Advancing Zero Emissions Objectives through PJM's Energy Markets: **A Review of Carbon-Pricing Frameworks**

August 23, 2017

Introduction

PJM Interconnection believes market design can advance state policy initiatives and adapt to changing conditions to ensure the PJM region continues to reap the benefits of competitive markets. To address the desire of some states to subsidize supply resources to meet carbon-reduction initiatives, this paper explores how all or a subregion of PJM could affix a price on carbon that could be reflected in wholesale energy market prices. Specifically, we examine how regional and subregional carbon pricing could be implemented in the region PJM serves.

It is important to reiterate that a regional approach is preferred; however, PJM recognizes that a single perspective on carbon is not shared among the states comprising the PJM footprint. Accordingly, PJM believes a coordinated carbon policy could be advanced through the PJM markets by a sub-group of states prepared to adopt a common set of business rules that:

- Enable state policies that limit carbon emissions through a carbon price
- Preserve orderly and competitive economic dispatch across the *entire* PJM footprint
- Minimize, to the extent possible, the impacts of the subregion's policy choices on non-participating states, and vice-versa

Elements of a Carbon-Pricing Framework

A carbon-pricing framework would use an established price per ton of carbon emissions. Whether the framework is regional or subregional, the carbon price would:

- Apply to carbon-emitting suppliers on a per-ton basis and be reflected in offers
- Be revealed in wholesale market prices in the participating region or subregion
- Align with economic dispatch
- Improve the relative competitiveness of lower-emitting resources, including those that do not emit carbon

In addition, the framework would minimize emissions leakage, which is an issue for any subregional environmental regulation such as the Regional Greenhouse Gas Initiative (RGGI). Emissions leakage occurs when fossil fuel-based electricity from resources outside the carbon price region that is not subject to carbon costs is imported into the carbon price region or when exports from the carbon price region cease, causing the non-carbon price region to have to replace the energy. Establishing a carbon-pricing framework that is coordinated with PJM market constructs could more directly address emissions leakage and enhance the policy goals of states that adopt a carbon-pricing framework, while minimizing the impacts to those states that do not. However, in cases where resources in the participating subregion are being used to serve load outside it, the compliance costs reflected in a resource's offer may affect prices across the entire region because of the nature of the regional dispatch. As a result, subjecting supply resources to a carbon cost, whether regional or subregional, can affect prices across the entire region.

In this paper, PJM examines two potential carbon-pricing frameworks that could be used to achieve these objectives and discusses some of the advantages and disadvantages of each. RGGI could coexist with both of these frameworks. The approaches described here are an enhancement to a RGGI-like program because they address the emissions leakage issue.

Regional Carbon-Pricing Framework

A regional carbon-pricing framework would depend on the willingness of all states within the PJM footprint to agree to take policy action. Application of a uniform carbon price across all states in the PJM footprint is the most efficient and cost-effective implementation, as this framework would continue to capitalize on the economies of scale created by the size and diversity of resources within the PJM footprint.

More specifically, a regional carbon-pricing framework would:

- Use the current market design
- Treat all resources equitably with no differences within the PJM footprint
- Align with economic dispatch
- Eliminate emissions leakage concerns within the PJM footprint (these challenges would still need to be addressed to a lesser extent for energy transfers to and from regions outside of PJM)

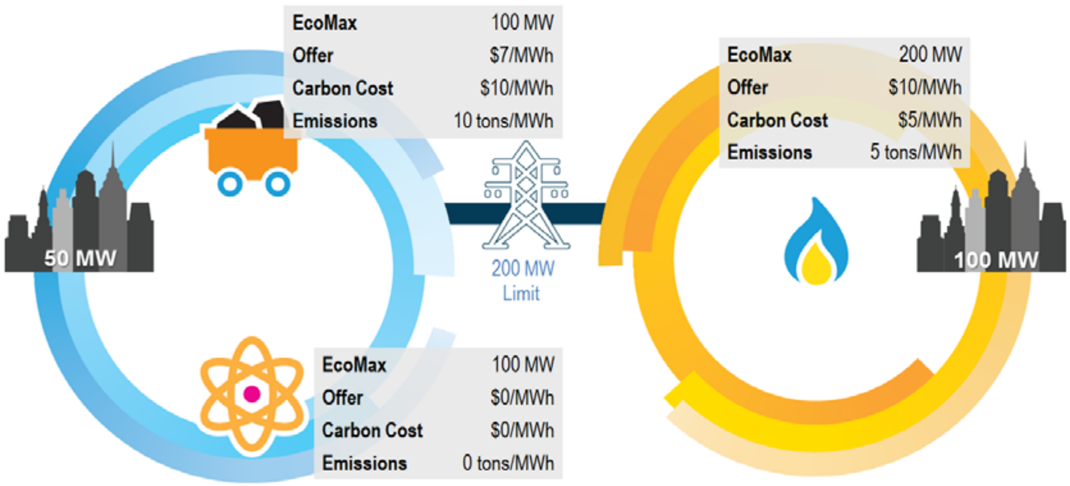
The PJM Energy Market already contains provisions recognizing that additional emission costs may be included in cost-based energy offers. Per PJM Manual 15: Cost Development Guidelines,[1] SO_2, CO_2 and NO_x allowance costs may, of course, be factored into a seller's price-based offer, and can also be included in the total fuel-related cost used to develop the cost-based offer. If all supply resources included these emission costs in their offers then energy prices within the PJM region would reflect the cost of carbon emissions.

[1] See PJM Manual 15: Cost Development Guidelines at http://www.pjm.com/~/media/documents/manuals/m15.ashx for more information.

Regional Carbon-Pricing Example

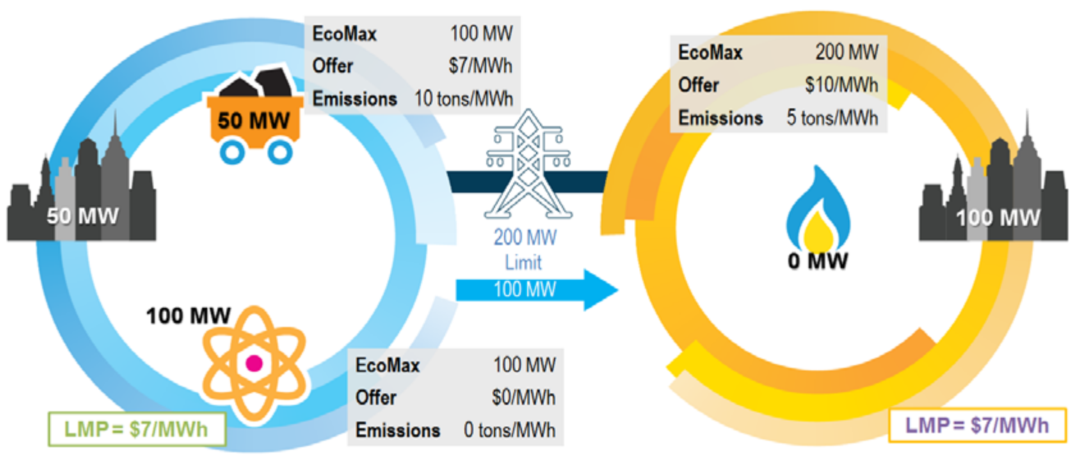
An example of the implementation of a regional carbon-pricing framework is shown in the figures below. **Figure 1** shows a simple two-node system. **Figure 2** shows the system dispatch without carbon costs included in each supply resource's offer, and **Figure 3** shows the system dispatch with carbon costs included. For the purposes of this example, the cost of carbon is set at $1 per ton. Therefore, a resource that emits 10 tons/MWh would have an effective carbon cost of $10/MWh ($1/ton x 10 tons/MWh = $10/MWh).

Figure 1. Two-Node System



In the two-node system, there are three supply resources.[2] In the left node, there is a coal unit and a nuclear unit, each with a 100 MW economic maximum and 50 MW of load. In the right node, there is a natural gas unit with a 200 MW economic maximum and 100 MW of load. Between the two nodes runs a transmission line with a limit of 200 MW.

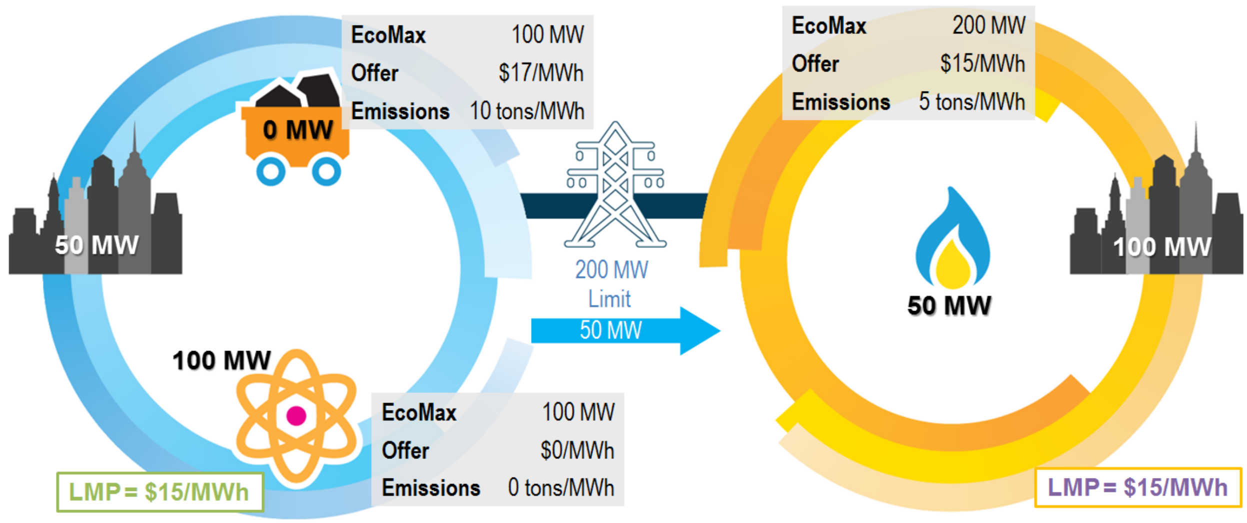
Figure 2. Two-Node System Dispatch without Carbon Costs



[2] Note: the example is for illustrative purposes only and would hold true for other resource types with similar parameters (e.g. offer price and emissions).

Figure 2 shows the system dispatch ignoring carbon costs. In this scenario, the coal and nuclear units are the most cost-effective resources and are therefore dispatched to serve the entire system's 150 MW of load at an LMP of $7/MWh. The LMP of $7/MWh is set by the coal resource because it would be dispatched to 51 MW if another 1 MW of load needed to be served. The transmission line connecting the two nodes is flowing 100 MW, which falls below the limit of 200 MW and consequently is not binding.

Figure 3. Two-Node System Dispatch with Carbon Costs



In **Figure 3**, carbon costs are included in the system dispatch. The inclusion of these costs increases the offer of the coal unit to $17/MWh and increases the offer of the natural gas unit to $15/MWh. The nuclear unit has zero emissions, and so has the same offer of $0/MWh as in **Figure 2**. Due to the inclusion of carbon compliance costs, the natural gas unit is now less expensive than the coal unit is and is dispatched to 50 MW. The coal unit is now dispatched to 0 MW. The nuclear unit's dispatch is unchanged as it is still at its economic maximum of 100 MW.

Because the natural gas unit is dispatched to meet the remaining system load, it is marginal. Since the transmission constraint between the nodes is not binding, the natural gas unit sets the system-wide LMP at $15/MWh.

Comparison with and without Carbon Costs

Comparing the two cases in **Table 1** shows that including carbon costs in each resource's supply offer results in a decrease in total emissions by shifting generation away from the higher-emitting coal unit to the lower-emitting natural gas unit.

Table 1. **Two-Node System Dispatch with and without Carbon Costs**

Unit Type	Offer without Carbon Costs ($/MWh)	Dispatch without Carbon Costs (MW)	Emissions without Carbon Costs (tons)	Offer with Carbon Costs ($/MWh)	Dispatch with Carbon Costs (MW)	Emissions with Carbon Costs (tons)
Nuclear	0	100	0	0	100	0
Coal	7	50	500	17	0	0
Natural Gas	10	0	0	15	50	250

Subregional Carbon-Pricing Framework

While a regional carbon-pricing framework is preferred because it maximizes market efficiency, PJM recognizes the challenge of having all states within the PJM footprint agree to take such policy action. Accordingly, PJM believes that a coordinated carbon policy could be advanced through the PJM markets by a sub-group of states prepared to adopt a common carbon-pricing framework. Such a framework would create two subregions, one with a carbon price and one without a carbon price, similar to the framework described in the California Independent System Operator's (CAISO) Energy Imbalance Market Final Proposal,[3] upon which this framework is based. In order to avoid significant complexity and potential implementation challenges, a single carbon price is required across the entire carbon price subregion.

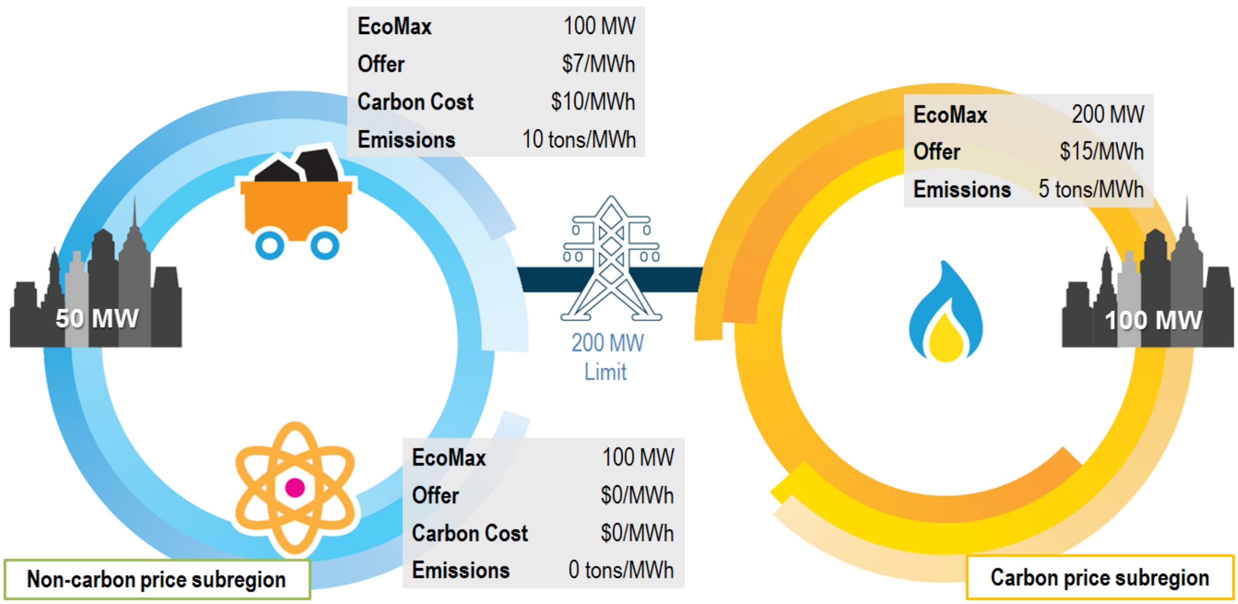
Subregional Carbon-Pricing Framework Overview

The subregional carbon-pricing framework is characterized by a carbon price subregion that includes states that have elected to implement a uniform carbon price and a non-carbon price subregion where no such policy action has been adopted. In the carbon price subregion, each supply resource incorporates its carbon compliance costs into its energy offer. In the non-carbon price subregion, each supply resource submits its normal energy offer and additionally submits what its carbon compliance costs would be if it were located in the carbon price subregion. The carbon compliance cost offer reflects the supplier's carbon compliance costs for energy that is dispatched to serve load in the carbon price subregion. This information is needed to ensure that any energy imports into the carbon price subregion include the cost of complying with the carbon price subregion's standards. Because the carbon compliance costs for resources outside the carbon price subregion are considered when they are being dispatched to serve load within the carbon price subregion, emissions leakage is minimized, since these resources, although outside the carbon price subregion, would appear more expensive when considered to meet the carbon price subregion's load.

[3] See CAISO's EIM Greenhouse Gas Enhancement Revised Draft Final Proposal at https://www.caiso.com/Documents/RevisedDraftFinalProposal-EnergyImbalanceMarketGreenhouseGasEnhancements.pdf for more information.

Figure 4 shows an example of the two-node system from **Figure 1** in which each supply resource's energy offer in the carbon price subregion includes carbon compliance costs and each supply resource's offer in the non-carbon price subregion includes a separate carbon compliance cost offer.

Figure 4. Two-Node Subregion System



In order to determine the economic dispatch for the subregional carbon-pricing framework, either a one-pass or a two-pass optimization process can be implemented. Both methods are described below.

One-Pass Optimization

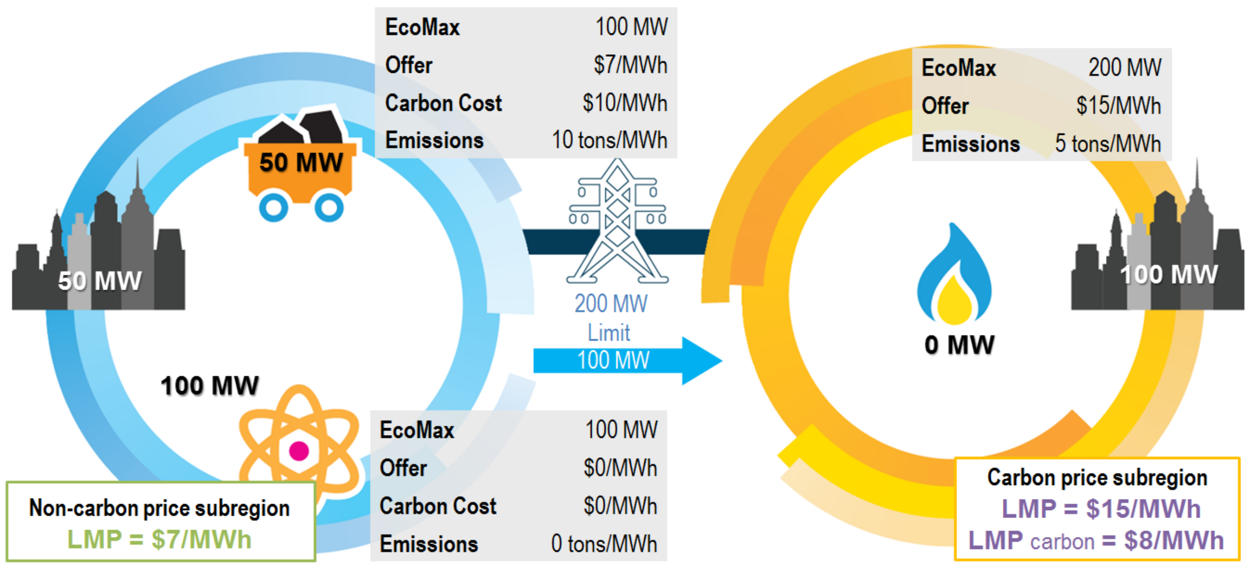
In the one-pass optimization process, all resources are dispatched economically based on their total submitted offer. In order to account for the carbon compliance costs for energy dispatched from the non-carbon price subregion to the carbon price subregion, a carbon price subregion import constraint is added to the optimization. The shadow price of this constraint is the marginal carbon compliance cost and determines the carbon component of the LMP. If there are net imports into the carbon price subregion, the import constraint will bind, there will be a non-zero shadow price and the LMP in the carbon price subregion will increase due to the carbon compliance costs. Load and supply resources in the carbon price subregion pay and are paid, respectively, the LMP for the carbon price subregion. Conversely, if there are net exports from the carbon price subregion to the non-carbon price subregion, then the constraint will not bind, the shadow price will be zero, and the carbon component of the LMP will be zero.

As described in CAISO's proposal, supply resources in the non-carbon price subregion that are dispatched to provide energy to the carbon price subregion are paid the carbon component of LMP. This is done to ensure that those resources, although outside the carbon price subregion, can recover their carbon compliance costs. In CAISO, all imports into the carbon price subregion are charged carbon compliance costs. The revenue to compensate these resources comes (via the LMP including the carbon component) from the money collected from load within the carbon price subregion. As a result, the CAISO model is revenue neutral with respect to carbon costs.

Although in the CAISO framework all imports into the carbon price subregion are charged carbon compliance costs and resources importing energy into the carbon price subregion are paid the carbon component of LMP, this is not required. Other frameworks could be adopted in which the surplus revenue collected from load inside the carbon price subregion is used differently.

The one-pass optimization dispatch solution shown in **Figure 4** for the two-node subregion system is shown in **Figure 5**.[4]

Figure 5. One-Pass Optimization Dispatch Results for Two-Node Subregion System



In **Figure 5**, 100 MW from the nuclear unit is attributed as supporting imports into the carbon price subregion. However, because the nuclear unit is dispatched at its economic maximum, it cannot serve the next 1 MW of load in the carbon price subregion. The next-least-expensive resource that can serve the remaining load in the non-carbon price subregion is the coal unit, with an offer of $7/MWh, which sets the LMP. The natural gas unit, with an offer of $15/MWh, would be used to serve the next 1 MW of load in the carbon price subregion, and therefore sets the LMP for that subregion at $15/MWh. The carbon component of the LMP in the carbon price subregion is $8/MWh, which is the additional cost to serve the next increment of load in the carbon price subregion due to the carbon import constraint. With a carbon component of the LMP of $8/MWh, the nuclear unit receives a carbon award of $800, since it is supporting 100 MW of imports into the carbon price subregion.

Two-Pass Optimization

In the two-pass optimization process, the first optimization pass determines the base schedules in the non-carbon price subregion by solving the economic dispatch problem while not allowing any net imports into the carbon price subregion. In the second optimization pass, the economic dispatch of all supply resources is determined while allowing net imports into the carbon price subregion. However, the net imports into the carbon price subregion are

[4] Note: actual system outcomes could vary depending on many factors including the resource mix in each subregion, congestion, etc.

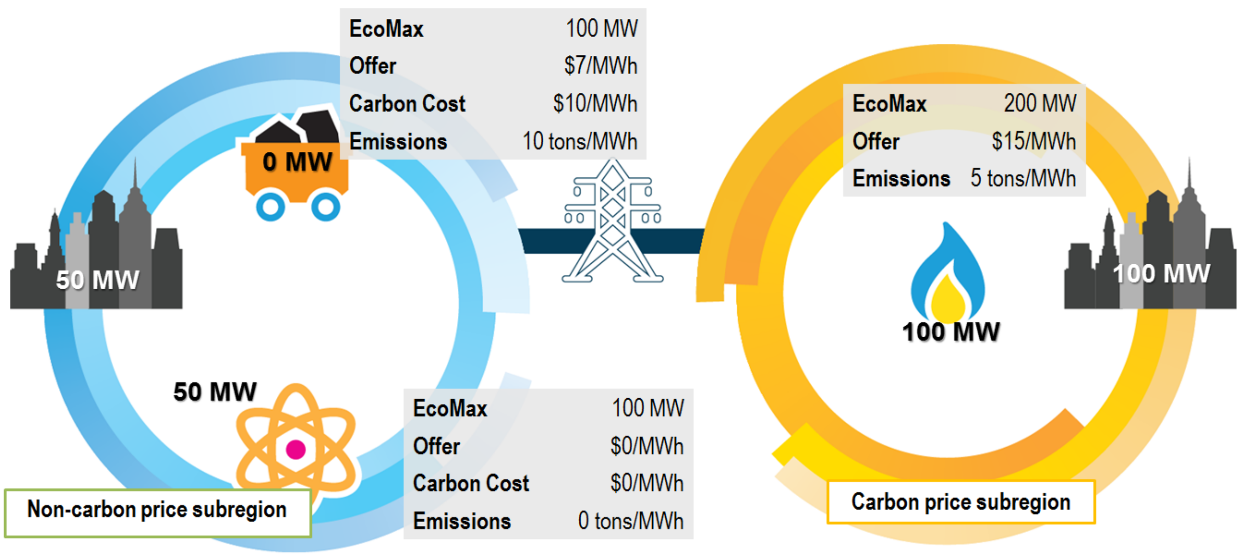
limited by the incremental dispatch above each unit's base schedule as determined in the first optimization pass. If there are no net imports, or if there are net exports from the carbon price subregion, the carbon price subregion import constraint does not bind and therefore the carbon component of LMP is zero.

One of the primary benefits of the two-pass optimization process is that it minimizes the backfill of low-emitting resources in the non-carbon price subregion dispatched to serve load in the carbon price subregion with high-emitting resources. This benefit is consistent with the objective to minimize the impacts of the carbon price subregion's policy choices on non-participating subregions. For this reason, in addition to others, CAISO has started working on implementing the two-pass optimization framework.

First Optimization Pass

The first optimization pass determines the base schedule for each supply resource in the non-carbon price subregion, while not allowing net imports into the carbon price subregion. However, net imports into the non-carbon price subregion are allowed. **Figure 6** shows the results of the first optimization pass for the example shown in **Figure 4**.

Figure 6. First Optimization Pass Dispatch Results for Two-Pass Process in Two-Node Subregion System



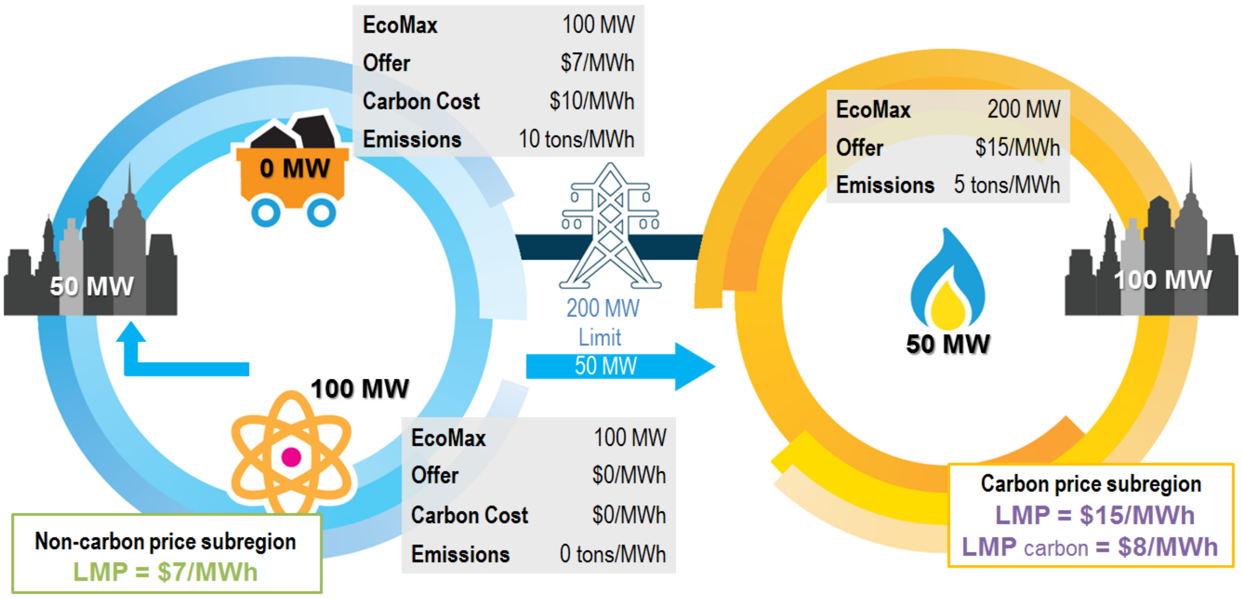
In the first optimization pass, 50 MW from the nuclear unit is dispatched to serve load in the non-carbon price subregion. Therefore, the base schedule for the nuclear unit is 50 MW, which is used as one of the inputs into the second optimization pass. The first optimization pass does not set LMP; it is simply used to establish a base dispatch for resources outside the carbon price subregion.

Second Optimization Pass

In the second optimization pass, the economic dispatch of all supply resources is determined while allowing net imports into the carbon price subregion. However, the net imports into the carbon price subregion are limited by the incremental dispatch above each unit's base schedule, as determined in the first optimization pass. In order to limit the net imports into the carbon price subregion to the incremental dispatch above the units' base schedules, the carbon price subregion import constraint described in the one-pass optimization process is modified to take into account each unit's base schedules.

Figure 7 shows the results of the second optimization pass, the final system dispatch, for the example shown in **Figure 4**.

Figure 7. Second Optimization Pass Dispatch Results for Two-Pass Process in Two-Node Subregion System



In this scenario, the dispatch of the nuclear unit is 100 MW, the coal unit is 0 MW and the natural gas unit is 50 MW. From the first pass, 50 MW from the nuclear unit is attributed to serving load in the non-carbon price subregion. Since that load has been served, any incremental dispatch from the nuclear unit or the coal unit would be used to serve load in the carbon price subregion. As a result, the carbon cost, as shown in **Figure 7**, is included in the cost to meet the carbon price subregion's load. The resulting offers are $0/MWh, $15/MWh and $17/MWh for the nuclear, natural gas and coal units, respectively. Using these offers, the nuclear unit is dispatched to 100 MW and the natural gas unit is dispatched to 50 MW. The natural gas and coal units are marginal, yielding LMPs of $7/MWh and $15/MWh for the non-carbon and carbon price subregions, respectively.

Recall from the first pass that 50 MW from the nuclear unit was used to serve native load in the non-carbon price subregion. This means that its additional 50 MW output in the second pass is used to serve load in the carbon price subregion. As a result, the nuclear unit would be credited $400 for its carbon award ($50 MW x $8/MWh = $400). While the nuclear unit has no compliance costs, the marginal price for carbon compliance is $8/MWh, so the nuclear unit is credited at that rate for the energy provided to the carbon price subregion.

Comparing One-Pass and Two-Pass Optimization Results

Table 2 compares the results of the one-pass and two-pass optimization processes. The two-pass optimization results in lower total emissions. This occurs because in the two-pass solution, the natural gas unit is dispatched instead of the coal unit. In the one-pass optimization, the entire 100 MW output of the nuclear unit is imported into the carbon price subregion, and the coal unit, with an offer of $7/MWh (not including carbon compliance costs), is used to serve the non-carbon price subregion load because it is less expensive than the $15/MWh (including carbon compliance costs) natural gas unit. This example illustrates how low-emitting resources in the non-carbon price subregion can be backfilled with higher-emitting resources when the low-emitting resources are exported to serve a neighboring carbon price subregion's load. The two-pass optimization successfully eliminates this phenomenon.

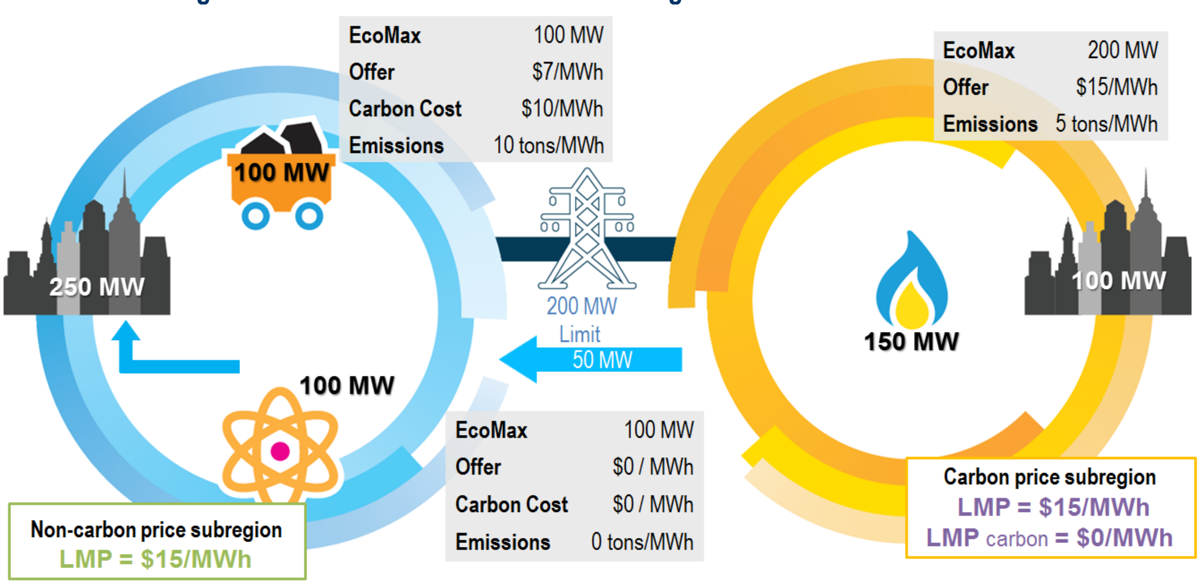
Table 2. **Comparison of One-Pass and Two-Pass Dispatch Results for Two-Node Subregion System**

Unit	One-Pass Optimization Dispatch (MW)	One-Pass Optimization Emissions (tons)	Two-Pass Optimization Dispatch (MW)	Two-Pass Optimization Emissions (tons)
Nuclear	100	0	100	0
Coal	50	500	0	0
Natural Gas	0	0	50	250

Regional Price Impacts of a Subregional Carbon-Pricing Framework

As currently designed, the subregional carbon-pricing framework does not prevent regional pricing impacts due to carbon compliance costs from occurring. For example, if the load in the non-carbon price subregion in the example shown in **Figure 4** is increased to 250 MW, the LMP in the non-carbon price subregion increases to $15/MWh. The second optimization pass dispatch results for the system with increased load are shown in **Figure 8**.

Figure 8. Second Optimization Pass Dispatch Results for Two-Node Subregion System with Increased Subregion Load in the Non-Carbon Price Subregion



In **Figure 8**, since the natural gas unit in the carbon price subregion is exporting energy to the non-carbon price subregion, it sets the LMP for the entire system. As a result, load in the non-carbon price subregion is paying a higher price because of the natural gas unit's carbon compliance costs, which are included in its energy offer. The natural gas unit is obligated to pay carbon compliance costs regardless of which subregion uses the energy. Even with its carbon compliance costs included in its offer, the natural gas unit is still the next-least-expensive unit available for dispatch (in **Figure 8**, it is the only remaining unit available). If a more economic unit in the non-carbon price subregion had been available, then it would have been dispatched first.

Day-Ahead Market in a Subregional Carbon-Pricing Framework

The preceding discussion on the two-pass optimization process has focused on a real-time market structure, but is general and could apply to all markets. A similar framework could also be applied to the day-ahead unit commitment and dispatch process with some modifications. The day-ahead market introduces an additional level of complexity with this carbon-pricing framework because a large amount of demand in the day-ahead market is price sensitive. Price-sensitive demand, decrement bids and export transactions all may clear differently between the first and second optimization passes, which weakens the assumption that supply resources dispatched up between the first and second optimization passes are being dispatched up in order to serve load in the carbon price subregion. They could also be dispatched up because of an increase in cleared price-sensitive demand. This area would benefit from more analysis and discussion to optimize the design and prevent potential manipulation or gaming opportunities.

Areas for Further Development

Implementing a carbon price subregion within the PJM footprint could potentially have effects on other parts of PJM's markets and operations. Should a collection of states show interest in implementing this type of carbon-pricing framework, additional analysis would be required in the following areas:

- Any impact to the Capacity Market and net cost of new entry inside and outside of the carbon price subregion
- Changes that may be needed to modify interchange to account for carbon in certain circumstances
- Price impacts to ancillary services (including reserves and regulation service)
- Potential congestion impacts
- Possible impacts during shortage conditions

Appendix

See the presentation linked below for additional examples.