DRAFT of Algorithm for Determining Optimal ESR Schedule

Locating peaks and troughs

1. If LBMP at HB0 < LBMP at HB1, HB 0 is a local trough
   HB 0 should not be considered a local peak

2. If LBMP at HB23 > LBMP at HB22, HB 23 is a local peak
   HB 23 should not be considered a local trough

3. For non-endpoint hours, HB 01-22
   If LBMP in an hour, is less than both the LBMPs from prior hour and the following hour, the hour is a local trough
   If LBMP in an hour, is greater than both the LBMPs from prior hour and the following hour, the hour is a local peak

4. For all non-peak and non-trough hours, assume an optimal schedule of 0 MWs

*note: if LBMPs for consecutive hours are equal, the LBMP for the latter hour should be increased by a penny for the purposes of determining the optimal schedule and calculating opportunity costs

Determining optimal schedules

P = a set of peak LBMPs

x = the number of elements in set P

T = a set of trough LBMPs

y = the number of elements in set T

E = round trip efficiency

M_{Px} = scheduled MWs for the hour associated with peak x

M_{Ty} = scheduled MWs for the hour associated with trough y

1. Calculate $P_x - (T_y/E)$
    a. If negative, do P_{x-1} and T_{y-1} both exist?
        i. If no, set $M_{Px} = 0$ and $M_{Ty} = 0$
           End Algorithm
        ii. If yes, is $P_x > P_{x-1}$?
            1. If no, set $M_{Px} = 0$ and $M_{Ty} = 0$, remove P_x and T_y sets
               Loop Back to Step 1
            2. If yes, set $M_{Px-1} = 0$ and $M_{Ty} = 0$, remove P_{x-1} and T_y sets
               Loop Back to Step 1

    b. If positive, do both P_{x-1} and T_{y-1} exist?
        i. If no, set M_{Px} = max injection and M_{Ty} = max withdrawal
           End Algorithm
        ii. If yes, calculate $P_{x-1} - (T_y/E)$
            1. If positive, set M_{Px} to max inject and M_{Ty} to max withdrawal
               Remove P_x and T_y from sets of peaks and troughs
               Loop Back to Step 1
            2. If negative, is $T_y > T_{y-1}$?
                a. If no, set $M_{Px-1} = 0$ and $M_{Ty-1} = 0$
                   Remove P_{x-1} and T_{y-1} from sets
                   Loop Back to Step 1.b
                b. If yes, set $M_{Px-1} = 0$ and $M_{Ty} = 0$
                   Remove P_{x-1} and T_y from sets
                   Loop Back to Step 1.b

DRAFT of Derivation of Incremental Opportunity Costs of ESRs

For each segment of the ESR's reference curve, Incremental Opportunity Cost is calculated by looking at the impact of injecting an extra MW or withdrawing one less MW (as compared to the optimal schedule) on the total revenue the unit receives, accounting for the least costly offsetting changes to the ESR's daily schedule that are needed to make the incremental injection feasible.

Based on the optimal schedule the unit's revenue would be calculated as follows:

$Rev = P_1 MW_P - T_1 MW_T + P_2 MW_P - T_2 MW_T + \ldots$

Where:

P is the LBMP in the hour of a scheduled peak

T is the LBMP in the hour of a scheduled trough

MW_P is the amount of MWhs the unit is scheduled for during a max injection

MW_T is the amount of MWhs the unit is scheduled for during a max withdrawal

This formula could expand out depending on the number of round trips that are scheduled, or it may reduce further for cases where there are zero or only one scheduled round trips.

The relationship between MW_P and MW_T can be written as:

$MW_P = MW_T E$

Where:

E is the round trip efficiency of the unit

The unit's revenue for the optimal schedule can then be rewritten as:

$Rev = (P_1 E - T_1 + P_2 E - T_2 + \ldots)MW_T$

Once an incremental change to the schedule is assumed, the revenue of the unit will be recalculated. The exact formula for this revised revenue will depend on the incremental change and where the hour being reviewed falls in comparison to the optimal schedule. The revised revenue for the suboptimal will be referred to as Rev*.

With the revenue associated with the optimal schedule defined, the formulas for the revised revenues for the various hours and changes can now be defined. Once both Rev and Rev* have been determined, we can then calculate the Opportunity Cost for a given incremental change and hour.

Hours Before the First Scheduled Trough

Opportunity Cost on the Withdrawal Side of the Energy Curve

There are two options for schedule changes to accommodate a withdrawal in hour H, where H is some hour prior to the first optimally scheduled trough

1.) Withdraw then inject before the scheduled trough

$Rev^* = (P_1E - T_1 + \ldots)MW_T - (LBMP_H)\Delta MW_T + \max(LBMP_{H+1->HT-1})\Delta MW_P$

Where:

$LBMP_{H+1->HT-1}$ is the expected LBMP in each hour following hour H through the hour before the next scheduled trough (the max of these will represent the best opportunity to inject before the scheduled trough)

$LBMP_H$ is the expected LBMP in hour H*

ΔMW_T is the incremental amount of energy withdrawn*

ΔMW_P is the incremental amount of energy injected*

* note: these definitions will hold true for all examples to follow

$\Delta MW_P = \Delta MW_T E$

$Rev^* = (P_1E - T_1 + \ldots)MW_T + (-LBMP_H + \max(LBMP_{H+1->HT-1})E)\Delta MW_T$

To calculate the Opportunity Cost, set Rev = Rev*, replace $LBMP_H$ with the variable OC and solve for OC

$(P_1E - T_1 + \ldots)MW_T = (P_1E - T_1 + \ldots)MW_T + (-OC + \max(LBMP_{H+1->HT-1})E)\Delta MW_T$

$OC = \max(LBMP_{H+1->HT-1})E$

2.) Withdraw now instead of the next scheduled trough

$Rev^* = (P_1E - T_1 + \ldots)MW_T - (LBMP_H)\Delta MW_T + T_1\Delta MW_T$

set Rev = Rev*, replacing $LBMP_H$ with the variable OC and solve for OC

$(P_1E - T_1 + \ldots)MW_T = (P_1E - T_1 + \ldots)MW_T - (OC)\Delta MW_T + T_1\Delta MW_T$

$OC = T_1$

The true opportunity cost is the maximum OC from option 1 or 2

$OC = \max[\max(LBMP_{H+1->HT-1})*E, T_1]$

Opportunity Cost on the Injection Side of the Energy Curve

Due to our assumption of a minimum starting storage level, there is only one option for a schedule change to accommodate an injection in hour H, where H is some hour prior to the first optimally scheduled trough

1.) Inject by withdrawing in a prior hour

$Rev^* = (P_1E - T_1 + \ldots)MW_T + (LBMP_H)\Delta MW_P - \min(LBMP_{HB0\text{->}H-1})\Delta MW_T$

Where:

$LBMP_{HB0\text{->}H-1}$ is the expected LBMP in each hour from HB00 through the hour prior to hour H (the min of these LBMPs will represent the best opportunity to withdraw before hour H)

$\Delta MW_P = \Delta MW_T E$

$Rev^* = (P_1E - T_1 + \ldots)MW_T + ((LBMP_H)E - \min(LBMP_{HB0\text{->}H-1}))\Delta MW_T$

set Rev = Rev*, replacing $LBMP_H$ with the variable OC

$(P_1E - T_1 + \ldots)MW_T = (P_1E - T_1 + \ldots)MW_T + ((OC)E - \min(LBMP_{HB0\text{->}H-1}))\Delta MW_T$

$OC = \min(LBMP_{HB0\text{->}H-1})/E$

However, for HB 00:

There is no chance to withdraw prior to HB 00, but if the starting storage level is greater than the minimum level, there will need to be a price signal to determine what to do with those MWs.

Those MWs could be injected or they could be held and the unit would need to withdraw less at the optimally scheduled first trough and the tipping point for this decision is T_1/E

If the LBMP in HB 00 is less than T_1/E, then the most profitable decision is to hold those MWs and withdraw less during the first schedule trough

If the LBMP in HB 00 is greater than T_1/E, then the most profitable decision is to inject those MWs and withdraw back up during the first schedule trough

Using T_1/E as the opportunity cost for an incremental injection in HB 00 can result in a non-monotonically increasing energy cost curve, so the opportunity cost should be set to be the max of T_1/E and the opportunity cost on the withdrawal side plus a penny

$OC = \max[T_1/E, \max(\max(LBMP_{H+1\text{->}HT-1})*E, T_1) + .01]$

T_1/E will always be greater than T_1 therefore

$OC = \max[T_1/E, \max(LBMP_{H+1\text{->}HT-1})*E + .01]$

Hours After a Scheduled Trough and Before a Scheduled Peak

Opportunity Cost on the Withdrawal Side of the Energy Curve

There are two options for schedule changes to accommodate a withdrawal in hour H, where H is some hour after an optimally scheduled trough and prior to an optimally scheduled peak

1.) Withdraw after an unscheduled injection between hour H and previous scheduled trough

$Rev^* = (P_1E - T_1 + ...)MW_T - (LBMP_H)\Delta MW_T + \max(LBMP_{HT+1->H-1})\Delta MW_P$

Where:

$LBMP_{HT+1->H-1}$ is the expected LBMP in each hour following the previous scheduled trough through the hour prior to hour H (the max of these will represent the best opportunity to inject after the previous trough and before hour H)

set Rev = Rev*, replacing $LBMP_H$ with the variable OC

$\Delta MW_P = \Delta MW_TE$

$Rev^* = (P_1E - T_1 + ...)MW_T + (-LBMP_H + \max(LBMP_{HT+1->H-1})E)\Delta MW_T$

$(P_1E - T_1 + ...)MW_T = (P_1E - T_1 + ...)MW_T + (-OC + \max(LBMP_{HT+1->H-1})E)\Delta MW_T$

$OC = \max(LBMP_{HT+1->H-1})E$

2.) Withdraw now instead of the previous scheduled trough

$Rev^* = (P_1E - T_1 + ...)MW_T - (LBMP_H)\Delta MW_T + T_1\Delta MW_T$

set Rev = Rev*, replacing $LBMP_H$ with the variable OC

$(P_1E – T_1 + ...)MW_T = (P_1E - T_1 + ...)MW_T - (OC)\Delta MW_T + T_1\Delta MW_T$

$OC = T_1$

* In this example the OC is T_1, but the opportunity cost would be the LBMP in the previous scheduled trough, whether that be T_1, T_2, T_3, etc.

The actual opportunity cost is the maximum OC from option 1 or 2

$OC = \max[\max(LBMP_{HT+1->H-1})*E , T]$

Where:

T is the LBMP in the first scheduled trough prior to hour H

Opportunity Cost on the Injection Side of the Energy Curve

There are two options for schedule changes to accommodate an injection in hour H, where H is some hour after an optimally scheduled trough and prior to an optimally scheduled peak

1.) Inject and then withdraw before the next scheduled peak

$Rev^* = (P_1E - T_1 + \ldots)MW_T + (LBMP_H)\Delta MW_P - \min(LBMP_{H+1\text{->}HP-1})\Delta MW_T$

Where:

$LBMP_{H+1\text{->}HP-1}$ is the expected LBMP in each hour following hour H through the hour prior to the next scheduled peak (the min of these will represent the best opportunity to withdraw after hour H and before the next peak)

$\Delta MW_P = \Delta MW_T E$

$Rev^* = (P_1E - T_1 + \ldots)MW_T + ((LBMP_H)E - \min(LBMP_{H+1\text{->}HP-1}))\Delta MW_T$

set Rev = Rev*, replacing $LBMP_H$ with the variable OC

$(P_1E - T_1 + \ldots)MW_T = (P_1E - T_1 + \ldots)MW_T + ((OC)E - \min(LBMP_{H+1\text{->}HP-1}))\Delta MW_T$

$OC = \min(LBMP_{H+1\text{->}HP-1})/E$

2.) Inject now instead of the next scheduled peak

$Rev^* = (P_1E - T_1 + \ldots)MW_T + (LBMP_H)\Delta MW_P - P_1\Delta MW_P$

set Rev = Rev*, replacing $LBMP_H$ with the variable OC

$(P_1E - T_1 + \ldots)MW_T = (P_1E - T_1 + \ldots)MW_T + (OC)\Delta MW_P - P_1\Delta MW_P$

$OC = P_1$

* In this example the OC is P_1, but the opportunity cost would be the LBMP in the next scheduled peak, whether that be P_1, P_2, P_3, etc.

The actual opportunity cost is the minimum OC from option 1 or 2

$OC = \min[\ \min(LBMP_{H+1\text{->}HP-1})/E\ ,\ P\ ]$

Where:

P is the LBMP in the first scheduled peak after hour H

Hours After a Scheduled Peak and Before a Scheduled Trough

Opportunity Cost on the Withdrawal Side of the Energy Curve

There are two options for schedule changes to accommodate a withdrawal in hour H, where H is some hour after an optimally scheduled peak and prior to an optimally scheduled trough

1.) Withdraw then inject before the next scheduled trough

$Rev^* = (P_1E - T_1 + ...)MW_T - (LBMP_H)\Delta MW_T + \max(LBMP_{H+1->HT-1})\Delta MW_P$

Where:

$LBMP_{H+1->HT-1}$ is the expected LBMP in each hour following hour H through the hour before the next scheduled trough (the max of these will represent the best opportunity to inject after hour H and before the next scheduled trough)

$\Delta MW_P = \Delta MW_T E$

$Rev^* = (P_1E - T_1 + ...)MW_T + (-(LBMP_H) + \max(LBMP_{H+1->HT-1})E)\Delta MW_T$

set Rev = Rev*, replacing $LBMP_H$ with the variable OC

$(P_1E - T_1 + ...)MW_T = (P_1E - T_1 + ...)MW_T + (-(OC) + \max(LBMP_{H+1->HT-1})E)\Delta MW_T$

$OC = \max(LBMP_{H+1->HT-1})E$

2.) Withdraw now instead of the next scheduled trough

$Rev^* = (P_1E - T_1 + P_2E - T_2 + ...)MW_T - (LBMP_H)\Delta MW_T + T_2\Delta MW_T$

set Rev = Rev*, replacing $LBMP_H$ with the variable OC

$(P_1E - T_1 + P_2E - T_2 + ...)MW_T = (P_1E - T_1 + P_2E - T_2 + ...)MW_T - (OC)\Delta MW_T + T_2\Delta MW_T$

$OC = T_2$

* In this example the OC is T_2, but the opportunity cost would be the LBMP in the next scheduled trough, whether that be T_2, T_3, etc.

The actual opportunity cost is the maximum OC from option 1 or 2

$OC = \max[\max(LBMP_{H+1->HT-1})*E , T]$

Where:

T is the LBMP in the first scheduled trough after hour H

Opportunity Cost on the Injection Side of the Energy Curve

There are two options for schedule changes to accommodate an injection in hour H, where H is some hour after an optimally scheduled peak and prior to an optimally scheduled trough

1.) Inject by withdrawing in a prior hour

$Rev^* = (P_1E - T_1 + \ldots)MW_T + (LBMP_H)\Delta MW_P - \min(LBMP_{HP+1\text{->}H-1})\Delta MW_T$

Where:

$LBMP_{HP+1\text{->}H-1}$ is the expected LBMP in each hour following prior scheduled peak through the hour prior to hour H (the min of these will represent the best opportunity to withdraw after the previous scheduled peak and before hour H)

$\Delta MW_P = \Delta MW_T E$

$Rev^* = (P_1E - T_1 + \ldots)MW_T + ((LBMP_H)E - \min(LBMP_{HP+1\text{->}H-1}))\Delta MW_T$

set Rev = Rev*, replacing $LBMP_H$ with the variable OC

$(P_1E - T_1 + \ldots)MW_T = (P_1E - T_1 + \ldots)MW_T + ((OC)E - \min(LBMP_{HP+1\text{->}H-1}))\Delta MW_T$

$OC = \min(LBMP_{HP+1\text{->}H-1})/E$

2.) Inject now instead of the previous scheduled peak

$Rev^* = (P_1E - T_1 + \ldots)MW_T + (LBMP_H)\Delta MW_P - P_1\Delta MW_P$

set Rev = Rev*, replacing $LBMP_H$ with the variable OC

$(P_1 - T_1/E + \ldots)MW = (P_1E - T_1 + \ldots)MW_T + (OC)\Delta MW_P - P_1\Delta MW_P$

$OC = P_1$

* In this example the OC is P_1, but the opportunity cost would be the LBMP in the previous scheduled peak, whether that be P_1, P_2, P_3, etc.

The actual opportunity cost is the minimum OC from option 1 or 2

$OC = \min[\ \min(LBMP_{HP+1\text{->}H-1})/E\ ,\ P\ ]$

* as stated above, P is the LBMP in the last scheduled peak prior to hour H

Hours After Last Peak

Opportunity Cost on the Withdrawal Side of the Energy Curve

There is only one option for schedule changes to accommodate a withdrawal in hour H, where H is some hour after the last optimally scheduled peak

1.) Withdraw then inject before the end of the day

$Rev^* = (P_1E - T_1 + ...)MW_T - (LBMP_H)\Delta MW_T + \max(LBMP_{H+1->HB23})\Delta MW_P$

Where:

$LBMP_{H+1->HB23}$ is the expected LBMP in each hour following hour H through HB23 (the max of these will represent the best opportunity to inject before the end of the day)

$\Delta MW_P = \Delta MW_T E$

$Rev^* = (P_1E - T_1 + ...)MW_T + (-(LBMP_H) + \max(LBMP_{H+1->HB23})E)\Delta MW_T$

set Rev = Rev*, replacing $LBMP_H$ with the variable OC

$(P_1E - T_1 + ...)MW_T = (P_1E - T_1 + ...)MW_T + (-(OC) + \max(LBMP_{H+1->HB23})E)\Delta MW_T$

$OC = \max(LBMP_{H+1->HB23})*E$

However, for HB 23:

$OC = 0$

There is no chance to inject after HB 23, so any withdrawal at a price greater than zero would reduce the revenue for the day

This is due to the optimization period being a single day

If it was possible to look ahead to the next day, the price for the next expected trough could be used to determine the opportunity cost for this hour

Lacking that ability, an alternative to setting the opportunity cost to zero, could be setting the opportunity cost to the minimum LBMP expected during the current day. This would assume the minimum LBMP in the following day would be similar to the minimum LBMP in the current market day.

$OC = \min(LBMP_{HB00->HB23})$ – possible alternative

Opportunity Cost on the Injection Side of the Energy Curve

There are two options for schedule changes to accommodate an injection in hour H, where H is some hour after the last optimally scheduled peak

1.) Inject by withdrawing in a prior hour

$Rev^* = (P_1E - T_1 + \dots)MW_T + (LBMP_H)\Delta MW_P - \min(LBMP_{HP+1\text{->}H-1})\Delta MW_T$

Where:

$LBMP_{HP+1\text{->}H-1}$ is the expected LBMP in each hour following prior scheduled peak through the hour prior to hour H (the min of these LBMPs will represent the best opportunity to withdraw after the previous scheduled peak and before hour H)

$\Delta MW_P = \Delta MW_T E$

$Rev^* = (P_1E - T_1 + \dots)MW_T + ((LBMP_H)E - \min(LBMP_{HP+1\text{->}H-1}))\Delta MW_T$

set Rev = Rev*, replacing $LBMP_H$ with the variable OC

$(P_1E - T_1 + \dots)MW_T = (P_1E - T_1 + \dots)MW_T + ((OC)E - \min(LBMP_{HP+1\text{->}H-1}))\Delta MW_T$

$OC = \min(LBMP_{HP+1\text{->}H-1})/E$

2.) Inject now instead of the previous scheduled peak

$Rev^* = (P_1E - T_1 + \dots)MW_T + (LBMP_H)\Delta MW_P - P_1\Delta MW_P$

set Rev = Rev*, replacing $LBMP_H$ with the variable OC

$(P_1E - T_1 + \dots)MW_T = (P_1E - T_1 + \dots)MW_T + (OC)\Delta MW_P - P_1\Delta MW_P$

$OC = P_1$

* In this example the OC is P_1, but the opportunity cost would be the LBMP in the last scheduled peak, whether that be P_1, P_2, P_3, etc.

The actual opportunity cost is the minimum OC from option 1 or 2

$OC = \min[\ \min(LBMP_{HP+1\text{->}H-1})/E\ ,\ P\ ]$

Where:

P is the expected LBMP in the last scheduled peak

Scheduled Trough

Opportunity Cost on the Withdrawal Side of the Energy Curve

The unit is already scheduled to withdraw, but an opportunity cost that accounts for the unit's preference to withdraw in this hour while also making sure not to overpay for a withdrawal needs to be set

$OC = \min[\min(LBMP_{HP+1->H-1,\ H+1->HPP-1}),\ P*E\ ]$

Where:

$LBMP_{HP+1->H-1,\ H+1->HPP-1}$ is the expected LBMP in each hour following the prior scheduled peak (or starting at HB00 if no prior peak exists) through the hour prior to hour H and each hour following hour H through the hour prior to the next scheduled peak (the min of these will represent the next best opportunity to withdraw instead of the scheduled trough, should prices go higher than expected)

P is the expected LBMP in the next scheduled peak (P*E represents the max price that can be paid for a withdrawal in this hour without becoming unprofitable by injecting at the scheduled peak)

Opportunity Cost on the Injection Side of the Energy Curve

There are two options for schedule changes to accommodate an injection in hour H, where H is an optimally scheduled trough

1.) Inject by withdrawing in a prior hour and also withdraw in a following hour to meet the later scheduled injection

$$Rev^* = (P_1E - T_1 + \ldots)MW_T - \min(LBMP_{HP+1\text{->}H-1})\Delta MW_T + (LBMP_H)\Delta MW_P$$
$$- \min(LBMP_{H+1\text{->}HP-1})\Delta MW_T + T_1\Delta MW_T$$

Where:

$LBMP_{HP+1\text{->}H-1}$ is the expected LBMP in each hour following the prior scheduled peak (or starting at HB00 if no prior peak exists) through the hour prior to hour H (the min of these will represent the best opportunity to withdraw after the prior peak, or HB00, and before hour H)

$LBMP_{H+1\text{->}HP-1}$ is the expected LBMP in each hour following hour H through the hour prior to the next scheduled peak (the min of these will represent the best opportunity to withdraw after hour h and before the next scheduled peak)

$$\Delta MW_P = \Delta MW_T E$$

$$Rev^* = (P_1E - T_1 + \ldots)MW_T - \min(LBMP_{HP+1\text{->}H-1})\Delta MW_T + (LBMP_H)(E)\Delta MW_T$$
$$- \min(LBMP_{H+1\text{->}HP-1})\Delta MW_T + T_1\Delta MW_T$$

set Rev = Rev*, replacing $LBMP_H$ with the variable OC

$$(P_1E - T_1 + \ldots)MW_T = (P_1E - T_1 + \ldots)MW_T - \min(LBMP_{HP+1\text{->}H-1})\Delta MW_T + (OC)(E)\Delta MW_T$$
$$- \min(LBMP_{H+1\text{->}HP-1})\Delta MW_T + T_1\Delta MW_T$$

$$OC = \min(LBMP_{HP+1\text{->}H-1})/E + \min(LBMP_{H+1\text{->}HP-1})/E - T_1/E +$$

* In this example the OC uses T_1, but the opportunity cost should use the LBMP in whichever trough is being reviewed, whether that be T_1, T_2, T_3, etc.

2.) Inject now instead of a previous scheduled peak and withdraw in a following hour to meet the later scheduled injection

$$Rev^* = (P_1E - T_1 + P_2E - T_2 + \dots)MW_T - \min(LBMP_{H+1->HP-1})\Delta MW_T$$

$$+ (LBMP_H)\Delta MW_P + T_2\Delta MW_T - P_1\Delta MW_P$$

Where:

$LBMP_{H+1->HP-1}$ is the expected LBMP in each hour following hour H through the hour prior to the next scheduled peak (the min of these will represent the best opportunity to withdraw after hour h and before the next scheduled peak)

$$\Delta MW_P = \Delta MW_T E$$

$$Rev^* = (P_1E - T_1 + P_2E - T_2 + \dots)MW_T - \min(LBMP_{H+1->HP-1})\Delta MW_T$$

$$+ (LBMP_H)(E)\Delta MW_T - T_2\Delta MW_T - P_1(E)\Delta MW_T$$

set Rev = Rev*, replacing $LBMP_H$ with the variable OC

$$(P_1E - T_1 + P_2E - T_2 + \dots)MW = (P_1E - T_1 + P_2E - T_2 + \dots)MW_T - \min(LBMP_{H+1->HP-1})\Delta MW_T$$

$$+ (OC)(E)\Delta MW_T + T_2\Delta MW_T - P_1(E)\Delta MW_T$$

$$OC = \min(LBMP_{H+1->HP-1})/E - T_2/E + P_1$$

* In this example the OC is using T_2 and P_1, but the opportunity cost should use the LBMP of whichever trough is being reviewed, whether that be T_2, T_3, etc., and whichever peak preceded the trough being reviewed, P_1, P_2, etc.

The actual opportunity cost is the minimum OC from option 1 or 2

$OC = \min[\ \min(LBMP_{HP+1->H-1})/E + \min(LBMP_{H+1->HP-1})/E - T/E,\ \min(LBMP_{H+1->HP-1})/E - T/E + P\ ]$

Where:

T is the expected LBMP of the trough that is being reviewed

P is the expected LBMP in the peak that preceded the trough being reviewed

If we are looking at the first trough of the day, there is no prior peak so the formula would reduce to just option 1 above

$$OC = \min(LBMP_{HP+1->H-1})/E + \min(LBMP_{H+1->HP-1})/E - T/E$$

Scheduled Peak

Opportunity Cost on the Injection Side of the Energy Curve

The unit is already scheduled to inject, but an opportunity cost that accounts for the unit's preference to inject during this hour while also making sure not to offer too low needs to be set

OC = max[max($LBMP_{HT+1->H-1,\ H+1->HTT-1}$), T/E]

Where:

$LBMP_{HT+1->H-1,\ H+1->HTT-1}$ is the expected LBMP in each hour following the prior scheduled trough through the hour prior to hour H and each hour following hour H through the hour prior to the next scheduled trough (or HB23 if there is no next scheduled trough) (the max of these will represent the next best opportunity to inject instead of the scheduled peak, should prices go lower than expected)

T is the expected LBMP in the prior scheduled trough (T/E represents the minimum price that must be received for an injection in this hour without becoming unprofitable based on the prior scheduled withdrawal)

Opportunity Cost on the Withdrawal Side of the Energy Curve

There are two options for schedule changes to accommodate a withdrawal in hour H, where H is an optimally scheduled peak

1.) Withdraw by injecting in a prior hour and also inject in a following hour make the most profit on the withdrawal in this hour

$$Rev^* = (P_1E - T_1 + \ldots)MW_T + \max(LBMP_{HT+1\text{->}H-1})\Delta MW_P - (LBMP_H)\Delta MW_T + \max(LBMP_{H+1\text{->}HT-1})\Delta MW_P - P_1\Delta MW_p$$

Where:

$LBMP_{H+1\text{->}HT-1}$ is the expected LBMP in each hour following hour H through the hour prior to the next scheduled trough (or HB 23 if there is no next scheduled trough) (the max of these LBMPs will represent the best opportunity to inject after hour h and before the next scheduled trough, or HB23)

$LBMP_{HT+1\text{->}H-1}$ is the expected LBMP in each hour following the prior scheduled trough through the hour prior to hour H (the max of these LBMPs will represent the best opportunity to inject after the prior trough and before hour H)

$$\Delta MW_P = \Delta MW_T E$$

$$Rev^* = (P_1E - T_1 + \ldots)MW_T + \max(LBMP_{HT+1\text{->}H-1})(E)\Delta MW_T - (LBMP_H)\Delta MW_T + \max(LBMP_{H+1\text{->}HT-1})(E)\Delta MW_T - P_1(E)\Delta MW_T$$

set Rev = Rev*, replacing $LBMP_H$ with the variable OC

$$(P_1E - T_1 + \ldots)MW_T = (P_1E - T_1 + \ldots)MW_T + \max(LBMP_{HT+1\text{->}H-1})(E)\Delta MW_T - (OC)\Delta MW_T + \max(LBMP_{H+1\text{->}HT-1})(E)\Delta MW_T - P_1(E)\Delta MW_T$$

$$OC = (\max(LBMP_{HT+1\text{->}H-1}) + \max(LBMP_{H+1\text{->}HT-1}) - P_1)E$$

* In this example the OC uses P_1, but the opportunity cost should use the LBMP in whichever peak is being reviewed, whether that be P_1, P_2, P_3, etc.

2.) Withdraw now instead of the next scheduled trough and inject in a previous hour to make room for the withdrawal in this hour

$$Rev^* = (P_1E - T_1 + P_2E - T_2 \ldots.)MW_T + \max(LBMP_{HT+1\text{->}H-1})\Delta MW_P - (LBMP_H)\Delta MW_T$$
$$- P_1\Delta MW_p + T_2\Delta MW_T$$

Where:

$LBMP_{HT+1\text{->}H-1}$ is the expected LBMP in each hour following prior scheduled trough through the hour prior to hour H (the max of these LBMPs will represent the best opportunity to inject after the prior scheduled peak and before hour H)

$$\Delta MW_P = \Delta MW_T E$$

$$Rev^* = (P_1E - T_1 + P_2E - T_2 \ldots.)MW_T + \max(LBMP_{HT+1\text{->}H-1})(E)\Delta MW_T - (LBMP_H)\Delta MW_T$$
$$- P_1(E)\Delta MW_T + T_2\Delta MW_T$$

set Rev = Rev*, replacing $LBMP_H$ with the variable OC

$$(P_1E - T_1 + P_2E - T_2 + \ldots.)MW_T = (P_1E - T_1 + P_2E - T_2 \ldots.)MW_T - (OC)\Delta MW_T$$
$$+ \max(LBMP_{HT+1\text{->}H-1})(E)\Delta MW_T - P_1(E)\Delta MW_T + T_2\Delta MW_T$$

$$OC = \max(LBMP_{HT+1\text{->}H-1})E - P_1E + T_2$$

* In this example the OC is using P_1 and T_2, but the opportunity cost should use the LBMP of whichever peak is being review, whether that be P_1, P_2, etc., and whichever trough follows the peak being reviewed, T_2, T_3, etc.

The actual opportunity cost is the maximum OC from option 1 or 2

$OC = \max[\ (\max(LBMP_{HT+1\text{->}H-1}) + \max(LBMP_{H+1\text{->}HT-1}) - P\ )E\ ,\ \max(LBMP_{HT+1\text{->}H-1})E - PE + T\ ]$

Where:

P is the LBMP of the peak that is being reviewed

T is the LBMP in the trough that follows the peak being reviewed

If we are looking at the last peak of the day, there is no following trough so the formula would reduce to just option 1 above

$$OC = (-P_1 + \max(LBMP_{H+1\text{->}HT-1}) + \max(LBMP_{HT+1\text{->}H-1}))E$$

For Days with No Scheduled Troughs or Peaks

Opportunity Cost on the Withdrawal Side of the Energy Curve

The unit should be willing to withdraw if prices drop low enough that it could expect to make a profit in the remaining hours

$OC = max(LBMP_{H+1->HB23})*E$

Where:

$LBMP_{H+1->HB23}$ is the LBMP in each hour following hour H through the end of the day

However, as mentioned previously, for HB23

$OC = 0$

$OC = min(LBMP_{HB00->HB23})$ – possible alternative

Opportunity Cost on the Injection Side of the Energy Curve

The unit would be will to inject if prices went high enough that it could expect to make a profit on a withdrawal in a prior hour

$OC = min(LBMP_{HB00 -> H-1})/E$

Where:

$LBMP_{HB00->H-1}$ is the LBMP for hours HB00 through the hour prior to hour H

However, for HB 00

$OC = max(LBMP_{HB00 -> HB23})$

Where:

$LBMP_{HB00 -> HB23}$ is the LBMP for all hour hours of the day

If the unit did not start the day with the minimum storage level, it would be willing to inject any MWs it carried over as long as it would receive the highest expected price for the day