the secondary fuel schedule is

$$\mathbf{EMISS\_MRSF_i} = \mathbf{START\_EMISS\_SF_i} + \mathbf{EMISS\_RATE\_SF_i} \cdot \mathbf{ECOMAX\_SF} \cdot \mathbf{MINRUN\_SF}.$$

The environmental constraint for pollutant i and compliance period C_k in Section 3.5 is updated by reducing the limit by the amount of emissions from operating on the secondary fuel schedule.

$$\mathbf{EMISS\_HIST(i, C_k)} + \sum_{\mathbf{h \in C_k}} \mathbf{EMISS\_RATE_i} \cdot \mathbf{OUTPUT(h)} + \sum_{\mathbf{h \in C_k}} \mathbf{START\_EMISS_i} \cdot \mathbf{START(h)}$$
$$+ \sum_{\mathbf{h \in C_k}} \mathbf{DFEMISS\_RATE_i} \cdot \mathbf{DFMW} \cdot \mathbf{DFON(h)} \leq \mathbf{EMISS\_LIMIT_i} - \mathbf{EMISS\_MRSF_i}$$

The operating hours and start constraints are modified as follows:

$$\mathbf{OPHOUR\_HIST(C_k)} + \sum_{\mathbf{h \in C_k}} \mathbf{HOURON(h)} \leq \mathbf{OPHOUR\_LIMIT} - \mathbf{MINRUN\_SF}$$

$$\mathbf{START\_HIST(C_k)} + \sum_{\mathbf{h \in C_k}} \mathbf{START(h)} \leq \mathbf{START\_LIMIT} - \mathbf{1}$$

In cases where a fuel throughput limit applies to generation on the primary fuel and the secondary fuel, the operating permit includes a conversion factor to reflect the generation using the secondary fuel in terms of generation using the primary fuel. For example, gallons of diesel for a minimum run would be calculated as

$$\mathbf{MINRUN\_SEC\_FUEL} = \mathbf{MINRUN\_SF \cdot ECOMAX\_SF \cdot HEATRATE\_SF/(0.138)}\,.$$ [30]

The gallons of fuel are converted to a MMBtu value applicable to the fuel throughput limit using a conversion factor, $SFPF\_CONV$, specified in the operating permit. This value is converted to primary fuel MWh by dividing by the primary fuel heat rate.

$$\mathbf{MWH\_MRSF = MINRUN\_SEC\_FUEL \cdot SFPF\_CONV\,/HEATRATE}\,.$$

The updated MWh environmental constraint is

$$\mathbf{MWH\_HIST(C_k)} + \sum_{\mathbf{h \in C_k}} \mathbf{OUTPUT(h)} + \sum_{\mathbf{h \in C_k}} \mathbf{DFMW \cdot DFON(h) \le MWH\_LIMIT - MWH\_MRSF}\,.$$

The optimization model then repeats the series of optimizations done for the base unit opportunity cost. Net revenue is optimized over the forward year using the updated environmental constraints that reflect a reduction in the limit due to a commitment on the secondary fuel.

Optimization 7: Maximize Z subject to the operating constraints in Sections 3.4, the duct or peak firing operating hours constraint in Section 3.5 and the updated environmental constraints in Section 3.8 where

$$\mathbf{Z} = \sum_{h=25}^{H_0} \mathbf{OUTPUT(h) \cdot MARGIN(h) + DFMW \cdot \big(1 - DFOUTAGE(h)\big) \cdot DFMARGIN(h) \cdot DFON(h)}$$

$$\mathbf{- STARTCOST \cdot START(h) - VOM\_HRLY \cdot HOURON(h)}\,.$$ [31] [32]

A comparison of the optimal net revenue from Optimization 7 with the optimal net revenue from Optimization 1 indicates whether or not there is an opportunity cost. If $Z_1 = Z_7$ then the opportunity cost due to a commitment on the secondary fuel schedule is $0. If $Z_1 > Z_7$ then a commitment on the secondary fuel schedule does affect the net revenue and the opportunity cost is nonzero. Proceeding as in Section 3.6, the earliest binding constraint and binding monitored element are determined.

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30 The default heat content ratio for diesel is assumed to be 0.138 MMBtu per gal.

31 This optimization is comparable to Optimization 2 in Section 3.6.

32 The optimization assumes the unit generates on secondary fuel on the first day of the forward year and is available for commitment and dispatch on the primary fuel beginning on day 2 (or hour 25).

The earliest binding compliance period, equal to the binding compliance period with the smallest value of k, is denoted by C_f.

After establishing the earliest binding compliance period, an optimization over the compliance period C_f is solved. The objective function is optimized over compliance period C_f subject to the original environmental constraints in Section 3.5.[33]

Optimization 8: Maximize Z subject to the constraints in Sections 3.4 and 3.5 where

$$\mathbf{Z} = \sum_{\substack{h \in C_f \\ h \geq 25}} \mathbf{OUTPUT(h) \cdot MARGIN(h) + DFMW \cdot \left(1 - DFOUTAGE(h)\right) \cdot DFMARGIN(h) \cdot DFON(h)} \\ \mathbf{- STARTCOST \cdot START(h) - VOM\_HRLY \cdot HOURON(h)}$$

The final optimization to determine the secondary fuel marginal opportunity cost finds the optimal net revenue using the updated environmental constraints that reflect a reduction in the limit due to a commitment on the secondary fuel.

Optimization 9: Maximize Z subject to the operating constraints in Sections 3.4, the duct or peak firing hours constraint in Section 3.5 and the updated environmental constraints in Section 3.8 where

$$\mathbf{Z} = \sum_{\substack{h \in C_f \\ h \geq 25}} \mathbf{OUTPUT(h) \cdot MARGIN(h) + DFMW \cdot \left(1 - DFOUTAGE(h)\right) \cdot DFMARGIN(h) \cdot DFON(h)} \\ \mathbf{- STARTCOST \cdot START(h) - VOM\_HRLY \cdot HOURON(h)}\,.$$

The secondary fuel marginal opportunity cost is the difference in the optimal net revenue values for Optimization 8 and Optimization 9, $Z_8 - Z_9$. This value is converted to \$ per MWh by dividing by the number of MWh in the assumed commitment and dispatch on the secondary fuel schedule,

$$\mathbf{MRG\_OPP\_COST\_SF(s)} = \frac{\boldsymbol{Z_8 - Z_9}}{\boldsymbol{MINRUN\_SF \cdot ECOMAX\_SF}}\,.$$

The secondary fuel opportunity cost adder is the average of the three scenarios.

$$\mathbf{OPP\_COST\_ADDER\_SF} = \frac{\mathbf{1}}{\mathbf{3}} \cdot \sum_{\mathbf{s=1}}^{\mathbf{3}} \mathbf{MRG\_OPP\_COST\_SF(s)}$$

The secondary fuel opportunity cost adder may be included in the secondary fuel cost based energy offer.

[33] This establishes what the optimal net revenue is expected to be without a commitment on the secondary fuel schedule.

4 Examples

Examples of the margin calculation and the optimization model are available in spreadsheets that accompany this document.

4.1 Forward Margin

The spreadsheet, FORWARD MARGIN EXAMPLE, contains a detailed example of the forward margin calculations. The forward margins are inputs into the optimization model. The spreadsheet includes the future to historical hour mapping described in Section 2.3.1 and includes all the necessary data to replicate the forward LMP and forward operating cost calculations described in Sections 2.3.2 – 2.3.6.

4.2 Optimization Model

Two examples of the optimization model are provided. See spreadsheets, OPTIMIZATION MODEL EXAMPLE 1 and OPTIMIZATION MODEL EXAMPLE 2. Both spreadsheets provide a detailed solution of the optimization model. In example 1, the generator has an operating hours limit. In Example 2, two emission constraints are modeled. Example 2 includes a duct or peak firing opportunity cost calculation and a secondary fuel opportunity cost calculation. Both examples use the forward margin values provided in the FORWARD MARGIN EXAMPLE spreadsheet.

The spreadsheets include parameter and emissions data for the resource in the format required by MIRA (see the MIRA Parameter Data and MIRA Emission Data tabs). The Model Parameter and Emission History by Period tabs show the input data for the optimization model.

Hourly solution data for each scenario is provided (see Solution Data tabs). This data includes the hourly commitment and dispatch by the optimization model. The Solution Summary tabs provide a summary for each scenario. The Redispatch tabs show the change in the dispatch that results from lowering the environmental limit by one hour (or a one hour equivalent). The Binding Constraints tabs show the calculations to determine the earliest binding constraint for each scenario and for each opportunity cost calculations.