memo

To: NEPOOL Markets Committee

From: Markets Development

Date: October 9, 2018

Subject: Energy Market Opportunity Costs for Oil and Dual-Fuel Resources with Inter-temporal Production Limitations – **Revised Edition**

Goal of this Memo

The ISO is engaged in designing and implementing a comprehensive, transparent methodology to estimate opportunity costs that are understandable, economically sound, and appropriate to each specific resource. In the initial phase, the ISO will focus on addressing for the coming winter energy opportunity costs of oil-fired and dual fuel generators with fuel supply limitations over a short term seven day horizon. A second phase is also underway to design a more comprehensive, generalized approach that can address resource energy limitations of any type over the horizon relevant to the specific limitation. These limitations could be due to annual (unpriced) emissions regulations, permit restrictions, seasonal river flows, storage capacity or other factors, with horizons ranging from days to a full year.

The remainder of this memo addresses only the initial phase of the project. It provides a series of detailed examples with increasing realism and sophistication to explain and illustrate the opportunity cost estimation methodology. The examples are designed to provide insight into the factors that influence energy opportunity costs. Each example builds upon the previous example. The introduction to each example identifies the significant points illustrated by the example and will guide the reader in a logical fashion to a full understanding of the economic underpinnings behind the opportunity cost estimates.

This expanded version of the memo includes additional examples to address the greater complexity of opportunity costs for dual-fuel resources.

Background – The Motivation for Enhanced Energy Opportunity Costs

During cold-weather periods this past winter, Market Participants inquired about how they may incorporate into their energy supply offers the opportunity costs associated with burning their limited remaining fuel stocks, including contracted LNG. During such conditions, including opportunity costs in energy supply offers can help the market preserve limited fuel stocks that can later be used to supply energy during hours with higher demand, stressed operating conditions, and higher energy prices.

Participants' feedback after this past winter indicated it would be valuable to clarify how participants may incorporate their resource-specific opportunity costs into energy market supply offers in different situations. Importantly, that request includes how a resource's Reference Level price (also referred to in this document as "reference price", and used by the ISO for energy market mitigation purposes) will account for its fuel-related energy opportunity costs when these situations occur.

Estimating energy market opportunity costs during stressed winter operations is an involved, resource-specific process. In an effort to be responsive to stakeholders' feedback and to improve both market and operational performance during the cold-weather season, the ISO is working to enhance the current treatment of resources' opportunity costs in energy supply offers ahead of the 2018-19 winter period.

Objectives of the Energy Market Opportunity Cost Project Initial Phase

The broad design goals for the first phase of the opportunity cost enhancement project are to:

- Produce timely opportunity cost estimates that are understandable, economically sound, and appropriate to the resource;
- Facilitate the most efficient use of fuel-constrained power supply resources over varying time horizons, thereby improving both reliability and overall cost-effectiveness of the power system;
- Improve energy market price formation by accurately reflecting the opportunity costs of energy supply limitations in market prices;
- Reduce the potential for manual actions to manage limited fuel stocks (e.g., posturing fuel-limited resources during stressed conditions);

Implementation Notes – What Participants Can Expect

The ISO is proposing to implement a system on or about the 1st of December to estimate an energy opportunity cost for oil and dual-fuel resources. The estimated opportunity costs will be included in reference prices applicable to the Day-Ahead Market. The ISO's preliminary determination is that Appendix A of Market Rule 1 already enables a participant to submit (and the ISO to approve) an energy supply offer that includes its opportunity costs, and no tariff changes are anticipated to support the improved implementation of opportunity costs in reference prices for oil and dual-fuel resources for the coming winter.

Generator-specific opportunity costs will be made available by approximately 9am each day, prior to the 10am close of the Day-Ahead Market. While a Market Participant's offer should always reflect a Participant's expectation of costs, Participants are strongly encouraged to include opportunity costs in their offers and to review the opportunity cost estimates posted by the ISO when formulating those offers.

Reference prices currently include opportunity costs estimated on a weekly basis by the Internal Market Monitor (IMM) for resources impacted by the Massachusetts CO_2 emission limitations. The opportunity cost included in any generator's reference price will be the greater of MA CO_2 estimated opportunity cost and the new daily oil/dual-fuel estimated opportunity cost.

Once a generator's estimated opportunity cost has been calculated, it will be included as part of the generator's reference price and used in the review and mitigation of energy supply offers for resources anticipated to have market power. As a reminder, opportunity costs and reference prices do not come into play for a resource that doesn't trigger the tests used to determine potential market power under the ISO's mitigation process.

As will be clear in the examples that follow, the estimation methodology requires forecasts of replacement fuel costs and future hourly electricity prices. Fuel price forecasts will be based on the same fuel index prices currently used in IMM's calculation of reference prices.[1] Hourly electricity price forecasts will be provided by an independent vendor. After arrangements with data providers have been finalized, the ISO will provide vendor contact information for each input data source.

The ISO welcomes comments and feedback from Market Participants at any point prior to or following implementation of the opportunity cost estimation system. Specific comments related to how well the proposed methodology aligns with a Market Participant's perspective on the opportunity costs of a specific generator is of particular value , and will help the ISO to further enhance the methodology.

Context and Problem Summary

Resources that fully or partially rely on stored fuel to generate electricity may face a tradeoff between running now versus later: generating now could limit the ability of the resource to generate later. Therefore, the economic cost in the current period for such a resource is not just the replacement cost of the fuel used in this period, but also the intertemporal energy opportunity cost entailed by generating electricity in the current period. That is, the expected net revenue the resource forgoes in a future period if it increases its output now is part of the economic cost the resource faces.

The ISO, as the administrator of the organized wholesale electricity markets in New England, uses resources' offers to determine least-cost dispatch. If these tradeoffs are not considered in the offers of a resource with limited stored fuel, its fuel might be used inefficiently or prematurely.

Consider the simple case of a hypothetical 1 MW resource that has just enough oil in its tank to produce 1 MWh of electricity. Additionally, assume the expected price in every hour until its scheduled refueling is above its replacement cost, so the resource is facing several nominally profitable periods in which to sell its output. Assume expected prices are higher when it is closer to its scheduled refueling time. Although the resource is nominally profitable in every period, the desired outcome from the resource's perspective, as well from an efficiency (and cost-effectiveness) perspective, is to use the fuel in the resource's tank during the hour in which the electricity is valued the highest.

If the intertemporal opportunity cost of using its fuel is not included as part of its offer, the unit might offer its output simply at replacement cost. The ISO, using the resource's offered price, could dispatch the resource in the first hour, which would deplete its fuel inventory and make it unavailable in future higher-valued periods. This outcome is clearly inefficient as it fails to use the fuel of the resource when it is most valuable. If intertemporal energy opportunity costs had been incorporated with the replacement cost of fuel in the offer price, it would have only dispatched when price was above its *economic cost*.

As the above simple example demonstrates, the resource's incentive to maximize its net revenue is closely aligned with the ISO's design goal to achieve efficient market outcomes. It improves the system's overall cost-effectiveness, by using limited fuel inventory at the times when it best displaces higher-cost alternative generation.

The ISO Tariff allows resources to include documented opportunity costs as part of their energy market offers.[2] This memo discusses the framework the ISO will use to calculate the intertemporal energy

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[1] The ISO's gas price forecasting method is discussed in a separate memorandum.

[2] See Market Rule 1, Appendix A, Section 7.5.1.

opportunity cost of the resources that are subject to limited stored fuel. ISO will then add the calculated intertemporal opportunity cost for each resource to its Reference Level price used in energy market mitigation (for resources subject to mitigation), so that competitive intertemporal opportunity costs can be properly reflected in resources' offers.

Taxonomy and high-level mathematical specification of the models

In phase 1 of the implementation, ISO is seeking to incorporate its estimate of intertemporal opportunity costs that arise due to limitations of stored fuel in resources' Reference Level price. In particular, the short-horizon fuel limitations of two types of resources will be modeled:

1. Oil-only resource with limited fuel stock, and
2. Oil/gas dual fuel units with limited oil stock.

In this memorandum, we discuss both models. This revised memorandum includes additional examples with intertemporal opportunity costs for oil/gas dual fuel units.

The ISO's model uses a resource level optimization program to calculate intertemporal opportunity cost. The objective function of this optimization problem is to maximize expected net revenue of the resource. It also explicitly models a resource's limited stored fuel. Conceptually, the shadow price of this constraint in the (linearized) optimization problem is the resource's intertemporal opportunity cost: it captures the changes in the resource's net expected revenues in response to a (small) change in the level of fuel in its tank, expressed in dollars per MWh. This will be made clear by the examples below.

Once calculated, the resource's estimated intertemporal opportunity cost will be added to its Reference Level price. It is important to emphasize that ISO will not replace resource's offers with its own estimate. It would only update reference levels to allow resources to properly reflect their competitive economic costs (that include intertemporal opportunity costs). Similar to today's practice, resources may choose to offer below their reference level for a number of reasons, including the fact that they might face additional constraints that are not visible, trackable, or verifiable by the ISO.

Mathematical specification of intertemporal opportunity cost of a single fuel oil resource[3]

Mathematical formulation for the owner of a single fuel oil resource follows the discussion above. Suppose $p_1, p_2, \ldots, p_T$ are the prices that the resource owner expects before refueling at time *T*, w is the cost of refueling (adjusted for the heat rate of the resource), and $q_1^{oil}, q_2^{oil}, \ldots, q_T^{oil}$ are the output of the oil resource. The optimization problem that maximizes the expected net profit of the resource, subject to its intertemporal fuel constraint, is given as follows:

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[3] This formulation is for illustrative purposes only and is intentionally summarized at a high level. Detailed formulation includes many other resource-level constraints.

$$\begin{aligned} &\max_{q_t} && \sum_{t=1}^{T}\left(p_t \times q_t^{oil} - w \times q_t^{oil}\right) \\ &s.t. && \\ & && \sum_{t=1}^{T} q_t^{oil} \le \bar{Q}^{oil} \qquad (\lambda) \end{aligned}$$

In the formulation above, $\bar{Q}^{oil}$ is the current fuel level of the fuel in the tank and λ is the shadow price of the intertemporal fuel constraint in the linearized optimization, which will be reported as the intertemporal opportunity cost of the resource (we will elaborate on this in the discussion of the examples).

At the end of fueling cycle, assume the resource owner has two options: it could refill the tank to the original level, or sell the residual oil left in tank. This formulation can be used in both cases

- If oil tank is refilled to the original level, then its direct replacement cost is $\sum_{t=1}^{T}\left(w \times q_t^{oil}\right)$
- If the resource sells the oil in the tank at the market price (presumably the same as the replacement cost), the potential sales revenue lost on the fuel that was consumed is $\sum_{t=1}^{T}\left(w \times q_t^{oil}\right)$.

Therefore, the formulation in **Error! Reference source not found.** is suitable in both cases.

Mathematical specification of intertemporal opportunity cost of a dual fuel gas/oil resource

A dual fuel unit faces a similar problem. The main difference is that, because natural gas is delivered by pipeline and not (locally) stored, a dual fuel capable resource does not face an intertemporal opportunity cost for its natural gas. The problem that a dual fuel capable unit faces is more complex because a dual fuel resource needs to compare expected profit margins on both fuels over time. Further, the dual fuel resource faces a myriad of additional constraints. The concept of intertemporal opportunity cost and the basic way it is calculated and interpreted, however, is the same.

A dual fuel resource owner would need an additional price forecast about the expected gas prices. Suppose $g_1, g_2, \ldots g_T$ are expected gas price for hours 1, 2, … , *T*. Moreover, assume $q_1^{gas}, q_2^{gas}, \cdots, q_T^{gas}$ are quantities of the output generated by natural gas (adjusted for the resource's heat rate). The owner of an oil/gas dual fuel unit maximizes its net profit subject to the intertemporal oil constraint:

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\begin{aligned}
&\max_{q_t} \quad \sum_{t=1}^{T}\left(p_t \times q_t - w \times q_t^{oil} - g_t \times q_t^{gas}\right) \\
&s.t. \\
&\qquad \sum_{t=1}^{T} q_t^{oil} \le \bar{Q}_{oil} \qquad\qquad (\lambda) \\
&\qquad q_t = q_t^{oil} + q_t^{gas} \qquad\qquad \forall t
\end{aligned}
$$

The way resource's intertemporal opportunity cost is calculated and interpreted is the same as the single fuel resource. Note the second constraint listed above is the equality constraint, which requires that the output of the resource in any period is simply sum of its oil- and gas-fired outputs. When the resource is running on one fuel it generally cannot run on the other fuel at the same time. So, it is generally the case that in any given hour only one of the two quantities, q_t^{oil} or q_t^{gas} , is positive and the other one is zero.

Numerical Examples of intertemporal opportunity cost of single fuel resources

To illustrate the ISO's approach to modeling intertemporal opportunity cost, we consider several examples. In the first series of examples 1 through 4, a single fuel unit maximizes its net revenue subject to its fuel limitations.

Example 1

This example shows that if the oil resource is infrequently profitable, it does not face a tradeoff between producing electricity in the current period versus in a future period. The resource can run in every profitable interval and still finish the fueling cycle with some fuel in its tank. As a result, its intertemporal fuel limitation is not binding and the intertemporal opportunity cost of the resource is zero.

Oil Unit

Consider an oil unit with EcoMax of 170 MW and EcoMin of 0 MW. This unit has enough oil in its tank to produce 3,000 MWh and has a scheduled delivery in 48 hours. The refueling cost is:

Cost of oil ($/MMBtu) × Heat Rate (MMBtu/MWh)

We assume that the cost of oil is $12/MMBtu and that the unit's heat rate is 10 MMBtu/MWh. Therefore, the cost of fuel is:

$12/MMBtu × 10 MMBtu/MWh =$120/MWh

Moreover, we assume that, other than the fuel constraint, the resource is not subject to any intertemporal constraints. This means that:

- The Minimum Run Time (MRT) of the resource is 1 hour
- The Minimum Down Time (MDT) of the resource is 1 hour
- The resource has a very high ramp rate and can move up and down its dispatchable range very quickly

The analysis and optimization are simpler and the intuitions are easier to obtain without MRT and MDT constraints, but the economics of the problem largely remains the same. We will allow more intertemporal operational constraints later in this memo.

Prices and Optimal Schedule

The resource's actual net revenue depends on realized prices, not expected prices. Actual spot prices can only be observed in real time and as a result the resource owner can only use *expected* prices to calculate its opportunity cost.

In this example we assume the resource owner forecasts electricity prices for the entire study period of 48 hours.[4] We emphasize two points regarding the price sequence:

- Assume the unit forecasts its replacement fuel price during the study period to remain constant at $120/MWh.
- Electricity prices are forecasted to be above the generator's cost per MWh (based on its heat rate and projected refueling cost) only "sporadically" (we will elaborate below)

Figure 1 below shows the evolution of the input costs and output prices:

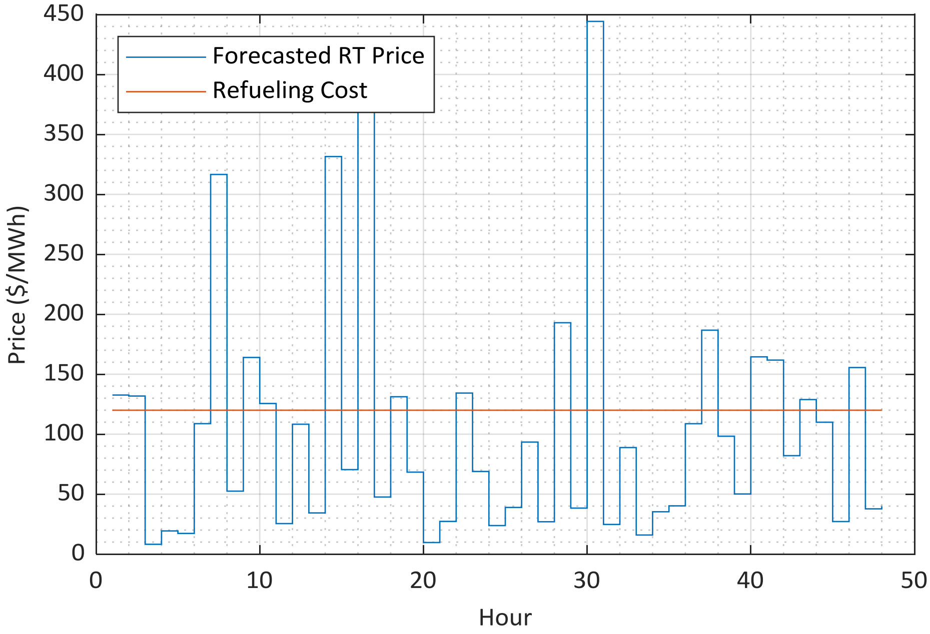

Figure 1- Forecasted Electricity Prices and Refueling Cost of an oil unit. Prices are above refueling cost sporadically.

In this sequence of forecasted prices, electricity prices are above the refueling cost of the unit (adjusted for heat rate) in only 16 hours of the 48 hour study period. Electricity prices are *below* refueling cost in the

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[4] Prices for Example 1 are listed in tabular form in Appendix A - Prices in Example 1

remaining 32 periods. It is clear that the resource owner does not find it economically sensible to run the unit at a loss in any of these 32 hours. So, it will, at most, run the unit for the profitable 16 hours.

Now that the resource owner knows it can obtain a profit in 16 of the 48 hours, the owner must determine if it has enough fuel to produce in all of those hours. More specifically, the owner must determine if it has enough fuel to produce 170 MW (its EcoMax) in each of the 16 potentially profitable periods. Doing so would require having:

$$16 \text{ (hours in which } p_{MW} > \textit{Refueling Cost}) \times 170 \text{ (MW of EcoMax)} = 2{,}720 \text{ MWh}$$

of fuel in the tank. Given that the resource has 3,000 MWh of oil in its tank, it can produce 170 MW in each of the 16 profitable periods.

Intertemporal Opportunity Cost of the Resource

The intertemporal opportunity cost of the resource is the net revenue of the last MWh of fuel in the tank. Alternatively, the intertemporal opportunity cost is the net revenue the resource gives up if the fuel tank held only 2,999 MWh worth of oil instead of 3,000 MWh of oil.

The net revenue of the 3,000th MWh in the tank is zero: the optimal schedule of the unit requires only 2,720 MWh of fuel. Any fuel left in tank above this level has an incremental net revenue of zero (in this fueling cycle) because it cannot be profitably converted to electricity. Put differently, having 2,999 MWh of fuel in the tank would not have improved the net revenue of the resource owner in this cycle. Therefore, the intertemporal opportunity cost of the resource in this example is zero: resource's fuel limitation does not change the optimal solution.

Key to this result is the fact that the resource owner does not expect to have 'too many' hours in which the price of the output is greater than or equal to the cost of input. In particular, this unit, with 3,000 MWh of fuel in tank can run for 3,000 MWh/170 MW= 17.64 hours at its EcoMax of 170 MW. If the number of profitable hours (those in which the price of output is not less than the cost of input) is less than or equal to 17, the unit can ignore its fuel limitations and run at its EcoMax during all profitable hours without violating its tank limitations. That is, the fuel constraint is non-binding. When the fuel constraint is non-binding, the resource has no intertemporal opportunity cost.

To rephrase this in the standard lexicon of optimization models, the "shadow price" of the fuel constraint is zero. We will see this concept recur frequently as we examine more complex examples that may require multiple constraints to accurately model the intertemporal limitations on available fuel supply.

At what price should this resource offer to produce electricity?

The only cost the unit faces in this example is the refueling cost. It does not face an opportunity cost. As a result, its optimal competitive offer only includes its $120/MWh fuel replacement cost. An offer higher than that could prevent the resource from being dispatched in an hour that could have increased its net revenue.

Example 2

This example shows that if the oil resource is frequently profitable, it faces a tradeoff between producing electricity in the current period versus in a future period. The resource can no longer run in every profitable interval in the fueling cycle because it does not have enough fuel in its tank to do so. As a result, its intertemporal fuel limitation is binding and the intertemporal opportunity cost of the resource is not zero. We explain how we calculate the intertemporal opportunity cost of the resource, how it changes over the study period and how the output of the resource should be offered so that the limited fuel of the resource is used during times it is expected to be most efficient.

Oil Unit

This example considers the same resource as in Example 1. This resource is assumed to have the same characteristics, refueling costs, and refueling schedule.

Prices and Optimal Schedule

In this example, expected electricity prices are generally higher compared to the prices of the previous example. We will again assume that the unit owner forecasts a sequence of 48 electricity prices spanning the duration of the study period.[5]

Electricity Prices in the 48 hour study period of this example are ‘routinely’ higher than the refueling cost of the resource (we will elaborate on this concept below). As we will see, this property is at the core of what creates intertemporal opportunity cost.

Figure 2 below shows forecasted electricity prices and refueling cost of the unit in this study period:

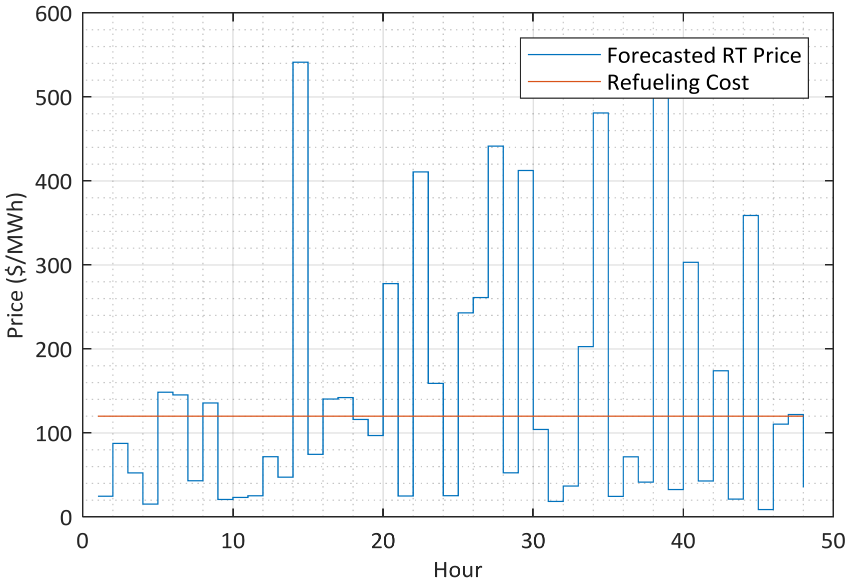

Figure 2- Forecasted Electricity Prices and Refueling Cost of an oil unit. Prices are above refueling cost routinely.

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[5] The hourly prices for Example 2 are listed in tabular form in Appendix B - Prices in Example 2.

Unlike the previous example, in which electricity prices were above the refueling costs during only 16 hours of the 48 hour study period, in this example, output prices are above the refueling costs during 20 hours of the study period. If possible, running the unit at its EcoMax of 170 MW is profitable. However, doing so would require:

$$20 \text{ (hours in which } p_{MW} > \text{Refueling Cost)} \times 170 \text{ (MW of EcoMax)} = 3{,}400 \text{ MWh}$$

of fuel in the tank. Unfortunately, the resource has 3,000 MWh of oil in tank and so it cannot produce its 170 MW maximum output in all these 20 hours. That is, the fuel constraint is binding. The resource owner is facing a tradeoff as the unit cannot run during all profitable hours: running the unit at a higher level now means that it has to reduce output during some hour in the future.

The resource owner finds it optimal to have the resource run in hours in which it earns the highest net revenue. It, therefore, can achieve the highest overall net revenue by following these steps:

1. Rank the intervals from highest to the lowest profit margin (electricity price, net of refueling cost)
2. Set the schedule of the unit to run at EcoMax in the 17 hours with highest margin (remember that resource has enough fuel to run at EcoMax for 17 hours, but not 18 hours).
3. Set the schedule of the unit such that it runs at 110 MW in the hour that corresponds to the 18th highest margin.[6] Doing so would use all the fuel in the tank:

$$170 \text{ (MW, EcoMax)} \times 17 \text{ hours} + 110 \text{ MW} \times 1 \text{ hour} = 3{,}000 \text{ MWh}$$

The above steps would result in the highest possible net revenue, subject to the unit's fuel limitations. The unit cannot earn more net revenue because it is running at maximum output during the highest profit periods.

Intertemporal Opportunity Cost of the Resource

Repeating our definition above, the intertemporal opportunity cost of the resource is the net revenue of the last MWh of fuel in the tank or the net revenue it gives up if the fuel in the tank was 2,999 MWh instead of 3,000 MWh.

Unlike the previous example, the net revenue of the last MWh of fuel in this example is not zero. Because all 3,000 MWh of fuel in the tank are spoken for, a reduction in fuel inventory of 1 MWh would cause the unit to need to reduce its output in the fueling cycle by 1 MWh. We make the following observations about the options the unit has:

- It cannot reduce the output in periods in which its output is at its EcoMin
- It is not optimal to reduce the output in the intervals with highest expected profit margins.
- If it has to, the unit will reduce output during the interval in which (1) its output is above EcoMin, and (2) the profit margin is lower than all other intervals in which the resource has positive output.

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[6] For simplicity, this example assumes the generator has a constant heat rate over its operating range from EcoMin to EcoMax.

Using the above logic, the unit will find it optimal to respond to an incremental energy limitation by reducing output in the period with the 18th highest margin, where its output is 110 MW. In this example, that would correspond to hour 16 of the study period with expected energy price of \$140.42/MWh. Given the refueling cost of \$120/MWh, the net revenue that the resource gives up if its tank was 1 MWh smaller is:

$$\$140.42/\text{MWh} - \$120/\text{MWh} = \$20.42/\text{MWh}$$

That is, \$20.42/MWh is the opportunity cost of the 3,000th MWh of fuel in unit's tank.

An important point here is that the intertemporal opportunity cost of the unit is not constant during the study period. After hour 16 of the study period that corresponds to the period with 18th highest margin, reducing output in this interval is no longer possible. Therefore, the opportunity cost of the unit after hour 16 is not \$20.42/MWh. To calculate the opportunity cost of the unit after hour 16 we should repeat the steps above with the fuel in the tank at the end of this hour. At the start of hour 17 (or end of hour 16) of the study period, the unit has 2,380 MWh of fuel in tank, enough to run for exactly 14 hours at it 170 MW EcoMax. Looking forward, at the beginning of hour 17, the 14th lowest expected profit margin in the hours ahead belongs to hour 17. This is the hour in which the unit would reduce its output if it had to after hour 16. We repeat this analysis at the beginning of hour 18 (end of hour 17) to get the new opportunity cost for that hour as well. The following figure shows the opportunity cost of the resource over the 48-hour study period:

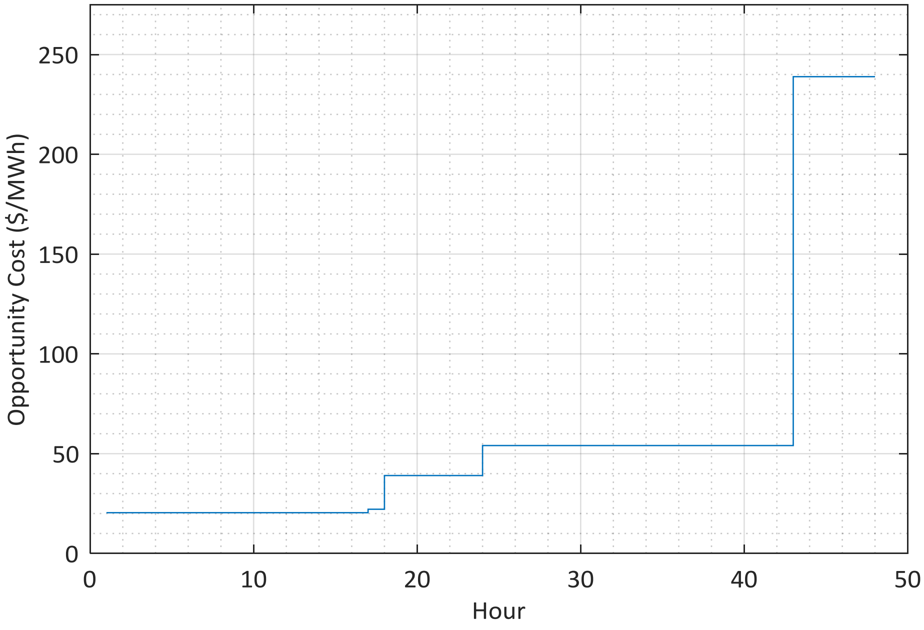

Figure 3 - Intertemporal Opportunity Cost of the resource in the study period.

In practice, we look at the *shadow price* of the fuel constraint to calculate the opportunity cost. In each period, we re-solve the optimization problem that maximizes the resource's net revenues and report the shadow price of the fuel constraint as the resource's opportunity cost in that period. We repeat these steps until we reach the final period of the study period. In other words, to calculate the opportunity cost profile, we solve a forward looking optimization problem to maximize expected net revenues at any point in time given the steps the resource has taken up to that period.

At what price should this resource offer to produce electricity?

In addition to the refueling cost of $120/MWh, the resource faces a sequence of opportunity costs shown in Figure 3. Its optimal competitive offer is the sum of its refueling cost and its intertemporal opportunity cost. Offering this way would ensure that price is above its total cost (refueling cost + intertemporal opportunity cost). The optimal schedule of the unit is shown in the figure below:

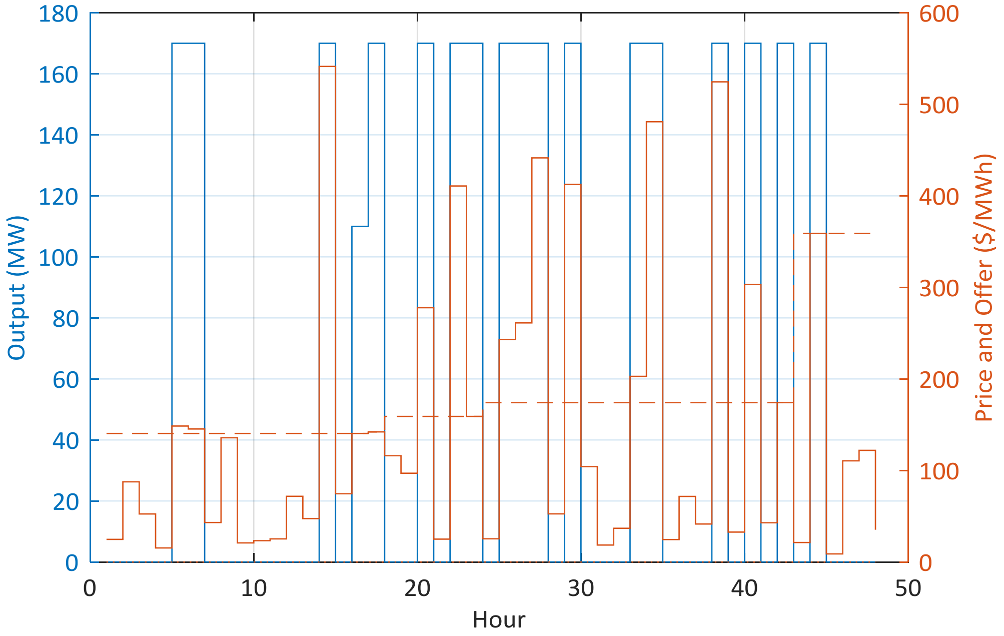

Figure 4- Output of the unit (left axis) and price and offer of the unit (right axis).

By submitting offers equal to the sum of its refueling and opportunity costs, the unit ensures that it is producing electricity exactly when it is optimal to do so to maximize its expected net revenue.

Example 3

This example starts with the same price expectation as the previous example. The resource owner obtains an updated price forecast halfway through the study period. We study the impact of this update on the optimal schedule and offer of the resource.

Oil Unit

This example considers the same unit as in the above examples, with identical unit characteristics, refueling costs, and refueling schedule.

Prices and Optimal Schedule

We assume that we are in the same fueling cycle as in Example 2, except that the resource owner updates its forecast of electricity prices 24 hours after the first forecast. Forecasted prices for the second half of the 48 hour study period are generally lower than the original forecast for these hours.

Figure 5 below shows initially forecasted and updated electricity prices, along with the refueling cost of the unit in this study period:

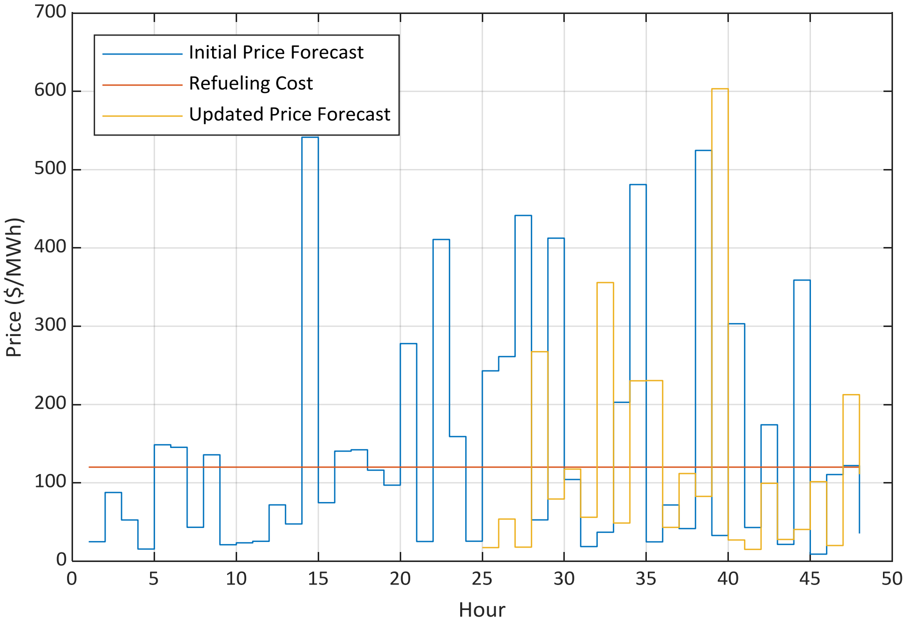

Figure 5- Forecasted Electricity Prices (initial and updated) and Refueling Cost of an oil unit.

Initially, the resource owner forecasts 20 profitable hours and allocates its output to maximize its expected net revenues over the 48 hour study period: 9 hours in the first 24 hours and 11 in the second 24 hours of the study.[7] This implies that the resource would not produce in hours deemed insufficiently profitable. Remember, to maximize expected net revenues, the unit will choose to have its maximum output in the 17 highest priced hours, with the remaining 110 MWh of the fuel in tank being produced in the hour with the 18th highest profit margin.

One of these 'insufficiently profitable' hours is hour 8, in which the price is $135.73/MWh (*see* Appendix C - Prices in Example 3)[8]. Despite an electricity price greater than the refueling cost, the resource's optimal schedule at the beginning of the first day (using the initial price forecast) is to produce 0 MW in this hour (*see* Figure 4).

The initial price forecast expects the resource be profitable in 11 hours in the second half of the study period (hours 25 through 48). Before updating the electricity price forecast at the end of hour 24 the

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[7] See Appendix B - Prices in Example 2 and Appendix C - Prices in Example 3

[8] The other hour is hour 47, in which the forecasted price is $121.97/MWh.

resource owner does not know if the resource will face more or fewer profitable hours for the balance of the study period (hours 25 through 48) than were anticipated in the initial forecast. In this example, the updated price forecast which becomes available at the end of hour 24 foresees only 6 profitable hours for the resource in the second half of the study period as opposed initial forecast of 11. Once a new price forecast is made, it will supersede the initial forecast and will be used to determine the resource's optimal schedule and opportunity cost in the remaining hours.

If the resource had the updated price forecasts for the second half of the study period in hour 1 rather than hour 25, its desired dispatch schedule would have been different. In this example, the sum of the number of expected profitable hours in the first half of the study based on the initial forecast and number of expected profitable hours in the second half of the study based on the updated forecast is 15. This means that if the forecast available to the resource owner initially was the combination of the original forecast for the first 24 hours and updated forecast for the second half of the study period, the resource owner would have preferred the resource run in *all* profitable hours[9], including hour 8, where the resource did not run.

Intertemporal Opportunity Cost of the Resource

The intertemporal opportunity cost of the resource is the net revenue of the last MWh of fuel in the tank or the net revenue it gives up if the fuel in the tank was 1 MWh less.

The problem in the first 24 hours is identical to Example 2. As a result, the opportunity cost in the first 24 hours is the same as before. We further note that just before the resource owner updates its forecast of electricity prices at the end of hour 24, the resource has already used 1,300 MWh of fuel and has 3,000 - 1,300=1,700 MWh of fuel in tank, enough to run for exactly 10 hours while (initially) expecting 11 profitable hours in the second half of the study period.

Once the resource owner updates its forecast, the resource no longer expects to have 11 profitable hours in hours 25 through 48. At the beginning of hour 25, the resource is expected to be profitable in only 6 of the remaining 24 hours before refueling. Following the logic in Example 1, its intertemporal opportunity cost at that point is zero because the fuel constraint is no longer expected to bind: if it ran in every profitable hour *based on updated price forecast*, it would only consume:

$$6 \text{ (hours in which } p_{MW} > \textit{Refueling Cost}) \times 170 \text{ (MW of EcoMax)} = 1{,}020 \text{ MWh}$$

of the remaining 1,700 MWh of fuel in its tank. If, for some reason, the resource has 1 MWh less fuel in its tank, it would still consume 1,020 MWh of fuel. Therefore, it does not give up any net revenues (in this fueling cycle) if it did not have the last MWh in tank. Therefore, at the beginning of period 25, the fuel constraint is not binding and thus, the 'shadow price' of this constraint, which is the intertemporal opportunity cost of the resource for hours 25 through 48, is zero.

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[9] The same logic discussed in Example 1 is applicable. The number of expected profitable hours based on the combined forecast is 15. If the resource runs at EcoMax during all profitable hours, it would consume 15 × 170 = 2,550 MWh.

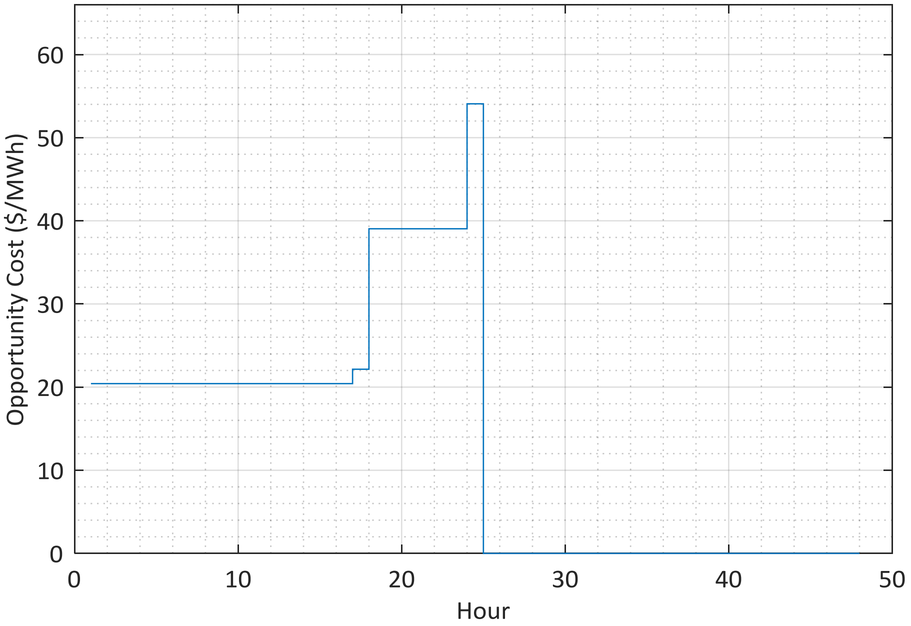

Figure 6- Intertemporal Opportunity Cost of the unit that updates its forecasted LMPs at the end of hour 24.

The intertemporal opportunity cost is calculated based on the best information available to the resource at any given point. This means that in the first half of the study period the intertemporal opportunity cost of the resource is determined by the initial forecast. Once expected electricity prices are updated based on the new forecast, the opportunity cost of the resource is determined based on the updated estimates as shown in Figure 6. Although not illustrated in the example, changes in anticipated fuel replacement cost could lead to similar outcomes.

At what price should this resource offer to produce electricity?

In addition to the refueling cost of $120/MWh, the resource faces a sequence of opportunity costs shown in Figure 6. As before, its optimal competitive offer is the sum of the resource's refueling cost and its intertemporal opportunity cost. Assuming realized prices are equal to the expected prices, such an offering strategy would ensure that the resource runs each hour that price is above its cost (refueling cost + intertemporal opportunity cost). The optimal schedule of the unit is shown in the figure below:

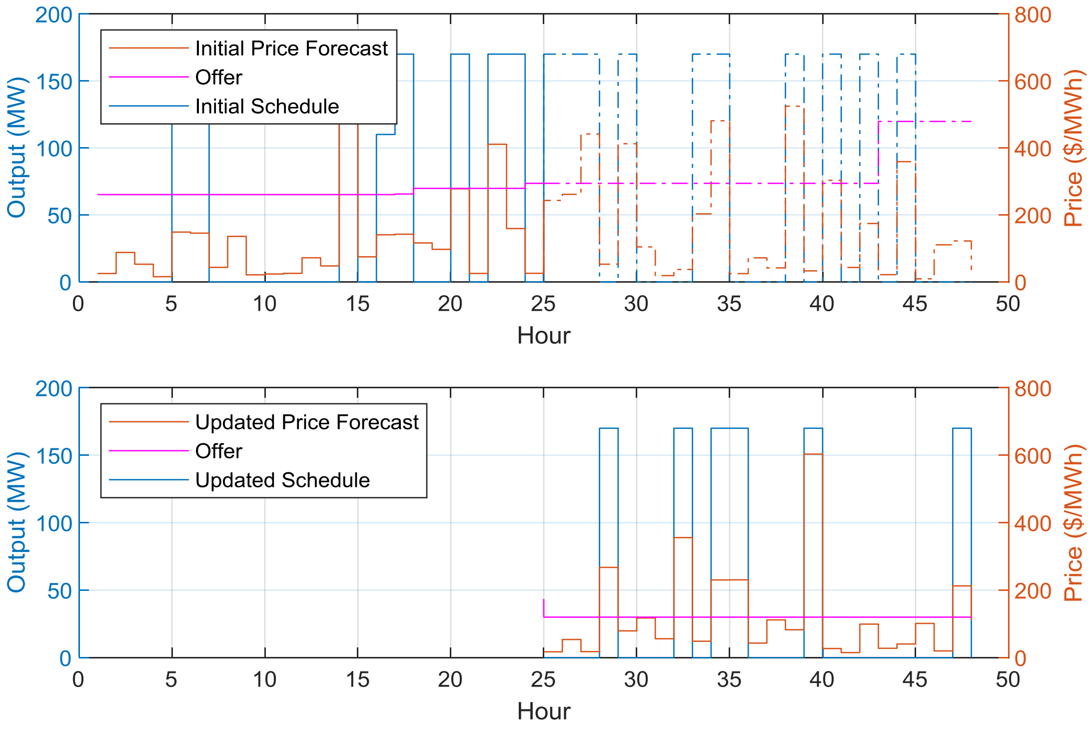

Figure 7- Initial and Updated Price Forecasts and Schedules

Example 4

This example shows the impact and complications that arise when the resource has operational intertemporal constraints (like Minimum Run Time) and a minimum generation constraint (*i.e.* EcoMin). We observe that the resource is spread thinner across more, some unprofitable, period and it is no longer the case that the resource is generating electricity only when it is expected to be profitable. We emphasize that the concept of opportunity cost is the same as before. Generally, intertemporal operational constraints like Minimum Run time reduce the net revenue of the resource.

Oil Unit

In this example, we consider a slightly different oil resource. The new oil unit has a Minimum Run Time (MRT) of 3 hours and a minimum generation level (EcoMin) of 30 MW, as opposed to 1 hour and 0 MW, respectively, in the previous examples. Otherwise, the unit has the same characteristics, fuel, and refueling schedule as above.

Prices and Optimal Schedule

Prices in this example are identical to those in Example 2. (See Appendix B for the prices in tabular form).

With the complexities provided by a nontrivial MRT (*i.e.* an MRT greater than 1 hour), the solution to the problem can no longer be summarized in the simple algorithmic fashion as in Example 2 above. The resource's problem is to produce in the most profitable sets of intervals greater than or equal to three hours (because MRT = 3). An intertemporal constraint like MRT forces the resource to potentially give up some very profitable hours that are in the middle of two really unprofitable ones, or could force the resource to operate at loss in one hour that is in the middle of two profitable ones. Indeed, it is possible that if every profitable hour is between two highly unprofitable hours, the resource could be better off not producing at all.

In fact, we see both cases in this example. For instance, the optimal output of the resource in hour 47 is zero despite the fact that price in that hour is greater than refueling cost. This is a result of the losses that would be incurred by producing in the surrounding hours. On the other hand, the optimal output of the resource in hour 43 is its EcoMin of 30 MW, despite the deep loss that the unit takes in this period. This loss is worthwhile because of the profits that can be obtained by producing in hours 42 and 44.

Overall, the solution to this problem can only be obtained through a formal optimization program in which all the above constraints and dependencies can be modeled. We then report the shadow price of the fuel constraint in the linearized optimization as the intertemporal opportunity cost of the resource. While this resource is modeled with several constraints (MRT and EcoMin) in addition to the limited fuel supply, the shadow price of the fuel constraint determines the opportunity cost. These parameters constrain the resource's ability to produce energy, but they are considered fixed characteristics of the resource not subject to change when determining the dispatch that optimizes net revenue. There is no inter-temporal substitution aspect to the MRT and EcoMin constraints, and therefore they have no direct role in determining the opportunity cost of using fuel now versus later. Essentially, as before, we report the intertemporal opportunity cost as the decrease in net revenue from a tank that is 1 MWh smaller.

Note that for the MRT constraint to be nontrivial, the resource's EcoMin must be non-zero as well. Otherwise the solution to the problem is the same as in Example 2 with the resource "running" in all unprofitable hours at 0 MWs and at EcoMax during profitable hours.

Intertemporal Opportunity Cost of the Resource

The intertemporal opportunity cost of the resource is the net revenue of the last MWh of fuel in the tank or the net revenue it would give up if the fuel in the tank was 1 MWh smaller.

Conceptually, once the optimal schedule of the unit is determined, we can apply the same logic as before to calculate the intertemporal opportunity cost of the resource. If faced with a fuel tank 1 MWh smaller, the resource owner would reduce the output of the unit during an hour in the future that satisfies two conditions:

- The output of the resource is strictly above its EcoMin
- The profit margin of the resource is lower than any other hour that satisfies the previous condition

In this example, the optimal schedule would run the resource for 25 hours (instead of 18 hours in Example 2). Because of the combination of nontrivial EcoMin and MRT, the resource must run at EcoMin in additional hours that it did not run with an MRT of 1 hour.

At the beginning of the study period the two conditions listed above would point to hour 16 with an output price of $140.42/MWh. If the resource had a 1 MWh smaller tank, it would reduce the output in this hour by 1 MW, resulting in a loss of:

$$\$140.42/\text{MWh} - \$120/\text{MWh} = \$20.42/\text{MWh}$$

Calculating the intertemporal opportunity cost for hours 18 and after follows the same logic discussed in previous examples. Figure 8 below shows the opportunity cost of the resource:

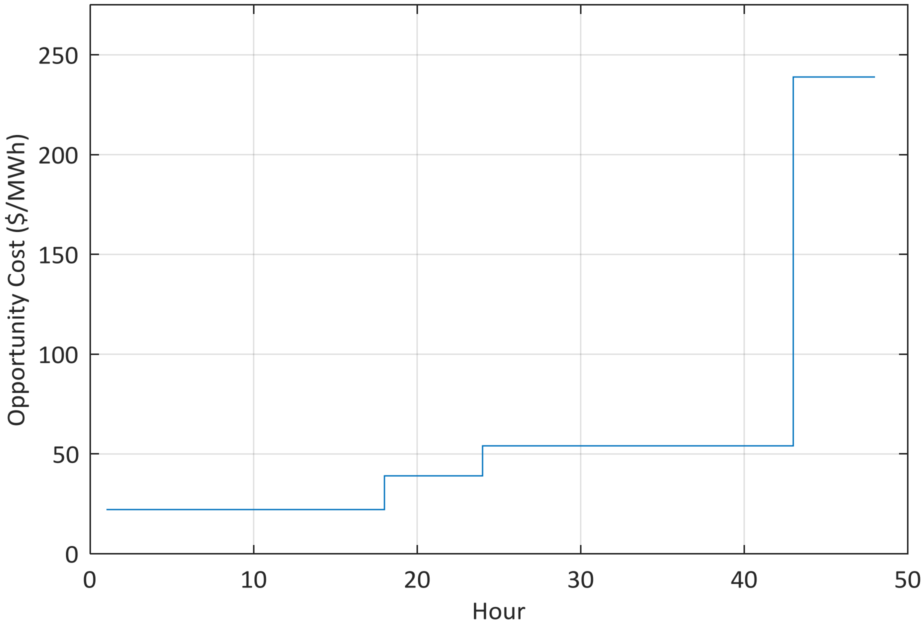

Figure 8 - Opportunity cost of the oil unit with MRT=3 hours.

At what price should this resource offer to produce electricity?

In addition to the refueling cost of $120/MWh, the resource faces a sequence of opportunity costs shown in Figure 8. Its optimal competitive offer is the sum of the resource's refueling cost and its intertemporal opportunity cost. The optimal schedule of the unit is shown in the figure below:

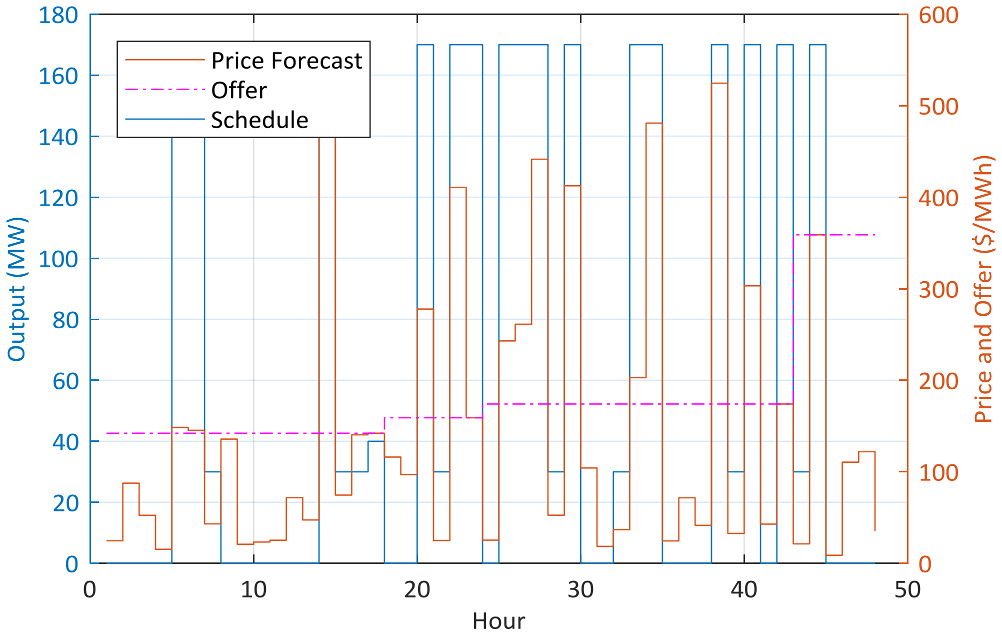

Figure 9- Optimal Schedule of the oil unit with MRT of 3 hours.

Offering based on Figure 9 would ensure that the resource runs at EcoMax every time price is above its economic cost (refueling cost + intertemporal opportunity cost). Unlike previous examples, however, the combination of nontrivial EcoMin and MRT means that the resource could be running, although not at EcoMax, during hours in which price is below cost (*e.g.* hours 7 and 15-16).

Numerical examples of intertemporal opportunity costs for dual fuel resources

Example 5

This example considers a very simple example of dual fuel unit over a three hour horizon to illustrate how the optimal dispatch of a dual fuel capable unit differs from that of a single fuel oil unit and the effect that has on the generator's opportunity cost. The simplistic "sorting and ranking by net revenue margin" used to determine the opportunity costs previously in Examples 2 and 3 will not produce a correct solution for even a very simple dual fuel scenario.

Dual Fuel Unit

The dual fuel generator in this example has the following characteristics:

EcoMax = 1MW
EcoMin = 0 MW
Oil tank capacity of 2 MWh, initially full
Oil inventory replenishment does not occur until after hour 3
No ramping or intertemporal constraints (Min Run Time = 0; Min Down Time = 0)

Prices and Optimal Schedule

We assume the same replacement price for oil as used in previous examples, \$120/MWh. In addition, we assume gas prices are \$123/MWh, \$135/MWh and \$125/MWh in hours 1, 2, and 3, respectively.[10] Electricity prices are \$140/MWh, \$160/MWh, and \$130/MWh in hours 1, 2, and 3, respectively. Note that both fuel types are in the money but nominally, gas is more expensive than oil.

	Hour		
	1	2	3
Oil Price	\$120/MWh	\$120/MWh	\$120/MWh
Gas Price	\$123/MWh	\$135/MWh	\$125/MWh
LMP	\$140/MWh	\$160/MWh	\$130/MWh

Table 1- Price Assumptions

If the unit was not dual fuel (*i.e.* it was a single-fuel oil unit), its optimal schedule would be to run in hours 1 and 2 only. Total fuel cost of the unit would be:

$$2 \text{ hours} \times \$120/\text{MWh} \times 1 \text{ MW EcoMax} = \$240$$

and the revenue produced would equal the sum of the LMP multiplied by the output of the unit for hours 1 and 2:

$$1 \text{ hour} \times \$140/\text{MWh} \times 1 \text{ MW EcoMax} + 1 \text{ hour} \times \$160/\text{MWh} \times 1 \text{ MW EcoMax} = \$300$$

This provides the unit with a net revenue equal to the revenue less the fuel cost:

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[10] Assuming that natural gas prices vary by hour in this example, while possibly unrealistic, will help to illustrate key properties in the context of this simple example (with only 3 hours in total).

Net revenue if unit was single fuel: $300- $240= $60

In this example, the generator's dual fuel capability creates additional optionality for the unit that translates into higher net revenues.

The dual fuel capable unit is faced with the following profit margins on oil and gas:

Hour	1	2	3
Profit Margin on Oil ($/MWh)	20	40	10
Profit Margin on Gas ($/MWh)	17	25	5

Table 2 - Profit Margin By Fuel Type

If the duel fuel unit had no oil inventory limitations, the most profitable course of action would be to run the unit on oil in all three hours. Given that the unit has a 2 MWh tank, this is not possible. Even in this simple example and with no resource level intertemporal constraints (like MRT and MDT), the solution to the net revenue maximization problem faced by the generator cannot be obtained by following the simple heuristic used in Example 2. Selecting the highest margin on all fuel types (while respecting the oil inventory) leads to the wrong solution: the outcome of such a heuristic would be to run on oil in hours 1 and 2 and on gas in hour 3, earning a net revenue of $40+$20+$5= $65. This, however, is not the correct solution. The correct solution requires running the unit on oil in hours 2 and 3 and on gas in hour 1 with the net revenue of $40+$10+$17= $67/MWh. It should run on gas in hour 1 because the 'spread' between its profit on gas versus oil is smallest in hour 1 (and it is still profitable on gas in hour 1).

Intertemporal Opportunity Cost of the Resource

The intertemporal opportunity cost of the resource is the revenue the resource foregoes if it has 1 MWh less fuel in tank. The unit's response to having 1 MWh of oil at its disposal (instead of 2 MWh) is to reduce oil output in hour 3 by 1 MW. This means that it would lose the profit margin in hour 3 that it currently earns by running on oil. As seen in Table 1 above, this is $10/MWh.

For a single fuel oil unit this would mark the end of intertemporal opportunity cost calculation as the resource has no other alternative in hand.[11] A dual fuel capable unit does indeed have other options at its disposal. In this example, it can increase its *gas* output in hour 3 by 1 MW as it decreases its oil output due to tighter oil limits. This means that while the unit gives up its oil profit margin in hour 3, it can replace part of that lost revenue by selling 1 MWh on gas in that hour, earning a gas margin in hour 3 of $5/MWh, as seen in Table 2.

To summarize, facing a reduction of 1 MWh less oil in the tank means that the resource gives up $10/MWh in hour 3 in oil profit margin but would make $5/MWh in gas margin in that hour. The change in net revenue from 1 MWh less oil is $5. Therefore, the oil-related opportunity cost for the dual fuel unit is $5/MWh.

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[11] We are ignoring the fact that a single fuel oil unit would have a different schedule altogether.

Since the “marginal” hour in this example is the last hour before refueling, we do not need to consider the opportunity cost after the expiration of this hour.

At what price should this resource offer to produce electricity?

A dual fuel unit makes two sets of offers (each is known as a schedule): an oil schedule and a gas schedule. Since pipeline gas is not stored on site and is consumed on demand, gas-based offers of the unit do not have an intertemporal opportunity cost component. In this simple example, the dual fuel capable unit’s gas offers are simply the market price to purchase gas in each hour: $123/MWh, $135/MWh and $125/MWh in hours 1, 2, and 3, respectively.

Similar to the earlier examples 1 through 4, the oil-based offer of the unit is the sum of the cost of oil ($120/MWh) and the opportunity cost of oil ($5/MWh). This means that the oil is offered at $125/MWh in hours 1 and 2. It is straightforward to verify that with this offer schedule, the unit will be economically dispatched to run on gas in hour 1 and on oil in hour 2 and 3.[12]

Hour	1	2	3
Oil Offer ($/MWh)	125	125	125
Gas Offer ($/MWh)	123	135	125
Unit Runs on	Gas	Oil	Oil

Table 3 - Dual Fuel Unit’s Oil and Gas Offer Schedules.

Example 6

This example shows that even when the dual fuel unit is nominally in merit on both fuel types in some hours, it might not be optimal to run the unit on gas because the profit margin on gas is less than oil and the number of opportunities to generate profit is limited. In addition, the example illustrates a situation where both gas and oil are in merit, the maximum net revenue solution does not use the gas, but the existence of dual fuel capability still impacts the unit’s oil-related opportunity cost.

Dual Fuel Unit

Example 6 is based on a dual fuel unit with the same characteristics as in Example 5:

EcoMax = 1MW
EcoMin = 0 MW
Oil tank capacity of 2 MWh, initially full
Oil inventory replenishment does not occur until after hour 3
No ramping or intertemporal constraints (Min Run Time = 0; Min Down Time = 0)

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[12] In theory, with these offers the unit can be dispatched on oil or gas in hour 3. We assume that the unit would prefer to operate on the nominally less expensive fuel when its offer schedules have identical offers (including the opportunity cost) for oil and gas. To accomplish this outcome, the generator might choose to lower the oil offer by a fraction of a penny to ensure the economic dispatch of the generators would be on oil in hour 3, not gas.

Prices and Optimal Schedule

We assume the same oil price used in previous examples, $120/MWh. In addition, we, assume that gas price constant as $135/MWh throughout the study period. Electricity prices are $140/MWh, $160/MWh, and $130/MWh in hours 1, 2, and 3, respectively.

	Hour		
	1	2	3
Oil Price	$120/MWh	$120/MWh	$120/MWh
Gas Price	$135/MWh	$135/MWh	$135/MWh
LMP	$140/MWh	$160/MWh	$130/MWh

Table 4 - Price Assumptions

If the unit was not dual fuel capable (*i.e.* it was a single-fuel oil unit), its optimal schedule would be to run in hours 1 and 2 only. Total cost of the unit would be:

2 hours × $120/MWh × 1 MW EcoMax= $240

and its gross revenue would be just the sum of the LMP multiplied by the output of the unit for hours 1 and 2:

1 hour × $140/MWh × 1 MW EcoMax + 1 hour × $160/MWh × 1 MW EcoMax = $300

giving the unit a net revenue of the difference of the two numbers above:

Net revenue if unit was single fuel: $300- $240= $60.

In Example 5 we saw that dual fuel capability provided additional optionality that translated into higher net revenue for the generator. One might expect that to always be the case. Example 6 demonstrates this will not always be the case.

Based on the prices in Table 4, the example generator is nominally profitable on oil in all hours and on gas in hours 1 and 2. Since gas is more expensive than oil, the unit is nominally more profitable on oil than gas in all hours. Therefore, if the unit was to run in hours 1 and 2 only (and not hour 3), it would do so on oil (which is the same outcome we would see if the unit was an oil unit only).

The only option to improve net revenue is to run the unit in hour 3, which is only profitable if running on oil. Doing so, however, would leave the unit with only 1 MWh of oil to run during hours 1 and 2. Since the dual fuel unit is nominally profitable on oil and gas in both hours 1 and 2, it can allocate its 1 remaining MWh of oil to one hour and run at EcoMax on gas during the other. Without loss of generality, assume that the unit runs on gas (at 1 MW EcoMax) for the first hour and on oil (at 1 MW EcoMax) in hours 2 and 3.[13] The cost of this dispatch schedule is the cost of oil in hours 2 and 3 and gas in hour 1:

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[13] The reader can test the alternative case where the unit runs on oil in hours 1 and 3 and on gas in hour 2, all at 1 MW EcoMax.

(1 hour × \$135/MWh gas price × 1 MW + 2 hours × \$120/MWh oil price × 1 MW) = \$375

The gross revenue of this schedule is:

(1 hour × \$140/MWh × 1 MW + 1 hour × \$160/MWh × 1 MW + 1 hour × \$130/MWh × 1 MW) = \$430

If the generator runs in every hour, this dispatch results in a net revenue of:

gross revenue less fuel cost = \$430 - \$375 = \$55

This is less than the net revenue the resource could produce if it was a single fuel oil resource and only runs for two of the three hours. In other words, having the dual fuel capability in this example does not improve the net revenue of the resource - the owner of the unit could ignore the dual fuel capability of the unit without incurring any losses.

Therefore, the optimal dispatch schedule of the dual fuel unit is to run in hours 1 and 2 on oil and not run in hour 3.

Intertemporal Opportunity Cost of the Resource

The intertemporal opportunity cost of the generator in hour 1 is determined by the oil and gas profit margins in hour 1. If the tank had 1 MWh less oil in it at the beginning of hour 1, the resource would give up production (on oil) in hour 1 (instead of the more profitable hour 2). This would cost the resource the profit margin it earns on oil in hour 1, which is \$20/MWh, as can be seen in Table 5.

Hour	1	2	3
LMP	140	160	130
Oil Price (\$/MWh)	120	120	120
Gas Price (\$/MWh)	135	135	135
Operating Margin on Oil (\$/MWh)	20	40	10
Operating Margin on Gas (\$/MWh)	5	25	5

Table 5 – Operating Margins

This is not the end of story, however. The unit would pick up production on *gas* in hour 1 and earn the profit margin on gas in that hour if the tank had 1 MWh less oil in it. As shown in Table 5, the unit's profit margin on gas in hour 1 is \$5/MWh.

To summarize, facing a 1 MWh reduction of oil in the tank means that the resource gives up \$20/MWh in hour 1 in oil profit margin but gains \$5/MWh in gas margin. Therefore, the dual fuel generator faces a \$15/MWh opportunity for the last MWh of fuel oil.

By the same reasoning, we can conclude that the unit's opportunity cost for oil at the beginning of the second hour is the \$40/MWh profit margin the unit would give up on oil in hour 2 offset by the \$25/MWh profit margin on gas it would gain. This results in an opportunity cost for hour 2 of $40/MWh - $25/MWh = $15/MWh.

Without dual fuel capability, the unit would not be able to increase the gas output in the face of lower fuel in the tank, in other words, it could not earn the $5/MWh and $25/MWh gas profit margins (in hours 1 and 2, respectively) that a dual fuel capable unit could earn. Therefore, although the optimal dispatch schedules for both the single-fuel oil unit and the dual fuel unit are the same in this example (burn oil in hours 1 & 2, stay offline in hour 3), the single fuel and dual fuel units face different opportunity costs. In particular, the opportunity cost of a single fuel oil unit would not be reduced by the gas profit margin and would be $20/MWh and $40/MWh in hours 1 and 2, respectively.

At what price should this resource offer to produce electricity?

As noted previously, a dual fuel unit makes two sets of offers (known as schedules): an oil schedule and a gas schedule. The gas-based offers of the unit do not have an intertemporal opportunity cost component. In this simple example, the dual fuel unit's offer schedule on gas is simply the price of gas: $135/MWh for hours 1-3.

Similar to the examples 1 through 5, the oil-based offer of the unit is the sum of the cost of oil ($120/MWh) and the opportunity cost of oil ($15/MWh). This means that the oil is offered at $135/MWh in hours 1 and 2. The unit will be out of oil in hour 3, and the oil offer in hour 3 will be irrelevant if the optimal offers are submitted for hours 1 and 2.

Hour	1	2	3
Oil Offer ($/MWh)	135	135	N/A
Gas Offer ($/MWh)	135	135	135
Unit Runs on	Oil	Oil	None

Table 6 - Dual Fuel Unit's Oil and Gas Offer Schedule.

Finally, to ensure the generator is economically dispatched to run on oil, the fuel with the lower nominal price, the generator may wish to submit an oil offer price that is just slightly lower than the optimal gas offer price.

Appendices

Appendix A - Prices in Example 1

Hour	Price ($/MWh)	Hour	Price ($/MWh)	Hour	Price ($/MWh)	Hour	Price ($/MWh)
1	132.61	13	32.8	25	39.53	37	186.24
2	131.89	14	331.89	26	91.29	38	98.26
3	8.26	15	70.75	27	28.48	39	50.02
4	18.36	16	400.47	28	192.8	40	162.52
5	16.66	17	48.77	29	39.89	41	160.57
6	108.33	18	131.47	30	443.29	42	82.28
7	317.17	19	70.77	31	22.15	43	129.92
8	51.98	20	9.46	32	88.1	44	110.44
9	162.00	21	27.98	33	15.64	45	26.27
10	125.35	22	135.6	34	35.99	46	155.45
11	25.78	23	70.46	35	40.75	47	39.38
12	108.83	24	23.32	36	108.63	48	39.85

Appendix B - Prices in Example 2 and Example 4

Hour	Price ($/MWh)	Hour	Price ($/MWh)	Hour	Price ($/MWh)	Hour	Price ($/MWh)
1	24.72	13	47.4	25	242.98	37	41.51
2	87.6	14	541.37	26	261.22	38	524.55
3	52.49	15	74.57	27	441.48	39	32.68
4	15.36	16	140.42	28	52.59	40	303.17
5	148.53	17	142.15	29	412.48	41	42.87
6	145.32	18	116.11	30	104.2	42	174.07
7	43.14	19	96.98	31	18.53	43	21.3
8	135.73	20	277.8	32	36.84	44	358.91
9	20.87	21	24.99	33	202.81	45	8.85

10	23.29	22	410.79	34	480.95	46	110.53
11	25.26	23	159.04	35	24.52	47	121.97
12	71.77	24	25.36	36	71.64	48	35.24

Appendix C - Prices in Example 3

Hour	Price ($/MWh)	Hour	Price ($/MWh)	Hour	Price ($/MWh)	Hour	Price ($/MWh)
1	24.72	13	47.4	25	17.22	37	111.82
2	87.6	14	541.37	26	53.68	38	82.61
3	52.49	15	74.57	27	17.8	39	603.34
4	15.36	16	140.42	28	267.45	40	26.93
5	148.53	17	142.15	29	79.27	41	14.92
6	145.32	18	116.11	30	117.5	42	99.32
7	43.14	19	96.98	31	55.96	43	27.6
8	135.73	20	277.8	32	355.79	44	40.38
9	20.87	21	24.99	33	48.59	45	101.38
10	23.29	22	410.79	34	230.26	46	19.87
11	25.26	23	159.04	35	230.58	47	212.55
12	71.77	24	25.36	36	43.03	48	110.93