Emission Constrained Dispatch

Technical Documentation

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Introduction

Emission Constrained Dispatch is an bulk electric system dispatch technique which allows a specific BAA to limit the overall emissions allocated to it during a given dispatch interval. The method described here builds off the Resource Specific approach used by the CAISO in the EDAM to assign specific generators, or portions thereof, to be serving the load of the specific BAA. The Resource Specific approach, which is applicable to BAA's subject to a priced GHG program, determines the optimal dispatch solution by applying an additional cost of compliance called a GHG Adder, i.e., the cost of a CO_2 allowance times the generator's emission factor, to the bid price of generators assigned to serve the BAA. Emission constrained dispatch is applicable to BAA's that are subject to a non-priced GHG reduction program, i.e., are subject to a restriction on the amount of GHG emitted by the aggregate generation serving the load of the BAA over the course of the compliance period. Therefore, there is no GHG Adder since there is no requirement to purchase allowances, but the BAA must be able to demonstrate that during the compliance period the electricity generated to serve its load did not exceed the maximum allowed for the compliance period.

This technical document describes the necessary linear optimization factors required to implement emission constrained dispatch

Glossary

Balancing Area Authority (BAA)

The entity that is responsible for matching generation and load, responsible for maintaining scheduled interchange with other balancing authority areas, and that is responsible for maintaining the frequency in real-time, of the balancing area, i.e., the physical electrical infrastructure of a specific portion of an electric power system. In an RTO, the market operator functions as the BAA for the RTO footprint. In the EDAM/WEIM and Markets+/WEIS integrated markets, though, each member that was a BAA prior to joining the market, remains a separate BAA in the market.

California Independent System Operator (CAISO)

The entity which operates the RTO for about 80% of California, operates the WEIM in the West, and provides Reliability Coordination services in parts of the West. It is developing a day-ahead market offering called EDAM.

Day-Ahead Market (DAM)

A Day-Ahead Energy Market allows market participants commit to buy or sell wholesale electricity up to one day before the operating day, to help avoid price volatility. This market produces a financial settlement.

Dispatch Interval

The period for which the market operator will be running the linear optimization to produce a dispatch solution. In a DAM, a dispatch interval is typically one specific hour in the dispatch day. In a RTM, the dispatch interval will be a smaller unit of time to account for uncertainties. In the EDAM/WEIM, it is 5 minutes and 15 minutes. In Markets+/WEIS, it is proposed to be 5 minutes.

Economic Dispatch

A set of orders from the market operator to start, stop, ramp up or ramp down, the electricity generators comprising the market, based on the costs and other operational characteristics of the generators.

Emission Factor

For a generation resource, the rate at which GHG emissions are created expressed in metric tons per MWH.

Energy Imbalance Market

An organized wholesale electricity market comprised of several LSEs, electricity generators and a single market operator which economically dispatches generators to meet intra-hour deviations in electricity demand or supply in the RTM from what was forecasted in the DAM or base schedule.

Equality Constraint

See linear optimization.

Extended Day Ahead Market (EDAM)

The DAM being developed by CAISO.

Greenhouse Gases (GHG)

Gases that trap heat in the atmosphere. The EPA considers carbon dioxide (CO_2), methane (CH4), nitrous oxide (N2O) and fluorinated gases to be greenhouse gases of main concern.

GHG Adder

See GHG Marginal Price.

GHG Marginal Price

The marginal price associated with a constraint on GHG zones that determines which generation will serve the load of the priced GHG zone. In the case of priced GHG programs each generator must specify if it is willing to serve the GHG zone and what additional price (GHG Adder) it will require to do so. In the case of non-priced GHG programs, the GHG marginal price is associated with a limitation on how much GHG can be emitted by the generation chosen to serve the load of the non-priced GHG zone.

GHG Reduction Zone

The BAA(s) to which the State-Mandated Non-Priced GHG Reduction Program applies.

Inequality Constraint

See linear optimization.

Linear Optimization

A mathematical process which tries to produce a solution to a mathematical system consisting of several decision variables, an objective function, which is a linear expression involving the decision variables and set of linear constraints which limit the domains of the decision variables.

A constraint is a mathematical expression that looks like the following:

$$\text{LHS} \le \text{RHS} \quad \text{or} \quad \text{LHS} = \text{RHS}$$

where LHS (left-hand side) is a linear expression involving the decision variables, and RHS (right-hand side) is a constant numeric value. The first type of constraint is called an inequality constraint, the second an equality constraint. Note that if the constraint has the constant on the LHS, then we can easily put it on the RHS by multiplying across the constraint by -1, which also reverses the inequality. This is called the canonical form of the constraint*. The canonical form of the constraint is critical to giving the correct interpretation to a shadow price (see Shadow Price). Linear Optimization programs always rearrange the constraints into canonical form as the first step, making it unnecessary to specify the constraints in canonical form.

A solution is a set of values for the decision variables producing either an absolute minimum or absolute maximum value for the objective function, whichever has been specified for the Linear Optimization problem, while enforcing the constraints on the decision variables. A linear optimization that has no solution is called infeasible. Computers can quickly solve linear optimization problems with thousands of variables and constraints using the Simplex method. While a description of the Simplex method is beyond the scope of this document, a property of the Simplex method that is important to electricity markets is that it automatically produces shadow prices.

As used in this paper, linear optimization is the process by which the market operator arrives at a dispatch solution for the generators in the market. The decision variables are the generators and the primary transmission paths of the grid containing the generators and the LSEs. There can be many constraints, however primary constraints include maximum and minimum generation levels for each generator, ramping rates for generators, maximum transfer capacity on all transmission pathways, and power balance constraints. The objective function is the system production cost which the linear optimization seeks to minimize. The shadow prices of the power balance constraint are the energy marginal costs for the system. In some cases, a component of a market dispatch solution can require non-linear optimization. For example, this is proposed in Markets+. Non-linear optimization must use other methods to produce a solution and these methods do not create shadow prices. In this paper, we will notaddress non-linear optimization.

*Technically, this is not quite the canonical form. The canonical form also replaces every inequality constraint with an equality constraint by adding a “slack variable” to the LHS. However, this detail is not necessary for this document, so we will allow use of the term “canonical form” to include an inequality.

Locational Marginal Price

The sum of all marginal prices produced by the constraints in effect at a particular location in the market, as well as some other price factors. Typically, this would include the energy marginal price, the GHG marginal price (if it exists in the market), congestion marginal price as well as costs not based on marginal price such as transmission losses.

Marginal Price or Energy Marginal Price

In the context of this paper, we are primarily concerned with (i) the shadow price of the power balance constraint, i.e., the increase in the system production cost caused by increasing the right-side of the power balance constraint - the load - by 1 MWH; and (ii) the GHG marginal price. In North American electricity markets, a single market-wide energy marginal price is awarded to all dispatched generators. This is how the WEIM proposes to pay generators. In EDAM, however, the power balance constraints will be imposed on all BAAs, not on the whole market, which means that each BAA will have a marginal price associated with it, although these BAA marginal prices may be the same in many cases.

Power Balance Constraint

In the linear optimization run by the market operator to derive a dispatch solution, a power balance constraint ensures that in any dispatch interval, the generation that is dispatched in a BAA plus the imported power, minus the exported power is equal to the BAA's load, therefore fulfilling the BAA's obligation that load and generation are always matched. In the Markets+ integrated market, it is currently proposed that there be one power balance constraint for the entire market, even though the market will consist of multiple BAAs. In the case of the EDAM/WEIM integrated market, each BAA will have a power balance constraint associated with it.

Real-Time Market (RTM)

A Real-Time Market lets market participants buy and sell wholesale electricity during the operating day. The RTM balances the differences between DAM commitments and the actual real-time demand for and production of electricity. The RTM produces a separate, second financial settlement. It establishes the real-time LMP that is either paid or charged to participants in the DAM for demand or generation that deviates from the DAM commitments.

Shadow Price

In a linear optimization, every constraint has an associated shadow price, which is the change in the objective function value if the RHS of the constraint is increased by 1 unit. This definition of shadow price requires the constraint to be in canonical form (see Linear Optimization). For example, the shadow price of the power balance constraint is the cost to the system if the load were increased by 1 MWH. If the shadow price is non-zero, then the constraint is said to be binding. By its nature, an equality constraint is always binding. If an inequality constraint is non-binding, it means there was sufficient slack in the dispatch solution to allow the constraint to be increased by 1 unit without any additional cost. In theoretical mathematics, this change in objective function value is called a Lagrangian multiplier, though in economics the term shadow price is preferred. In the context of electricity markets, the shadow prices of various constraints produce the energy marginal price, the GHG marginal price (if present in the market), the congestion marginal price and possibly others.

State-Mandated Non-Priced GHG Reduction Program (non-priced GHG reduction program)

A program mandated and administered by the state under which certain electric companies must reduce the GHG emissions from electricity generation to meet the customer load. The program establishes levels of reduction which increase over time, or equivalently, maximum levels of emissions which decline over time. There is no explicit price attached to a quantity of GHG. In the context of this paper, an RPS is not considered to be a non-priced GHG program.

State-Mandated Priced GHG Reduction Program (priced GHG program).

A program mandated and administered by the state which establishes a price for an allowance (i.e., a permit) to emit a certain quantity of GHG (e.g., a metric ton) and a system within which allowances can be purchased by entities that emit GHG. When the entity performs the action which creates the emission, in this case the generation of electricity, the entity must surrender an equivalent number of allowances which are expired by the state administrating agency. Over time, the number of allowances made available by the state are reduced. In the US, the cap-and-trade systems of Washington, California and the states which are members of the Regional Greenhouse Gas Initiative are examples of state-mandate priced GHG reduction programs, Carbon tax programs, not currently used in the US, would also be an example.

System Production Cost

The total cost of the dispatch solution in the dispatch interval, i.e., the sum of each generator’s dispatch (MWH) times that generator’s offered price ($ per MWH), plus any other costs imposed by the dispatch, such as transfers between BAAs, or GHG adders.

Western Energy Imbalance Market (WEIM)

CAISO’s electricity imbalance market product.

Elements of Emission Constrained Dispatch

Notation

BAAs are denoted with the indices “j” and “k”.
$\mathcal{B}$ is the index set of the BAAs in the market.

J is the cardinality of $\mathcal{B}$, i.e., the number of BAAs in the market.

$\mathcal{B}_j$ denotes the index set of BAAs excluding j, i.e., {0,...,j-1,j+1,...,J}

B_j denotes the j^{th} BAA, where $j \in \mathcal{B}$.

B_0 denotes the GHG reduction zone.

Generators are denoted with the index “i”.
$\mathcal{G}$ denotes the index set of generators in the market.

N is the cardinality of $\mathcal{G}$, i.e., the number of generators in the market.

$\mathcal{G}_j$ denotes the index set of generators located in B_j , $j \in \mathcal{B}$

G_i denotes generator i for $i \in \mathcal{G}$

$\mathcal{G}_0$ is the index set of the generators located in B_0, the GHG reduction zone.

$\mathcal{G}_X$ is the index set of the generators located outside of the GHG reduction zone.

Note:

$\mathcal{G} = \cup_{j \in \mathcal{B}} \mathcal{G}_j = \mathcal{G}_0 \cup \mathcal{G}_X$

LMP_j is the locational marginal price for B_j.
GHGMP is the GHG marginal price.

Input Variables

The input variables for emission constrained dispatch are the generation and transmission characteristics, the BAA loads within the market and specified emissions maximum for the GHG reduction zone.

Generator Characteristics

$\forall\ i \in \mathcal{G}$:

1. Maximum MWH offer (DMax_i)
2. Offer price expressed as dollars/MWH (p_i)
3. Emission factor expressed as tonnes/MWH (e_i)

Note: in practice, these characteristics would be expressed as nomograms expressing the change in characteristic depending upon the generation output level and the ramping capability. In this document, for simplicity, generators will be characterized by a single set of characteristics.

Transmission Characteristics

$\forall\ j,k \in \mathcal{B}$

1. Maximum MWH transfer capability in the direction of B_j to B_k ($\text{TMax}_{j,k}$).
2. The price of transfers from B_j to B_k in \$/MWH ($t_{j,k}$). For purposes of this document, we have assumed that $t_{j,k}$ = \$0.001.

Load Characteristics

$\forall\ j \in \mathcal{B}$

1. The projected load of B_j in the market (L_j).

Emission Maximum for the GHG Reduction Zone

1. Maximum emission expressed as either an emission factor (tonnes/MWH) or as an absolute tonnage for the dispatch interval. In this document, we will refer to it as an emission factor (EFMax). The conversion to an absolute tonnage is EFMax * L_0.

Decision Variables

1. $\forall\ i \in \mathcal{G}$, $\boldsymbol{D_i}$ is the instructed dispatch level for G_i.
2. $\forall\ i \in \mathcal{G}_X$, $\boldsymbol{A_i}$ is the amount of dispatch for G_i that is assigned to B_0.
3. $\forall\ j,k \in \mathcal{B}$, $\boldsymbol{T_{jk}}$ is the amount of transfer from B_j to B_k.

Objective Function

The objective function to be minimized is:

$$[\sum_{i\in\mathcal{G}} p_i * \boldsymbol{D_i}] + 0.001*[\sum_{i\in\mathcal{G}_X} \boldsymbol{A_i}] + [\sum_{j\neq k\in\mathcal{B}} t_{j,k} * \boldsymbol{T_{j,k}}]$$

The price associated with the assignment of external generation to the GHG reduction zone is set to \$0.001/MWH. This forces the linear optimization to optimize these decision variables, even though there is no cost associated with the assignment of generation to the GHG reduction zone. Linear optimization programs (generally) ignore variables that are not utilized in the objective function.

Constraints

Inequality Constraints

1. $\forall\ i \in \mathcal{G},\ 0 \leq \mathbf{D}_i \leq \text{DMax}_i$

The instructed dispatch of each generator must be non-negative and may not exceed the maximum offered.

2. $\forall\ j,k \in \mathcal{B}, j\neq k,\ 0 \leq \boldsymbol{T}_{j,k} \leq \text{TMax}_{j,k}$

All transfers between BAAs must be non-negative. Transmission thermal limits must be enforced.

3. $\forall\ i \in \mathcal{G}_X,\ 0 \leq \boldsymbol{A}_i \leq \mathbf{D}_i$

For all external generators, the assigned amount to the GHG reduction zone, B_0,must be npon-negative and cannot exceed the dispatched amount.

4. $\forall\ j \in \mathcal{B}, j\neq 0, [\sum_{i\in\mathcal{G}_j} \boldsymbol{A}_i] \leq \boldsymbol{T}_{j,0} - \boldsymbol{T}_{0,j}$

For every BAA, B_j, not B_0, the amount assigned to B_0 cannot exceed the net transfers into B_0 from B_j.

5. $L_0 \leq [\sum_{i\in G_0} \boldsymbol{D}_i] + [\sum_{i\in\mathcal{G}_X} \boldsymbol{A_i}]$

The amount of generation from resources in B_0 plus the amount assigned to B_0 from the external resources must be at least equal to the load of B_0. Note that this implies that if a generator in B_0 is dispatched, the generator's energy and associated emissions will be assigned to B_0. If there are multi-owner or multi-jurisdictional resources in B_0, then modifications (not covered in this document) can be made to designate portions of those resources which are to be assigned to B_0 which can be exported to other BAAs.

6. $[\sum_{i \in G_0} e_i * \boldsymbol{D}_i] + [\sum_{i \in \mathcal{G}_X} e_i * \boldsymbol{A_i}] \leq$ EFMax * L_0

The emissions from resources in B_0 plus the emissions from generation assigned to B_0 from the external resources must not exceed the maximum emissions set for the dispatch interval.

Equality Constraints

7.1 through 7.J,

$\forall$ j $\in \mathcal{B}$, the power balance constraint for B_j is:

$[\sum_{i \in \mathcal{G}_j} \boldsymbol{D}_i] + \sum_{k \in \mathcal{B}_j} (\boldsymbol{T}_{k,j} - \boldsymbol{T}_{j,k}) = L_j$

The dispatched generation within B_j plus imports into B_j, minus exports from B_j, must equal the load of B_j.

Notes on Marginal Prices

1. GHG Marginal Price

The GHG Marginal Price is -1 times the shadow price of constraint 5. Note that the shadow price will be negative or zero, so we multiply it by -1 to form the GHG Marginal Price.

The reason this specific shadow price is negative is because the constraint, as written, is not in canonical form since the constant is on the LHS. Putting it in canonical form, the constraint would look like the following (which is not very intuitive and is why the constraint was not written this way in the previous text):

$-[\sum_{i \in G_0} \boldsymbol{D}_i] - [\sum_{i \in \mathcal{G}_X} \boldsymbol{A_i}] \leq -L_0$

Therefore, increasing the RHS by 1 actually reduces the load of the GHG reduction zone by 1 MWH, which is a relaxation of the constraint and causes the objective function to decrease, making the shadow price a negative number.

The GHG Marginal Price is non-zero if and only if the emission constraint binds. Since the GHG reduction zone has an obligation to offer a portfolio of generation than can meet the maximum emission rate, we might expect that the constraint very often would not bind, except generally when conditions are tight in the market.

An interpretation of the GHG Marginal Price is that it is the premium above the commodity price of electricity that is created by the additional non-commodity constraint on electricity for the GHG Reduction Zone. The commodity price of electricity is reflected in the Energy Marginal Price.

2. Energy Marginal Prices

The shadow prices of the power balance constraints (7.1 through 7.J) are the Energy Marginal Prices for each BAA. Note that the power balance constraints are in canonical form. Increasing the RHS by 1

MWH tightens the constraint, causing the objective function to increase. Hence the shadow prices are always positive values. As noted previously, the Energy Marginal Price represents the pure economic commodity price of electricity without other characteristics layered on it, e.g., GHG content.

3. CO_2 Marginal Price

The shadow price of constraint 6 is called the CO_2 Marginal Price. The constraint is in canonical form, however the shadow price is negative or zero. This is because increasing the RHS by one unit, i.e., allowing one more tonne of CO_2 to be emitted, is a relaxation of the constraint with a less expensive solution. Hence, the negative shadow price.

The CO_2 Marginal Price is not used for settlement in the Emission Constrained Dispatch approach. An interpretation of the CO_2 Marginal Price is that it is a proxy Allowance Price on a tonne of CO_2 that corresponds to the emission constraint placed on the dispatch.

Therefore, the CO_2 Marginal Price is informative as a yardstick measurement against Allowance Prices established through cap-and-trade auctions.

Like the GHG Marginal Price, the CO_2 Marginal Price is non-zero if and only if the emission constraint binds.

Settlement

1. $\forall j \in \mathcal{B},\ j \neq 0,\ LP_j = $ payment by $B_j = L_j * LMP_j$,
2. $LP_0 = $ payment by $B_0 = L_0 * (LMP_0 + GHGMP)$
3. $\forall i \in \mathcal{G}_0$, $GP_i = $ payment to $G_i = D_i * (LMP_0 + GHGMP)$
4. $\forall i \in \mathcal{G}_X$, $GP_i = $ payment to $G_i = D_i * LMP_i + A_i * GHGMP$

Differences between Emission Constrained Dispatch and the Resource Specific Approach

The Emission Constrained Dispatch approach builds off the Resource Specific approach by adding one additional constraint, #6. Additionally, the objective function does not apply a GHG adder to the generation assigned to the GHG reduction zone, since there is no allowance cost required for the emission of a tonne of CO_2. Instead, a nominal cost ($0.001) is applied to all generation assigned to the GHG reduction zone from external resources in order to force the linear optimization to use the assignment variables.

In all other respects, including settlement, the two approaches are the same.

Applicability to LSEs Which Are Not BAAs

The non-priced GHG programs in the western states are load-based, in the sense that they apply to the generation used to meet a specific load. The Emission Constrained Dispatch approach discussed in this technical document is implemented over a BAA. There may be instances where the applicable LSE is not the entire BAA.

In this case, the Emission Constrained Dispatch approach can still be implemented as the BAA level, subject to a relatively straightforward agreement between the LSEs within the BAA on how the energy and associated emissions will be apportioned to the LSEs within the BAA on a post-dispatch basis.