



Monitoring
Analytics

Constraint Based Congestion Calculations: Measuring Congestion Paid by Zone

The Independent Market Monitor for PJM
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Congestion

Congestion is the difference between energy charges and energy credits caused by binding transmission constraints in a security constrained, least cost dispatch based market with LMPs. More simply, congestion is the difference between what load pays for energy and what generation is paid for that energy due to price separation caused by binding transmission constraints.

The calculations explained in this paper allow a clear determination of the sources of congestion rent on a constraint specific basis based on the actual network solutions in a LMP based market. Comparing the congestion paid by load to the congestion made available to that load through the current ARR/FTR construct provides a metric by which to measure the efficiency of the current ARR/FTR construct as a means to achieve the promised efficiencies of an open access wholesale market. The results of this analysis, as reported in the State of the Market Report, show that the current ARR/FTR construct is not efficient because the rights to congestion revenues are not assigned to those who pay congestion. The current assignment of congestion rights does not align with actual network use.

Congestion Basics

In an LMP market, the lowest cost generation is dispatched to meet the load, subject to the ability of the transmission system to deliver that energy. When the lowest cost generation is remote from load centers, the physical transmission system permits that lowest cost generation to be delivered to load. This was true prior to the introduction of LMP markets and continues to be true in LMP markets. Prior to the introduction of LMP markets, contracts based on the physical rights associated with the transmission system were the mechanism used to provide for the delivery of low cost generation to load. Firm transmission customers who paid for the transmission system through rates or through bilateral contracts received the low cost generation.

The locational marginal price (LMP) is the incremental price of energy at a bus. The LMP at a bus is the sum of three components: the system marginal price (SMP) or energy component, the congestion component (CLMP), and the marginal loss component (MLMP). SMP, MLMP and CLMP are products of the least cost, security constrained dispatch of system resources to meet system load.

SMP is the incremental price of energy for the system, given the current dispatch, at the load-weighted reference bus, or LMP net of losses and congestion. SMP is the LMP at the load-weighted reference bus. The load-weighted reference bus is not a fixed location but varies with the distribution of load at system load buses.

CLMP is the incremental price of congestion at each bus, based on the shadow prices associated with the relief of binding constraints in the security constrained optimization. CLMPs are positive or negative depending on location relative to binding constraints and relative to the load-weighted reference bus. In an unconstrained system CLMPs will

be zero. The relative values of SMP and CLMP are arbitrary and depend on the reference bus.

When there are binding transmission constraints and locational price differences, load pays more for energy than generation is paid to produce that energy. The difference is congestion.¹

The level and distribution of congestion reflects the underlying characteristics of the power system, including the nature and capability of transmission facilities, the offers and geographic distribution of generation facilities, the level and geographic distribution of incremental bids and offers and the locational and temporal distribution of load.

Congestion is calculated on a constraint specific basis. Constraint based congestion reflects differences between credits and charges caused by binding transmission limits on power flow from generators, regardless of location, to load in a specific area.

Constraint based congestion reflects the underlying characteristics of the complete power system as it affects the defined area, including the nature and capability of transmission facilities, the offers and locational distribution of generation facilities, the level and locational distribution of incremental bids and offers and the locational and temporal distribution of load.

Congestion is neither good nor bad, but is a direct measure of the extent to which there are multiple marginal generating units with different offers dispatched to serve load as a result of transmission constraints. Congestion occurs when available, least-cost energy cannot be delivered to all load because transmission facilities are not adequate to deliver that energy to one or more areas, and higher cost units in the constrained area(s) must be dispatched to meet the load.² The result is that the price of energy in the constrained area(s) is higher than in the unconstrained area. Load in the constrained area pays the higher price for all energy including energy from low cost and energy from high cost generation while generators are paid the price at their bus.

¹ The difference in losses is not part of congestion.

² This is referred to as dispatching units out of economic merit order. Economic merit order is the order of all generator offers from lowest to highest cost. Congestion occurs when loadings on transmission facilities mean the next unit in merit order cannot be used and a higher cost unit must be used in its place. Dispatch within the constrained area follows merit order for the units available to relieve the constraint.

The PJM Bill Does Not Reflect Congestion Paid by that Customer

PJM billing items include Day-Ahead Transmission Congestion Charges, Day-Ahead Transmission Congestion Credits, Balancing Transmission Congestion Charges, and Balancing Transmission Congestion Credits. Those line items are calculated for each PJM member. The congestion bill shows the CLMP charges or credits collected from the PJM market participants. However, the sum of an individual customer's CLMP credits or charges on the customer's bill is not a measure of the congestion paid by that customer.

The congestion paid by a customer is the difference between what the customer paid for energy and what all network sources of that energy were paid to serve that customer. A load customer's congestion bill, in contrast, merely indicates whether the LMP they paid for their withdrawals is higher or lower than the system energy price due to transmission constraints. The customer's bill is correct, but does not measure congestion paid by the customer, only how much the customer was charged and credited for their MW positions.

The congestion costs associated with specific constraints are the sum of the total day-ahead and balancing congestion costs associated with those constraints. Zonal congestion is calculated on a constraint by constraint basis. The congestion calculations are the total difference between what the zonal load pays in CLMP charges and what the generation that serves that load is paid, regardless of whether the zone is a net importer or a net exporter of generation. Congestion costs can be both positive and negative and CLMP charges and CLMP credits can be both positive and negative. CLMP charges, positive or negative, are paid by withdrawals and CLMP credits, positive or negative, are paid to injections. Total congestion costs (the sum of charges and credits), when positive, measure the net congestion payment by a participant group and when negative, measure the net congestion credit paid to a participant group. Explicit CLMP charges, when positive, measure the congestion payment to a PJM member and when negative, measure the congestion credit paid to a PJM member. Explicit CLMP charges are calculated for up to congestion transactions (UTCs).

The accounting definitions can be misleading. CLMP charges and credits are not in and of themselves congestion. CLMP charges and credits are adjustments to energy charges and credits reflecting marginal energy price differences caused by binding system constraints. Congestion is the sum of all congestion related charges and credits.

The CLMP is calculated with respect to the LMP at the system reference bus, also called the system marginal price (SMP). When a transmission constraint occurs, the resulting CLMP is positive on one side of the constraint and negative on the other side of the constraint and the corresponding congestion costs are positive or negative. For each transmission constraint, the CLMP reflects the cost of a constraint at a pricing node and is equal to the product of the constraint shadow price and the distribution factor at the

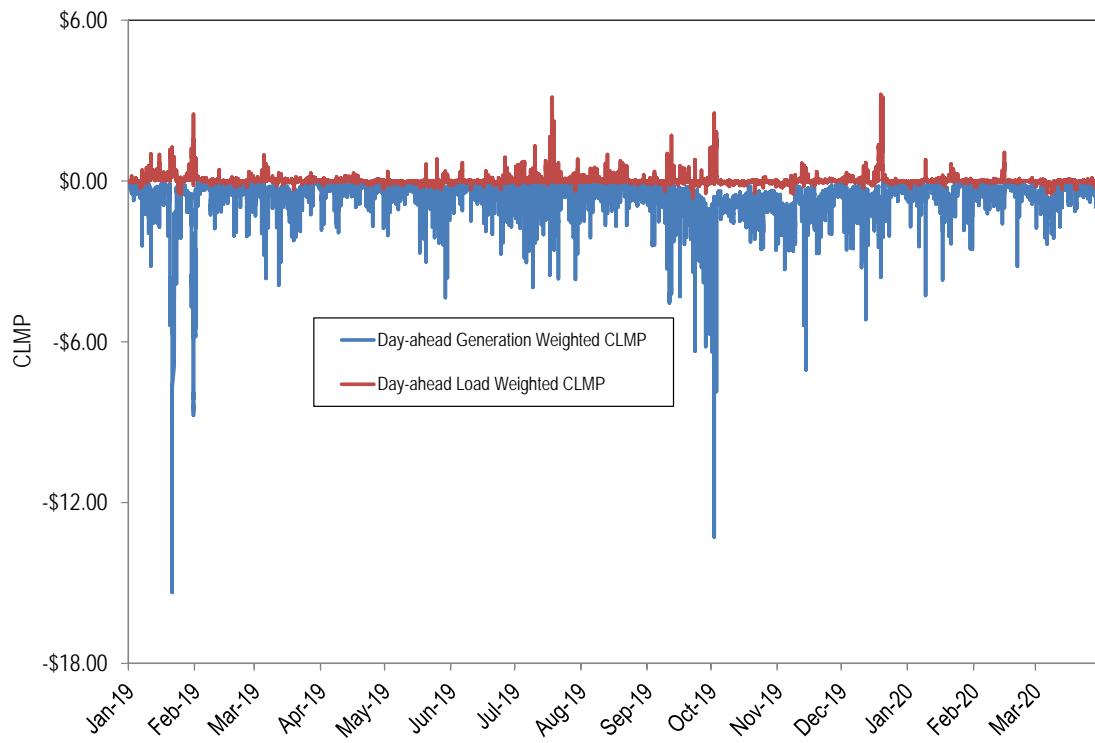
pricing node. The total CLMP at a pricing node is the sum of all constraint contributions to LMP and is equal to the difference between the actual LMP that results from transmission constraints, excluding losses, and the SMP. If an area experiences lower prices because of a constraint, the CLMP in that area is negative.³

Load-weighted LMP components are calculated relative to a load weighted average LMP. At the load weighted reference bus, which represents the load center of the system, the LMP includes no congestion or loss components, by definition. The load weighted average CLMP across all load buses, calculated relative to that reference bus, is equal to, or very close to, zero, with non-zero results caused by state estimator error and after the fact meter updates. The sum of load related CLMP charges is logically zero and the small differences are the result of accounting issues. A positive CLMP at a load bus indicates that the load at that bus has a total energy price higher than the average LMP, due to transmission constraints. A negative CLMP at a load bus indicates that the load at that bus has a total energy price lower than the average LMP, due to transmission constraints. The LMPs at the load buses are a function of marginal generation bus LMPs determined through the least cost security constrained economic dispatch which accounts for transmission constraints and marginal losses. Due to transmission constraints, the average generation weighted CLMP for generation resources is lower than the LMP at the load weighted reference bus price. Calculated relative to the load reference bus which has a CLMP of zero, this means that the average of the generation bus CLMPs is negative. This means that total generation CLMP credits are negative.

Figure 1 shows the weighted average CLMPs of generation and load in the day-ahead market. Figure 1 shows that in January 2019 through March 2020, day-ahead generation weighted CLMPs were generally negative and day-ahead load weighted CLMPs were generally positive. Figure 1 also shows that in January 2019 through March 2020, load paid more for energy as a result of transmission constraints than generation was paid to provide that energy. Figure 1 shows that CLMP charges to load are slightly positive and total CLMP credits to generation are relatively negative. Total CLMP load payments are higher than total CLMP generation credits. The difference in load payments and generation credits (load charges minus generation credits) is congestion.

³ For an example of the congestion accounting methods used in this section, see MMU Technical Reference for PJM Markets, at "FTRs and ARRs," <<http://www.monitoringanalytics.com/reports/Technical References/docs/2010-som-pjm-technical-reference.pdf>>.

Figure 1 Day-ahead generation weighted CLMPs and day-ahead load weighted CLMPs: January 2019 through March, 2020



Congestion Accounting Example: Actual Congestion versus Billed Congestion

Table 1 shows an example of Day-Ahead Transmission Congestion Charges shown on the PJM bill. The example assumes that there was only one constraint binding for an hour and only three customers (A, B and C) participated in the PJM Day-Ahead Energy Market. The top portion of the table shows the total day-ahead congestion in the PJM system for an hour is \$960. For customer B, the total day-ahead transmission CLMP charges on the customer bill are \$296. The total day-ahead transmission CLMP charges on customer B's bill are not equal to the day-ahead congestion paid by customer B.

The congestion paid by customer B is the difference between what Customer B pays for withdrawing energy and what all the injections needed to serve Customer B's withdrawal are paid to provide that energy. Customer B needs 6 MWh more injections from network sources than it supplied to meet its 60 MWh withdrawal. Customer B's bill does not reflect the difference between what it paid for the 6 MWh of energy from the network and what the resources that supplied the 6 MWh of network energy were paid. The total day-ahead congestion cost paid by customer B is \$192 (Table 2), not the \$296 (Table 1) in net CLMP credits found on its bill. Table 2 shows that the actual total

PJM day-ahead congestion costs paid by each customer due to the transmission constraint and the actual network sources of energy used to serve the customers.

Table 1 Example of day-ahead CLMP charges by customer in PJM bill

	Withdrawal	Injection	Day-Ahead (Total)			CLMP Charges
			CLMP	Implicit Withdrawal Charges	Implicit Injection Credits	
DEC	50.0	0.0	\$5.0	\$250.0	\$0.0	\$250.0
Demand	100.0	0.0	\$10.0	\$1,000.0	\$0.0	\$1,000.0
Export	30.0	0.0	\$7.0	\$210.0	\$0.0	\$210.0
Generation	0.0	150.0	\$2.0	\$0.0	\$300.0	(\$300.0)
Import	0.0	20.0	\$6.0		\$120.0	(\$120.0)
INC	0.0	10.0	\$8.0	\$0.0	\$80.0	(\$80.0)
Total	180.0	180.0		\$1,460.0	\$500.0	\$960.0
Day-Ahead (Customer A)						
DEC	20.0	0.0	\$5.0	\$100.0	\$0.0	\$100.0
Demand	10.0	0.0	\$10.0	\$100.0	\$0.0	\$100.0
Export	10.0	0.0	\$7.0	\$70.0	\$0.0	\$70.0
Generation	0.0	50.0	\$2.0	\$0.0	\$100.0	(\$100.0)
Import	0.0	6.0	\$6.0	\$0.0	\$36.0	(\$36.0)
INC	0.0	10.0	\$8.0	\$0.0	\$80.0	(\$80.0)
Total	40.0	66.0		\$270.0	\$216.0	\$54.0
Day-Ahead (Customer B)						
DEC	30.0	0.0	\$5.0	\$150.0	\$0.0	\$150.0
Demand	20.0	0.0	\$10.0	\$200.0	\$0.0	\$200.0
Export	10.0	0.0	\$7.0	\$70.0	\$0.0	\$70.0
Generation	0.0	50.0	\$2.0	\$0.0	\$100.0	(\$100.0)
Import	0.0	4.0	\$6.0	\$0.0	\$24.0	(\$24.0)
INC	0.0	0.0	\$8.0	\$0.0	\$0.0	\$0.0
Total	60.0	54.0		\$420.0	\$124.0	\$296.0
Day-Ahead (Customer C)						
DEC	0.0	0.0	\$5.0	\$0.0	\$0.0	\$0.0
Demand	70.0	0.0	\$10.0	\$700.0	\$0.0	\$700.0
Export	10.0	0.0	\$7.0	\$70.0	\$0.0	\$70.0
Generation	0.0	50.0	\$2.0	\$0.0	\$100.0	(\$100.0)
Import	0.0	10.0	\$6.0	\$0.0	\$60.0	(\$60.0)
INC	0.0	0.0	\$8.0	\$0.0	\$0.0	\$0.0
Total	80.0	60.0		\$770.0	\$160.0	\$610.0

Table 2 Example of day-ahead congestion by customer

	Day-Ahead					
	Withdrawal	Injection	CLMP	Implicit Withdrawal Charges	Implicit Injection Credits	CLMP Charges
DEC	50.0	0.0	\$5.0	\$250.0	\$0.0	\$250.0
Demand	100.0	0.0	\$10.0	\$1,000.0	\$0.0	\$1,000.0
Export	30.0	0.0	\$7.0	\$210.0	\$0.0	\$210.0
Generation	0.0	150.0	\$2.0	\$0.0	\$300.0	(\$300.0)
Import	0.0	20.0	\$6.0		\$120.0	(\$120.0)
INC	0.0	10.0	\$8.0	\$0.0	\$80.0	(\$80.0)
Total	180.0	180.0		\$1,460.0	\$500.0	\$960.0
Customer	Demand Charge					
	Demand	Injection	CLMP	Demand Charges	Proportion	Total Congestion
A	10.0	0.0	\$10.0	\$100.0	0.1	\$96.0
B	20.0	0.0	\$10.0	\$200.0	0.2	\$192.0
C	70.0	0.0	\$10.0	\$700.0	0.7	\$672.0
Total	100.0			\$1,000.0	1.0	\$960.0

Charges and Credits versus Congestion: Virtual Transactions, Load and Generation

In a two settlement system all virtual bids have net zero MW after their day-ahead and balancing positions are cleared, which means that virtual bids are fully settled in terms of CLMP credits and charges at the close of the market for any particular day, with either a net loss or profit due to differences between day-ahead and real-time prices. Net payouts (negative credits) to virtual bids appear as negative adjustments to either day-ahead or balancing congestion and net charges to virtual bids appear as positive adjustments to either day-ahead or balancing congestion.

Unlike virtual bids, physical load and generation have net MW at the close of a day's day-ahead and balancing settlement. The residual difference between total constraint based load charges (day-ahead and balancing) and constraint based generation credits (day-ahead and balancing) left over after virtual bids have settled there day-ahead and balancing positions is congestion. This means that load pays congestion. Congestion is the difference between what withdrawals (load) are paying for energy and what injections (generation) are being paid for energy due to binding transmission constraints. Generation does not pay congestion. Some generation receives a price lower than SMP and some generation receives a price greater than SMP but that does not mean that generation is paying congestion. It means that generation is being paid an LMP that is higher or lower than the system load-weighted average LMP.

Calculating bus, zone or aggregate congestion allocations by constraint

Zonal congestion is calculated on a constraint specific basis. Local congestion is the difference between what withdrawals (load) pay for energy and what injections (generation) are paid for energy due to individual binding transmission constraints. Local congestion includes all energy charges or credits incurred to serve zonal load. Local congestion calculations account for the total difference between what the zonal load pays in CLMP charges and what the generation that serves that load is paid, regardless of whether the zone is a net importer or a net exporter of generation.

Local congestion is calculated on a constraint specific basis. This constraint based congestion is the total congestion payments by withdrawals (load) at the buses within a defined area minus total CLMP credits received by all injections (generation) that supplied that load, given the transmission constraints, regardless of location. Constraint based congestion reflects the underlying characteristics of the complete power system as it affects the defined area, including the nature and capability of transmission facilities, the offers and geographic distribution of generation facilities, the level and geographic distribution of incremental bids and offers and the geographic and temporal distribution of load.

On a system wide basis, congestion results from transmission constraints that prevent the lowest cost generation from serving some load that must be served by higher cost generation.

The total congestion caused by a constraint is equal to the product of the constraint shadow price times the net market flow on the binding constraint. Total congestion caused by the constraint can also be calculated using the CLMPs caused by the constraint at every bus and the net MW injections or MW withdrawals at every affected bus. Congestion associated with a specific constraint is equal to load CLMP charges (CLMP of that specific constraint at each bus times load MW at each bus) caused by that constraint in excess of generation CLMP credits (CLMP of that specific constraint at each bus times generation MW at each bus) caused by that constraint.

Constraint specific CLMPs are determined relative to a reference bus, where there is no congestion and no losses. For purposes of allocating the congestion of an individual constraint, the reference bus for each constraint calculation is moved to the point that is just upstream of the constraint (the bus with the greatest negative price effect from the constraint), allowing any positive price effects of the constraint to be reflected as a positive CLMP.

In order to define the load that is actually paying congestion (withdrawal payments in excess of injection credits), constraint specific congestion is appropriately assigned to downstream (positive CLMP) load buses that paid the congestion caused by the constraint, in proportion to the CLMP charges collected from that load due to that constraint. The congestion collected from each load bus due to a constraint is equal to

the CLMP caused by that constraint times the MW of load at that load bus. This calculation is done for both day-ahead congestion and balancing congestion.

Table 3 shows the day-ahead and balancing congestion by zone for the first three months of 2020. Table 4 shows the congestion costs by zone for the first three months of 2019.

Table 3 Day-ahead and balancing congestion by zone (Dollars (Millions)): January through March, 2020

Control Zone	CLMP Credits and Charges (Millions)								Congestion Costs	
	Day-Ahead				Balancing					
	Implicit Withdrawal Charges	Implicit Injection Credits	Explicit Charges	Total	Implicit Withdrawal Charges	Implicit Injection Credits	Explicit Charges	Total		
AECO	\$0.2	(\$0.7)	\$0.2	\$1.1	(\$0.0)	\$0.0	(\$0.2)	(\$0.2)	\$0.9	
AEP	(\$0.1)	(\$14.7)	\$2.2	\$16.7	(\$0.0)	\$0.7	(\$2.4)	(\$3.1)	\$13.6	
APS	\$3.9	(\$2.9)	\$0.8	\$7.6	(\$0.0)	\$0.3	(\$0.9)	(\$1.2)	\$6.4	
ATSI	\$2.1	(\$6.2)	\$1.2	\$9.5	(\$0.0)	\$0.3	(\$1.2)	(\$1.5)	\$7.9	
BGE	\$0.8	(\$2.5)	\$0.4	\$3.7	(\$0.0)	\$0.2	(\$0.6)	(\$0.7)	\$3.0	
ComEd	(\$2.2)	(\$14.5)	\$3.0	\$15.2	\$0.0	\$0.4	(\$1.5)	(\$1.9)	\$13.3	
DAY	(\$0.2)	(\$2.0)	\$0.3	\$2.2	(\$0.0)	\$0.1	(\$0.3)	(\$0.4)	\$1.8	
DEOK	\$0.0	(\$2.6)	\$0.4	\$3.0	(\$0.0)	\$0.1	(\$0.5)	(\$0.6)	\$2.4	
DLCO	(\$0.0)	(\$1.2)	\$0.2	\$1.4	(\$0.0)	\$0.1	(\$0.2)	(\$0.3)	\$1.1	
Dominion	\$1.1	(\$9.7)	\$1.4	\$12.2	(\$0.0)	\$0.4	(\$1.9)	(\$2.3)	\$9.9	
DPL	\$1.5	(\$1.6)	\$0.5	\$3.6	(\$0.0)	\$0.1	(\$0.4)	(\$0.6)	\$3.0	
EKPC	(\$0.0)	(\$1.4)	\$0.2	\$1.7	(\$0.0)	\$0.1	(\$0.3)	(\$0.4)	\$1.3	
EXT	\$0.0	(\$0.0)	\$0.0	\$0.1	(\$0.0)	\$0.0	\$0.0	(\$0.0)	\$0.0	
JCPL	\$0.3	(\$1.9)	\$0.3	\$2.5	(\$0.0)	\$0.1	(\$0.4)	(\$0.5)	\$2.1	
Met-Ed	\$0.7	(\$1.2)	\$0.2	\$2.1	\$0.0	\$0.2	(\$0.3)	(\$0.4)	\$1.7	
OVEC	(\$0.0)	(\$0.0)	\$0.1	\$0.1	(\$0.0)	(\$0.0)	\$0.0	\$0.0	\$0.1	
PECO	\$0.3	(\$3.5)	\$0.5	\$4.3	(\$0.0)	\$0.2	(\$0.7)	(\$0.9)	\$3.4	
PENELEC	\$1.9	(\$0.4)	\$0.3	\$2.6	(\$0.0)	\$0.1	(\$0.3)	(\$0.4)	\$2.2	
Pepco	\$0.6	(\$2.3)	\$0.4	\$3.3	(\$0.0)	\$0.1	(\$0.5)	(\$0.6)	\$2.7	
PPL	\$1.5	(\$3.1)	\$0.9	\$5.5	(\$0.0)	\$0.2	(\$0.8)	(\$1.0)	\$4.6	
PSEG	\$1.1	(\$3.1)	\$0.6	\$4.7	(\$0.0)	\$0.2	(\$0.7)	(\$0.9)	\$3.8	
RECO	\$0.0	(\$0.1)	\$0.0	\$0.2	\$0.0	\$0.0	(\$0.0)	(\$0.0)	\$0.1	
Total	\$13.5	(\$75.7)	\$14.1	\$103.3	(\$0.2)	\$3.8	(\$14.2)	(\$18.2)	\$85.1	

Table 4 Day-ahead and balancing congestion by zone (Dollars (Millions)): January through March, 2019

Control Zone	CLMP Credits and Charges (Millions)										Congestion Costs
	Day-Ahead				Balancing						
	Implicit Withdrawal Charges	Implicit Injection Credits	Explicit Charges	Total	Implicit Withdrawal Charges	Implicit Injection Credits	Explicit Charges	Total	Congestion Costs		
AECO	\$1.8	(\$1.7)	\$0.3	\$3.8	\$0.0	\$0.3	(\$0.2)	(\$0.4)	\$3.3		
AEP	\$7.4	(\$18.5)	\$1.8	\$27.7	(\$0.2)	\$3.2	(\$2.6)	(\$6.0)	\$21.7		
APS	\$6.2	(\$8.5)	\$0.5	\$15.2	(\$0.1)	\$1.2	(\$1.1)	(\$2.4)	\$12.9		
ATSI	\$3.4	(\$9.3)	\$0.7	\$13.4	(\$0.1)	\$1.5	(\$1.5)	(\$3.1)	\$10.3		
BGE	\$2.0	(\$4.6)	\$0.2	\$6.8	(\$0.2)	\$0.9	(\$0.7)	(\$1.8)	\$5.0		
ComEd	\$4.4	(\$16.5)	\$2.5	\$23.5	(\$0.3)	\$2.2	(\$1.3)	(\$3.7)	\$19.8		
DAY	\$0.9	(\$2.1)	\$0.2	\$3.1	(\$0.0)	\$0.4	(\$0.4)	(\$0.8)	\$2.3		
DEOK	\$1.4	(\$3.3)	\$0.4	\$5.0	(\$0.0)	\$0.6	(\$0.5)	(\$1.2)	\$3.8		
DLCO	\$0.4	(\$1.3)	\$0.1	\$1.8	(\$0.0)	\$0.3	(\$0.3)	(\$0.6)	\$1.2		
Dominion	\$4.8	(\$14.8)	\$0.8	\$20.3	(\$0.1)	\$2.5	(\$1.9)	(\$4.5)	\$15.9		
DPL	\$3.6	(\$4.3)	\$0.8	\$8.7	(\$0.0)	\$0.6	(\$0.4)	(\$1.1)	\$7.7		
EKPC	\$0.6	(\$1.9)	\$0.2	\$2.7	(\$0.0)	\$0.3	(\$0.3)	(\$0.6)	\$2.0		
EXT	\$0.1	(\$0.0)	\$0.0	\$0.2	(\$0.2)	\$0.2	(\$0.8)	(\$1.2)	(\$1.0)		
JCPL	\$1.7	(\$5.9)	\$0.3	\$7.9	\$0.0	\$0.6	(\$0.5)	(\$1.1)	\$6.9		
Met-Ed	\$1.6	(\$3.7)	\$0.2	\$5.4	(\$0.1)	\$0.5	(\$0.4)	(\$1.0)	\$4.4		
OVEC	\$0.0	\$0.0	(\$0.0)	(\$0.0)	\$0.0	\$0.0	\$0.0	\$0.0	(\$0.0)		
PECO	\$1.7	(\$10.2)	\$0.4	\$12.3	(\$0.0)	\$1.2	(\$0.8)	(\$2.0)	\$10.4		
PENELEC	\$3.1	(\$3.5)	\$0.3	\$6.9	(\$0.1)	\$0.4	(\$0.4)	(\$0.9)	\$6.0		
Pepco	\$1.6	(\$4.1)	\$0.2	\$6.0	(\$0.0)	\$0.7	(\$0.6)	(\$1.3)	\$4.7		
PPL	\$3.6	(\$10.9)	\$0.9	\$15.4	(\$0.0)	\$1.1	(\$0.9)	(\$2.0)	\$13.4		
PSEG	\$2.7	(\$12.2)	\$0.6	\$15.5	(\$0.2)	\$1.3	(\$0.8)	(\$2.3)	\$13.2		
RECO	\$0.1	(\$0.4)	\$0.0	\$0.6	(\$0.0)	\$0.0	(\$0.3)	(\$0.4)	\$0.2		
Total	\$53.3	(\$137.7)	\$11.2	\$202.2	(\$1.8)	\$20.1	(\$16.4)	(\$38.3)	\$163.9		

In cases where the constraint causes net negative congestion and/or there is no load bus on the constrained side of a binding constraint, the congestion of the constraint is handled as a special case. In these special cases, the associated congestion is assigned to the control zone or residual load aggregate where the congestion is incurred and/or there are positive CLMPs from that constraint. In the first three months of 2020, the total congestion costs associated with the special cases were \$0.9 million or 1.1 percent of the total congestion costs. Table 3 and Table 4 include congestion allocations from these special case constraints.

There are five categories of constraint specific allocation special cases: congestion associated with constraints with no downstream load bus (no load bus); congestion associated with constraints with downstream load buses with zero value CLMPs (zero CLMP); congestion associated with closed loop interfaces (closed loop interfaces); CT price setting logic; and congestion associated with nontransmission facility constraints in the day-ahead energy market and/or any unaccounted for difference between PJM billed CLMP charges and calculated congestion costs including rounding errors (unclassified).

Table 5 and Table 6 show the allocation of total congestion by each special case allocation method, congestion allocated by the standard method and total allocation by zone. Closed loop interfaces and CT pricing logic generally result in negative congestion on a constraint specific basis. PJM's use of both the closed loop interfaces and CT Pricing Logic forces the affected resource bus LMP to match the marginal offer of the resource. This causes higher CLMP payments to the affected generation than the CLMP load charges to any affected load, resulting in negative congestion associated with the constraint. None of the closed loop interfaces were binding in the first three months of 2019 and 2020.

Table 5 Day-ahead and total balancing congestion assigned by zone and special case logic (Dollars (Millions)): January through March, 2020

Control Zone	Congestion Costs (Millions)														
	Day-Ahead						Balancing						Special Cases Total	Percent of Special Cases	
	Load Bus Zero CLMP	CT Price Setting Logic	Closed Loop Interfaces	No Load Buses	Unclassified Allocation	Total	Load Bus Zero CLMP	CT Price Setting Logic	Closed Loop Interfaces	No Load Buses	Unclassified Allocation	Total	Grand Total		
AECO	(\$0.0)	(\$0.0)	\$0.0	\$0.0	\$0.0	\$1.1	\$1.1	(\$0.0)	\$0.0	\$0.0	(\$0.0)	(\$0.2)	(\$0.2)	\$0.9	(\$0.0) (0.1%)
AEP	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	\$16.7	\$16.7	\$0.0	(\$0.0)	\$0.0	(\$0.1)	(\$0.0)	(\$3.0)	(\$3.1)	\$13.6 (\$0.0) (0.2%)
APS	\$0.0	\$0.0	\$0.0	\$0.0	(\$0.0)	\$7.6	\$7.6	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	(\$1.2)	(\$1.2)	\$6.4 \$0.0 (0.0%)
ATSI	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	\$9.5	\$9.5	\$0.0	(\$0.0)	\$0.0	\$0.0	(\$0.0)	(\$1.5)	(\$1.5)	\$7.9 (\$0.0) (0.2%)
BGE	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	\$3.7	\$3.7	\$0.0	(\$0.0)	\$0.0	\$0.0	(\$0.0)	(\$0.7)	(\$0.7)	\$3.0 \$0.0 (0.3%)
ComEd	\$0.0	(\$0.0)	\$0.0	\$0.9	(\$0.0)	\$14.3	\$15.2	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	(\$2.0)	(\$1.9)	\$13.3 \$0.9 (6.8%)
DAY	\$0.0	(\$0.0)	\$0.0	(\$0.0)	\$0.0	\$2.2	\$2.2	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	(\$0.4)	(\$0.4)	\$1.8 (\$0.0) (0.9%)
DEOK	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$3.0	\$3.0	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	(\$0.6)	(\$0.6)	\$2.4 (\$0.0) (0.6%)
DLCO	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	\$1.4	\$1.4	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	(\$0.3)	(\$0.3)	\$1.1 (\$0.0) (0.1%)
Dominion	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$12.2	\$12.2	\$0.0	(\$0.0)	\$0.0	(\$0.0)	\$0.0	(\$2.3)	(\$2.3)	\$9.9 \$0.0 (0.1%)
DPL	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	\$3.6	\$3.6	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	(\$0.6)	(\$0.6)	\$3.0 \$0.0 (0.2%)
EKPC	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$1.7	\$1.7	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	(\$0.3)	(\$0.4)	\$1.3 (\$0.0) (1.9%)
EXT	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.1	\$0.1	\$0.1	\$0.0	(\$0.0)	\$0.0	(\$0.0)	\$0.0	(\$0.0)	(\$0.0)	\$0.0 \$0.0 (100.0%)
JCPL	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	\$2.5	\$2.5	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	(\$0.5)	(\$0.5)	\$2.1 \$0.0 (0.5%)
Met-Ed	\$0.0	\$0.0	\$0.0	\$0.1	\$0.0	\$2.0	\$2.1	\$0.0	(\$0.0)	\$0.0	(\$0.1)	\$0.0	(\$0.3)	(\$0.4)	\$1.7 (\$0.0) (1.4%)
OVEC	\$0.0	(\$0.0)	\$0.0	\$0.1	(\$0.0)	\$0.0	\$0.1	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	(\$0.0)	(\$0.0)	\$0.1 \$0.1 (104.6%)
PECO	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$4.3	\$4.3	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	(\$0.9)	(\$0.9)	\$3.4 (\$0.0) (0.4%)
PENELEC	\$0.0	(\$0.0)	\$0.0	\$0.0	(\$0.0)	\$2.6	\$2.6	(\$0.0)	(\$0.0)	\$0.0	(\$0.0)	\$0.0	(\$0.4)	(\$0.4)	\$2.2 (\$0.0) (1.0%)
Pepco	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$3.3	\$3.3	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	(\$0.6)	(\$0.6)	\$2.7 \$0.0 (0.0%)
PPL	\$0.0	\$0.0	\$0.0	\$0.0	(\$0.0)	\$5.5	\$5.5	(\$0.0)	(\$0.0)	\$0.0	(\$0.0)	\$0.0	(\$1.0)	(\$1.0)	\$4.6 (\$0.0) (0.0%)
PSEG	(\$0.0)	\$0.0	\$0.0	\$0.0	\$0.0	\$4.7	\$4.7	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	(\$0.9)	(\$0.9)	\$3.8 \$0.0 (0.1%)
RECO	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.2	\$0.2	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	(\$0.0)	(\$0.0)	\$0.1 \$0.0 (2.9%)
Total	\$0.0	(\$0.0)	\$0.0	\$1.1	\$0.1	\$102.2	\$103.3	(\$0.0)	(\$0.0)	\$0.0	(\$0.2)	(\$0.0)	(\$18.0)	(\$18.2)	\$85.1 \$0.9 (1.1%)

Table 6 Day-ahead and total balancing congestion assigned by zone and special case logic (Dollars (Millions)): January through March, 2019

Control Zone	Congestion Costs (Millions)												Percent of Special Cases	Percent of Special Cases			
	Day-Ahead						Balancing										
	Load Bus Zero CLMP	CT Price Setting Logic	Closed Loop Interfaces	No Load Buses	Unclassified	Allocation	Load Bus Zero CLMP	CT Price Setting Logic	Closed Loop Interfaces	No Load Buses	Unclassified	Allocation	Total	Grand Total			
AECO	(\$0.0)	\$0.0	\$0.0	\$0.0	\$0.0	\$3.8	\$3.8	(\$0.0)	\$0.0	\$0.0	\$0.0	(\$0.0)	(\$0.4)	(\$0.4)	\$3.3	\$0.0	0.1%
AEP	\$0.0	(\$0.0)	\$0.0	\$0.5	(\$0.0)	\$27.3	\$27.7	\$0.0	(\$0.2)	\$0.0	\$0.0	(\$0.1)	(\$5.8)	(\$6.0)	\$21.7	\$0.2	0.8%
APS	\$0.0	(\$0.0)	\$0.0	\$0.0	(\$0.0)	\$15.3	\$15.2	\$0.0	(\$0.0)	\$0.0	\$0.0	(\$0.0)	(\$2.4)	(\$2.4)	\$12.9	(\$0.0)	(0.3%)
ATSI	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$13.4	\$13.4	\$0.0	(\$0.2)	\$0.0	\$0.0	(\$0.0)	(\$2.9)	(\$3.1)	\$10.3	(\$0.1)	(1.5%)
BGE	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	\$6.8	\$6.8	\$0.0	(\$0.0)	\$0.0	\$0.0	(\$0.0)	(\$1.8)	(\$1.8)	\$5.0	\$0.0	0.8%
ComEd	\$0.0	(\$0.0)	\$0.0	\$0.5	(\$0.0)	\$23.0	\$23.5	\$0.0	(\$0.2)	\$0.0	\$0.0	(\$0.0)	(\$3.5)	(\$3.7)	\$19.8	\$0.4	1.8%
DAY	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$3.1	\$3.1	\$0.0	(\$0.0)	\$0.0	\$0.0	(\$0.0)	(\$0.8)	(\$0.8)	\$2.3	(\$0.0)	(0.2%)
DEOK	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$5.0	\$5.0	\$0.0	(\$0.1)	\$0.0	\$0.0	(\$0.0)	(\$1.2)	(\$1.2)	\$3.8	(\$0.0)	(1.0%)
DLCO	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	\$1.8	\$1.8	\$0.0	(\$0.0)	\$0.0	\$0.0	(\$0.0)	(\$0.6)	(\$0.6)	\$1.2	(\$0.0)	(1.4%)
Dominion	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$20.3	\$20.3	\$0.0	(\$0.0)	\$0.0	\$0.0	(\$0.0)	(\$4.5)	(\$4.5)	\$15.9	\$0.0	0.1%
DPL	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	\$8.7	\$8.7	\$0.0	(\$0.0)	\$0.0	\$0.0	(\$0.0)	(\$1.1)	(\$1.1)	\$7.7	\$0.0	0.1%
EKPC	\$0.0	\$0.0	\$0.0	\$0.0	(\$0.0)	\$2.7	\$2.7	\$0.0	(\$0.0)	\$0.0	\$0.0	(\$0.0)	(\$0.6)	(\$0.6)	\$2.0	(\$0.0)	(0.2%)
EXT	\$0.0	(\$0.0)	\$0.0	\$0.1	\$0.1	\$0.0	\$0.2	\$0.0	(\$1.1)	\$0.0	\$0.0	(\$0.1)	(\$0.0)	(\$1.2)	\$1.0	(\$1.0)	100.0%
JCPL	\$0.0	(\$0.0)	\$0.0	\$0.0	\$0.0	\$7.9	\$7.9	\$0.0	(\$0.1)	\$0.0	\$0.0	(\$0.0)	(\$1.0)	(\$1.1)	\$6.9	(\$0.1)	(1.2%)
Met-Ed	\$0.0	\$0.0	\$0.0	\$0.1	\$0.0	\$5.3	\$5.4	\$0.0	(\$0.0)	\$0.0	\$0.0	(\$0.1)	(\$1.0)	(\$1.0)	\$4.4	\$0.0	1.0%
OVEC	\$0.0	(\$0.0)	\$0.0	\$0.0	(\$0.0)	\$0.0	(\$0.0)	\$0.0	(\$0.0)	\$0.0	\$0.0	(\$0.0)	(\$0.0)	(\$0.0)	\$0.0	(\$0.0)	(13.2%)
PECO	(\$0.0)	\$0.0	\$0.0	\$0.0	(\$0.0)	\$12.3	\$12.3	\$0.0	(\$0.1)	\$0.0	\$0.0	(\$0.0)	(\$1.9)	(\$2.0)	\$10.4	(\$0.0)	(0.1%)
PENELEC	\$0.0	(\$0.1)	\$0.0	\$0.1	(\$0.0)	\$6.9	\$6.9	\$0.0	(\$0.0)	\$0.0	\$0.0	(\$0.0)	(\$0.9)	(\$0.9)	\$6.0	(\$0.0)	(0.5%)
Pepco	\$0.0	(\$0.0)	\$0.0	(\$0.0)	\$0.0	\$6.0	\$6.0	\$0.0	(\$0.0)	\$0.0	\$0.0	(\$0.0)	(\$1.3)	(\$1.3)	\$4.7	(\$0.0)	(0.1%)
PPL	(\$0.0)	\$0.0	\$0.0	(\$0.0)	\$0.0	\$15.4	\$15.4	\$0.0	(\$0.1)	\$0.0	\$0.0	(\$0.0)	(\$1.9)	(\$2.0)	\$13.4	(\$0.1)	(0.9%)
PSEG	(\$0.0)	\$0.1	\$0.0	\$0.0	(\$0.0)	\$15.4	\$15.5	\$0.0	(\$0.0)	\$0.0	\$0.0	(\$0.0)	(\$2.3)	(\$2.3)	\$13.2	\$0.1	0.5%
RECO	\$0.0	\$0.0	\$0.0	\$0.0	\$0.0	\$0.5	\$0.6	\$0.0	(\$0.3)	\$0.0	\$0.0	(\$0.0)	(\$0.1)	(\$0.4)	\$0.2	(\$0.3)	(156.0%)
Total	\$0.0	(\$0.2)	\$0.0	\$1.4	\$0.1	\$200.8	\$202.2	(\$0.0)	(\$2.2)	\$0.0	\$0.0	(\$0.1)	(\$35.8)	(\$38.3)	\$163.9	(\$1.1)	(0.7%)

Day-Ahead Constraint Specific Congestion Cost: Basic Method

In the day-ahead market, load pays the CLMP caused by constraints. The total CLMP at a bus is the sum of all constraint specific effects, both positive or negative.

A negative CLMP from a constraint at a bus indicates that load at that bus is at the source side of the constraint and it is not paying congestion due to that constraint (the constraint is not a source of lower cost energy being imported to serve that load).

Where the CLMP of a constraint is positive, the load bus is downstream of the constraint and the constraint is isolating the load bus from a relatively low cost upstream source of energy. The difference between what the load is paying for that power and the energy source is being paid is the source of congestion charges being collected due to the constraint.

Every load bus with a positive CLMP from that constraint is contributing to the congestion collected due to that constraint, with total congestion being the shadow price of the constraint times the flow on the constrained line.

The relative contribution to the congestion collected from a downstream bus due to a specific constraint is determined by calculating total constraint specific congestion charges at the affected downstream load bus and dividing by the sum of the constraint specific load related congestion charges at every downstream (indicated by a positive CLMP from the constraint) affected load bus.

For this calculation, only positive CLMP components of LMP of a specific constraint on each load bus are used. To determine the full downstream price of the effect of a

constraint, the reference bus is moved to the source point of each constraint when determining constraint specific CLMP values on the system. The congestion (net congestion credits) associated with the constraint (determined by the shadow price and MW limit of the constraint) is used to determine the constraint specific congestion. The sources of the congestion caused by the constraint is determined by the proportion of the constraint's CLMP related charges collected from downstream physical load.

Performing this calculation for every constraint in every hour of the day-ahead market for every load bus provides a full, hourly determination of day-ahead congestion rents collected from downstream load. The end result is constraint specific day-ahead congestion charges collected by bus by hour.

Steps for Determining Sources of Day-Ahead Congestion

1. Collect CLMP by constraint by bus by hour.
2. Collect load by bus by hour.
3. Collect generation by bus by hour.
4. Collect day-ahead transactions by bus by hour (WHLIN, WHLOUT, IMPORT, EXPORT, UTCs, INTERNAL)
5. Calculate day-ahead congestion by constraint for each hour.
6. Move the reference bus to the location of the most negative CLMP caused by the studied constraint and update resulting CLMPs caused by the constraint studied.
7. By constraint, calculate downstream (+CLMP) congestion charges to load by bus by hour.
8. By constraint, calculate the proportion of downstream (+CLMP) congestion charges collected at each downstream bus by hour by physical load.
9. Congestion collected from a downstream load bus is each constraint's total congestion times the proportion of downstream (+CLMP) congestion charges collected at that bus by hour.

Day-Ahead Congestion Example

The following example shows the calculation of constraint specific day-ahead congestion and the allocation of this congestion to the load that pays it. The example uses a two bus model with one constraint. Generation is offered at Bus A (\$50) and Bus B (\$150). Bus B has two child nodes (B1 and B2) with load at each. There is one MW of transfer capability between A and B, defined by constraint AB. In the day-ahead market there is 0.5 MW load at B1 and 1.5 MW load at B2. Table 7 provides, by bus, constraint specific CLMP, generation congestion credits, load congestion charges and total congestion (the market has a system marginal price (SMP) of \$100). The market solution shows line AB binding, with CLMP based price separation between Bus A (\$-50) and Bus B (\$150) based on the marginal unit at A and B. Total congestion is \$100.

Table 7 Two Bus, One Constraint Model

Bus	Gen MW	Load MW	CLMP	Load Charges	Generation Credits	Congestion (Net Charges)
A	1			-\$50.00	\$0.00	-\$50.00
B1	1	0.5	\$50.00	\$25.00	\$50.00	
B2	0	1.5	\$50.00	\$75.00	\$0.00	
Total	2	2		\$100.00	\$0.00	\$100.00

Moving the reference bus to Bus A (the source point of the constraint) holds LMPs constant, but changes the CLMPs. Table 8 provides, by bus, constraint specific CLMP, proportion of downstream load charges, and congestion allocations after moving the reference bus to A. Constraint AB generated \$100 in total congestion (load charges in excess of generation credits). Bus B1 contributed \$50 in congestion charges (AB CLMP at B1 x Load MW at B1), which accounted for 25 percent of congestion charges attributed to load downstream of constraint AB. Bus B1 would then be allocated 25 percent, or (\$25), of the total congestion (\$100) generated by constraint AB. In short, a load bus that accounted for 10 percent of the downstream congestion charges generated by the constraint is credited with having contributed 10 percent of the congestion rents attributable to the constraint. This allows a clear determination of the constraint specific congestion that any specific load contributed to congestion, in proportion to the congestion dollars collected because of that constraint.

Table 8 Day-ahead congestion by load bus

Bus	Gen MW	Load MW	CLMP	Proportion of Constraint		
				Load Charges	Generation Credits	Congestion Charges to Load
A	1		0	\$0	\$0	
B1	1	0.5	\$100	\$50	\$100	25%
B2	0	1.5	\$100	\$150	\$0	75%
Total	2	2		\$200	\$100	\$100
					100%	\$100

The Determination of Sources of Balancing Congestion

Balancing congestion is a part of total congestion. Unless the day-ahead market model and results exactly matches the results of the actual physical system in real time, the congestion collected from day-ahead positions (the difference between charges and credits due to binding transmission constraints) will not match the actual amount of congestion surplus available after all real-time positions are settled. That is why total congestion must be accounted for as day-ahead plus balancing congestion.

The determination and allocation of balancing congestion is based on the same principle as the allocation of day-ahead congestion.

The system real-time optimization follows the same logic as the day-ahead optimization and provides the binding constraint, shadow prices and CLMP. In real time, the flows and prices on specific constraints are based on total real-time MW on the system, but the congestion collected (the difference between load charges and generation credits based on day-ahead and real-time MW deviations priced at real-time CLMPS) is based on the deviations from day-ahead positions. Any deviations in generation and/or load positions will be priced based on these CLMPS. In addition, changes in the line limits of constrained lines, or other changes in the transmission system, between day-ahead and real-time, and any resulting changes in MW positions, will generate balancing congestion, either positive or negative relative to each constraint.

With balancing, it is possible to incur a net increase or decrease in total charges (positive or negative balancing) with no change in load positions. For example, this would occur if load positions between day-ahead and real-time did not change, but transmission changes (less transfer capability) caused more expensive generation to run more (credits) and less expensive generation to run less (charges). In this event, there would be net negative balancing congestion that would reduce total congestion (day-ahead plus balancing) but no change in bus specific balancing congestion charges to load.

The opposite is also possible, with load positions remaining constant, but increased transfer capability could cause less expensive generation to run more (credits) and more expensive generation to run less (charges). In this event, there would be a positive balancing congestion but no change in bus specific congestion charges to load.

Using constraint specific CLMPS at each bus and deviation MW at each bus, total balancing congestion (load balancing charges minus generation balancing credits) can be calculated by constraint.

The relative contribution to real-time congestion caused by a specific constraint at a specific downstream location can be determined by calculating total constraint specific congestion charges at the affected load bus and dividing by the sum of the constraint specific load related congestion charges at every downstream affected load bus.

As in the day-ahead market, a negative CLMP from a constraint at bus indicates that load at that bus is at the source side of the constraint and any deviations will not pay congestion due to that constraint (the constraint is not a source of lower cost energy being imported to serve that load).

Where the CLMP of a constraint is positive, the load bus is downstream of the constraint and the constraint is isolating the load bus from a relatively low cost upstream source of energy. The difference between what the load deviations are paying for that power and the energy source is being paid for any deviations is the source of balancing congestion charges being collected due to the constraint.

As in the case of the day-ahead allocation calculations, only positive CLMP components of LMP of a specific constraint on each load bus are used to determine sources of congestion collected from each constraint. As in the case of the day-ahead calculations,

the reference bus is moved to the source of each constraint to isolate the full price effect of each constraint on the downstream network.

The balancing congestion of each constraint, positive or negative, is then credited (positive or negative) to each load bus downstream of that constraint (any load bus with positive CLMP from that constraint) in proportion to the real-time congestion charges (not balancing) that would have been charged to the load at the bus.

Total congestion allocated to the bus is equal to the sum of the day-ahead allocations and the net balancing allocation.

Steps for Determining Sources of Balancing Congestion

1. Collect real-time CLMP by studied constraint by bus/aggregate by 5 min interval.
2. Collect day-ahead and real-time load by aggregate by hour.
3. Collect day-ahead generation by bus by hour and real-time generation by bus by 5 min interval.
4. Collect day-ahead and real-time transactions by bus by 5 min interval.
5. Collect deviations by bus by 5 min interval or by aggregate by 5 min interval.
6. Calculate balancing congestion by constraint for each 5 min interval (based on deviations and constraint real time CLMP).
7. Move the reference bus to the location of the most negative CLMP caused by the studied constraint and update resulting CLMPs caused by the constraint studied.
8. By constraint, calculate downstream real-time (+CLMP) congestion charges to load by aggregate by 5 min interval (not balancing).
9. By constraint, calculate downstream real-time (+CLMP) congestion charges to load by bus by 5 min interval (not balancing) using aggregate to bus factors.
10. By constraint, calculate the proportion of real-time (not balancing) downstream (+CLMP) congestion charges collected at each downstream bus by 5 min interval.
11. Balancing congestion collected from a downstream load bus is each constraint's total balancing congestion times the proportion of downstream real-time (+CLMP) congestion charges that would have been collected at that bus by 5 min interval.

Balancing Congestion Example

The following example shows the calculation of constraint specific balancing congestion and the allocation of this congestion to load. The example uses the same 2 bus model with 1 constraint presented above, however, relative to the day-ahead market model, the AB constraint has increased transfer capability (1.5 instead of 1.0) and load at B1 is now 0.25 and load at B2 is now 1.75. Due to the change in the transfer limit, generation at A (the lower cost generator) has increased generation output (from 1 to 1.5) relative to the day-ahead output and Generation at B1 (the higher cost generator) has been reduced output from 1 to 0.5. The result of the changes results in generation and load deviations and balancing congestion associated with changes in the generation and load bill. For ease of exposition, prices are unchanged from the day ahead market result, and the reference bus has been moved to Bus A. Table 9 provides the real time load and

generation by bus, constraint specific CLMPS, total congestion and the proportion of congestion that would have been collected by bus if the market was settled based on real-time positions (no day-ahead market).

Table 9 Real-time positions, CLMP and real-time inferred congestion

Bus	Gen MW	Load MW	CLMP	Load Charges	Generation Credits	Congestion (Net Charges)	Proportion of CLMP Charges to Load
A	1.5		\$0.00	\$0.00	\$0.00		
B1	0.5	0.25	\$100.00	\$25.00	\$50.00		12.50%
B2	0	1.75	\$100.00	\$175.00	\$0.00		87.50%
Total	2	2		\$200.00	\$50.00	\$150.00	100.00%

Table 10 provides the example market's resulting balancing positions (comparing Table 7 and Table 9 results). Net load at B (the sum of B1 and B2) has not changed, but the individual customers have different positions than what was bought in the day-ahead market. Transmission capability on line AB has increased by 0.5 MW, allowing 0.5 MW increase in imports from A and 0.5 less generation to be used from A to meet the load at B. Balancing congestion is a positive \$50 due to a net decrease in the generation charges relative to day-ahead positions.

Table 10 Balancing positions, CLMP, Balancing Congestion

Bus	Gen Deviations	Load deviations	CLMP	Load Charges	Generation Credits	Balancing Congestion (Net Charges)
A	0.5		\$0.00	\$0.00	\$0.00	
B1	-0.5	-0.25	\$100.00	-\$25.00	-\$50.00	
B2	0	0.25	\$100.00	\$25.00	\$0.00	
Total	0	0		\$0.00	-\$50.00	\$50.00

Table 11 provides, by bus, constraint specific CLMP, proportion of downstream real-time load charges, and resulting balancing congestion paid by load. In this example, constraint AB generated \$50 in balancing congestion (load deviation congestion charges minus generation deviation congestion credits). If settled entirely at real-time prices, the load at Bus B2 would contribute \$132.25 in congestion charges (real-time AB CLMP at B2 x real-time load MW at B2), which accounted for 87.5 percent of congestion charges generated by load downstream of constraint AB. Bus B2 is responsible for 87.5 percent (Table 11), or (\$43.75), of the total balancing congestion (\$50) generated by constraint AB. Table 12 shows total congestion charged by bus is equal to the sum of the day-ahead congestion (Table 8) and balancing congestion (Table 9).

Table 11 Proportion of Real-time congestion and bus specific balancing congestion paid

Bus	Gen Deviations	Load deviations	CLMP	Load Charges	Generation Credits	Proportion of RT Solution		Constraint Specific Congestion Paid by Bus
						Balancing	CLMP	
A	0.5			\$0.00	\$0.00	\$0.00		
B1	-0.5	-0.25	\$100.00	-\$25.00	-\$50.00			12.50% \$6.25
B2	0	0.25	\$100.00	\$25.00	\$0.00			87.50% \$43.75
Total	0	0		\$0.00	-\$50.00	\$50.00	100.00%	\$50.00

Table 12 Total congestion paid by bus

Bus	Actual Gen (RT)	Actual Load (RT)	Load Charges	Generation Credits	Total Actual Congestion	DA Constraint	Balancing Constraint	Constraint Specific
						Specific	Specific	Paid by Bus
A	1.5	0	\$0.00	\$0.00				
B1	0.5	0.25	\$25.00	\$50.00		\$25	\$6.25	\$31.25
B2	0	1.75	\$175.00	\$0.00		\$75	\$43.75	\$118.75
Total	2	2	\$200.00	\$50.00	\$150.00	\$100	\$50.00	\$150.00

Day-Ahead Congestion Example: Moving the Reference Bus in a Multiple Bus Model

The following example shows the calculation of constraint specific day-ahead congestion by contributing load source. The example demonstrates how the reference bus is moved when calculating the bus specific downstream congestion costs caused by each constraint. The example uses a 12 bus model with 19 constraints. Generator offers, load bids, constraint limits as well as the market solution (cleared offers, shadow prices, constraint specific flows, bus LMP and total congestion) are shown in Table 13. The transmission system and solution is shown in Figure 2. The market solution shows two binding constraints (EL and FK) and three marginal units (D, E and F) and \$9,593.32 in day-ahead congestion. Constraint EL causes \$8,678.54 in congestion and Constraint FK causes \$914.78 in congestion.

Table 13 Twelve bus, 19 constraint day-ahead market: variables and solution

Congestion Calculations					Energy Market Offers and Bids				Energy Market Clearing				
Line	Flow (MW)	Limit (MW)	Shadow Price (\$/MWh)	Total Congestion \$	ID	Node	Gen Offer (\$/MWh)	Gen (MWh)	Load (MWh)	LMP	Gen	Load	
AB	-107.83	300.00	\$ -	\$ -	1	A	10.00	450.0		16.24	450.0	0.0	
AC	229.55	350.00	\$ -	\$ -	2	B	12.00	500.0		14.12	500.0	0.0	
AD	328.28	400.00	\$ -	\$ -	3	C	25.00	250.0		17.60	0.0	0.0	
BE	392.17	500.00	\$ -	\$ -	4	D	17.00	350.0		M	17.00	165.4	0.0
CF	-82.91	500.00	\$ -	\$ -	5	E	12.00	650.0		M	12.00	531.7	0.0
CG	312.46	500.00	\$ -	\$ -	6	F	10.00	450.0			18.00	450.0	0.0
DE	0.00	500.00	\$ -	\$ -	7	G	0.00	0.0	200.0		18.57	0.0	200.0
DG	213.72	500.00	\$ -	\$ -	8	H	0.00	0.0	290.0		16.19	0.0	290.0
DH	279.94	500.00	\$ -	\$ -	9	I	0.00	0.0	180.0		19.45	0.0	180.0
EH	323.88	500.00	\$ -	\$ -	10	J	0.00	0.0	140.0		19.56	0.0	140.0
EL	500.00	500.00	\$ (17.36)	\$ (8,678.54)	11	K	0.00	0.0	350.0		20.23	0.0	350.0
FK	500.00	500.00	\$ (1.83)	\$ (914.78)	12	L	0.00	0.0	500.0		23.05	0.0	500.0
GI	221.55	500.00	\$ -	\$ -	13	J	0.00	0.0	470.0		19.56	0.0	470.0
GK	104.63	500.00	\$ -	\$ -	14	F	18.00	400.0		M	18.00	132.9	0.0
HJ	313.82	500.00	\$ -	\$ -	15	E	0.00		100.0		12.00	0.0	100.0
U	158.48	500.00	\$ -	\$ -	16	C	0.00				17.60	0.0	0.0
IK	-116.93	500.00	\$ -	\$ -	17	D	0.00				17.00	0.0	0.0
JL	-137.70	500.00	\$ -	\$ -	18	E	0.00				12.00	0.0	0.0
KL	137.70	500.00	\$ -	\$ -	19	F	0.00				18.00	0.0	0.0
			Total	\$ (9,593.32)	20	G	0.00				18.57	0.0	0.0
			Generation Credits	\$ 34,053.48						Total	2230.0	2230.0	
			Load Payments	\$ 43,646.80									
			Net Congestion	\$ 9,593.32									

Figure 2 Day-ahead market solution for table 1 variables

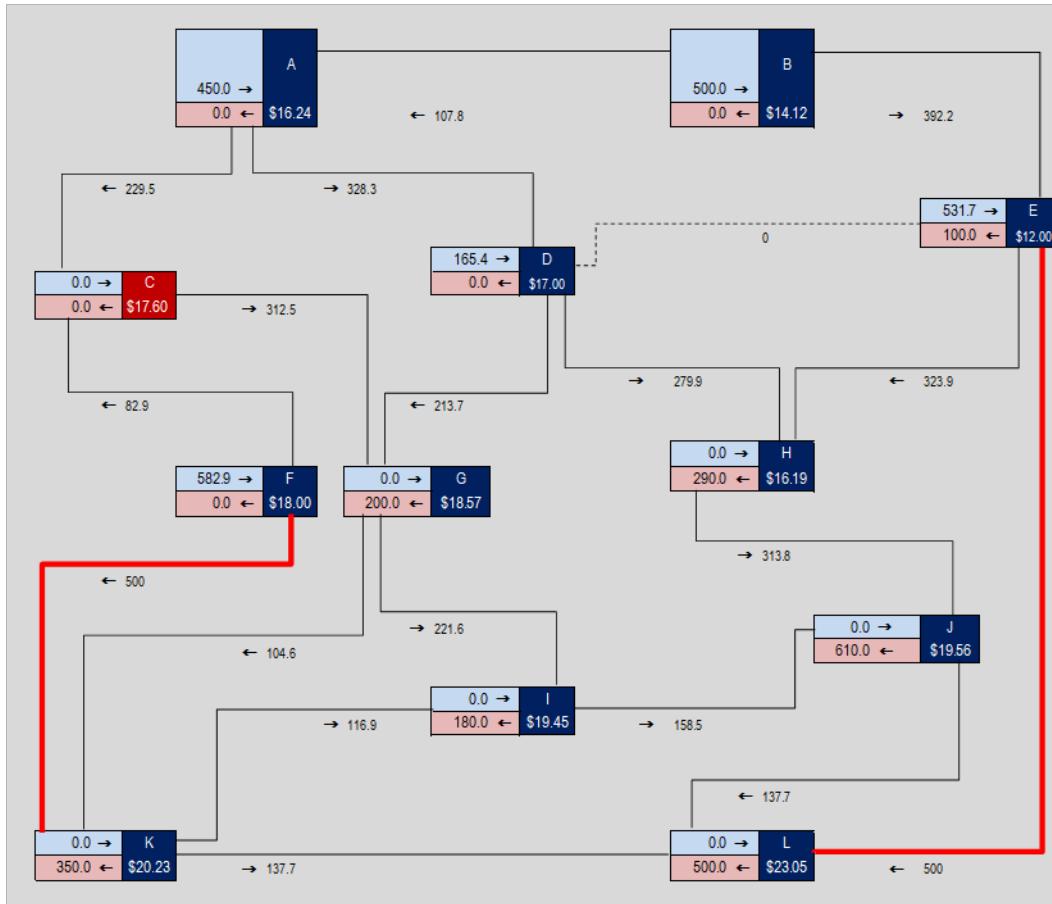
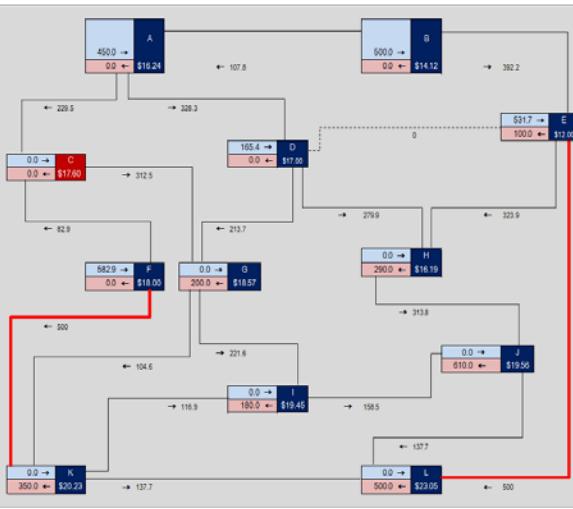


Table 14 provides, by bus, constraint specific component of LMP from the optimization solution. In the system solution, the SMP at the model's initial reference bus is \$17.60. Prices at any bus are either higher or lower than the SMP due to the sum of the constraint specific CLMPS of binding constraint EL and FK. In the system solution, the source side of EL is bus E, as evidenced by the lowest (most negative) CLMP (shadow price times dfax) caused by constraint EL is observed at bus E (-\$6.01). In the system solution, the source side of FK is bus F, as evidenced by the lowest (most negative) CLMP (shadow price times dfax) caused by constraint FK is observed at bus F (-\$0.59).

Table 14 Day-ahead market solution, constraint specific CLMP, generation credits, load charges and total congestion

	EL CLMP	FK CLMP	SMP	LMP
A	\$ (1.58)	\$ 0.21	\$ 17.60	16.24
B	\$ (3.80)	\$ 0.31	\$ 17.60	14.12
C	\$ -	\$ -	\$ 17.60	17.60
D	\$ (0.93)	\$ 0.33	\$ 17.60	17.00
E	\$ (6.01)	\$ 0.41	\$ 17.60	12.00
F	\$ 0.98	\$ (0.59)	\$ 17.60	18.00
G	\$ 0.59	\$ 0.37	\$ 17.60	18.57
H	\$ (1.82)	\$ 0.40	\$ 17.60	16.19
I	\$ 1.35	\$ 0.50	\$ 17.60	19.45
J	\$ 1.49	\$ 0.47	\$ 17.60	19.56
K	\$ 1.96	\$ 0.66	\$ 17.60	20.23
L	\$ 4.93	\$ 0.51	\$ 17.60	23.05



Moving the reference bus to bus E changes the components of price at every location, but does not change the LMP. The LMP at bus E is \$12.00 before and after the reference bus change. After moving the reference bus to bus E, the CLMP of constraint EL at bus E is \$0. The CLMP effect of constraint FK at bus E (Table 14) is still \$0.41. Removing the CLMPs of every binding constraint other than EL at every bus, including bus E, makes every LMP in the system a function of the SMP at bus E and the CLMP of constraint EL.

Table 15 shows the LMP at every bus after removing the CLMPs for every binding transmission constraint other than constraint EL. Table 15 also shows the resulting components of LMP after moving the reference bus to bus E. After removing the effect of constraint FK, the LMP at bus E, the reference bus, is \$11.59. Any bus with a positive CLMP relative to the reference bus E is, from network solution perspective, downstream of the constraint EL.

Table 15 Move the reference bus to the source of the studied constraint and remove all other constraint CLMPs

Bus	SMP + CLMP of EL		
	Only LMP	EL SMP	EL CLMP
A	\$16.02	\$11.59	\$4.43
B	\$13.80	\$11.59	\$2.21
C	\$17.60	\$11.59	\$6.01
D	\$16.67	\$11.59	\$5.08
E	\$11.59	\$11.59	\$0.00
F	\$18.58	\$11.59	\$6.99
G	\$18.19	\$11.59	\$6.60
H	\$15.78	\$11.59	\$4.19
I	\$18.95	\$11.59	\$7.36
J	\$19.09	\$11.59	\$7.50
K	\$19.56	\$11.59	\$7.97
L	\$22.53	\$11.59	\$10.94

Table 16 shows the CLMP for constraints downstream of constraint EL, the load by bus, the total congestion caused by constraint EL, the proportion of charges contributed by load downstream of constraint EL and the total congestion paid by each downstream load bus due to constraint EL.

Table 16 Constraint EL congestion cost by bus

	Total Congestion					Congestion Source	
	EL	\$ 8,678.54	Load	Charges	Proportion		
A	\$4.43	0.0	\$0.00	0.0%	\$0.00		
B	\$2.21	0.0	\$0.00	0.0%	\$0.00		
C	\$6.01	0.0	\$0.00	0.0%	\$0.00		
D	\$5.08	0.0	\$0.00	0.0%	\$0.00		
E	\$0.00	100.0	\$0.00	0.0%	\$0.00		
F	\$6.99	0.0	\$0.00	0.0%	\$0.00		
G	\$6.60	200.0	\$1,320.00	10.0%	\$869.87		
H	\$4.19	290.0	\$1,215.10	9.2%	\$800.74		
I	\$7.36	180.0	\$1,324.80	10.1%	\$873.03		
J	\$7.50	140.0	\$1,050.00	8.0%	\$691.94		
K	\$7.97	350.0	\$2,789.50	21.2%	\$1,838.26		
L	\$10.94	500.0	\$5,470.00	41.5%	\$3,604.69		
			\$13,169.40		\$8,678.54		

The constraint specific process is repeated for each constraint until all congestion costs are accounted for system wide.