Commissioner Primer

Locational Marginal Pricing

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EXECUTIVE SUMMARY

There are many wholesale electricity markets across the nation, and the shape and status of each of those markets has been characterized by frequent fluctuation and change. Some of these wholesale markets have evolved over many decades through bilateral or regional efforts and the development of trading hubs, power pools or exchanges. In more recent years, FERC has overseen the creation of *organized* regional wholesale markets in several parts of the nation. This process is still underway as FERC continues to encourage the organization of more regional markets and seeks adjustments of existing markets to make those markets more transparent, competitive, efficient and perhaps, ultimately, less regulated.

The operation of the wholesale electric market has a direct effect on the provision of retail electric service. Whether retail electric service is provided in a restructured retail market or in a traditionally regulated system, wholesale costs incurred by retail electricity providers directly affect retail rate setting. Consequently, the manner in which retail providers acquire wholesale supply and how that supply is priced and distributed are very important to state utility commissions. The Federal Energy Regulatory Commission (FERC) has endorsed a model of wholesale electricity pricing called locational marginal pricing (LMP).

This NRRI primer is a basic overview of LMP. The purpose is to provide state public utility commissioners with a general understanding of LMP within the very complex operation of the wholesale electric market. The primer does not attempt to explain all the technical issues that factor into electricity market operations. However, when theoretical principals of the wholesale market operation and a little technology are understood, it is easier to understand and monitor the factors that affect the actual operations of these markets. After reading this primer you should understand that:

- LMP is a centralized market structure method of wholesale pricing using quantity- and price-specific bids in an auction-type market for a specific market location
- LMP is intended to promote least-cost wholesale electricity supply and dispatch while enhancing reliability
- LMP is intended to encourage appropriate generation and transmission development by creating location-specific prices that identify where such development is needed

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SIMPLE MARKET OVERVIEW

Perfect Competition:
A Market Ideal

A perfectly competitive market consists of balanced producers and consumers. That is to say that neither the producers nor the consumers have a market advantage. In a perfect market, prices are set at the marginal cost of production; all firms take product price as a given; no single firm can increase or lower the market price through unilateral or coordinated action; the market determines the price based on supply and demand; and finally, there are no barriers to market entry or exit. In reality, it is rarely if ever possible to have a perfectly competitive market. Achieving perfect wholesale electric markets is especially difficult due to the nature of electric transmission and the fact that electricity is not a typical commodity that can be produced and stored for later sale. In this primer we show how the wholesale electricity markets would theoretically work if perfect conditions existed. Next, we consider how actual market conditions make perfect electricity wholesale markets impossible.

In a perfectly competitive market, a generator will bid its electricity into the market at their marginal cost of producing that electricity.

For this primer, electricity generation firms can generally be considered as the wholesale electricity market supply producers. Consumers are usually the retail electric service providers.[1] The generators and retail service providers enter into an auction market. This market, in theory, works very simply. The market operator works as the auctioneer. For this primer, we will assume the market operator is a Regional Transmission Organization (RTO) as defined by FERC; however, many wholesale market transactions occur outside of an RTO. The retail providers come forward to the auctioneer with an expected demand for electricity. This demand is often referred to as the load. The auctioneer, without telling the generators how much will be demanded, opens the auctions. The generators that wish to sell power place

Technical Fundamentals

A basic awareness of a few physical fundamentals of electricity transmission are necessary to explain LMP. The flow of electricity through transmission lines is dependent upon the characteristics of the lines on which it flows. The grid has certain thermal, voltage, and/or stability limits which may vary by weather, location, time, and the amount of generation and load. Here are four general guidelines on which to build further technical understanding:

1) Electricity flows do not reflect contract paths.

2) Electricity flows over all interconnected lines, in the path of least resistance between the generators and the load.

3) Generally, to increase or decrease the flow of electricity the generation of electricity must be increased or decreased.

4) Electricity flows must have balancing counter-flows. Reducing or increasing flow in one direction necessitates a balancing reduction or increase in flow in the counter direction.

5) All generated electricity must be transmitted. It cannot be stored nor discarded. Basically speaking, the supply must be equal to the load.

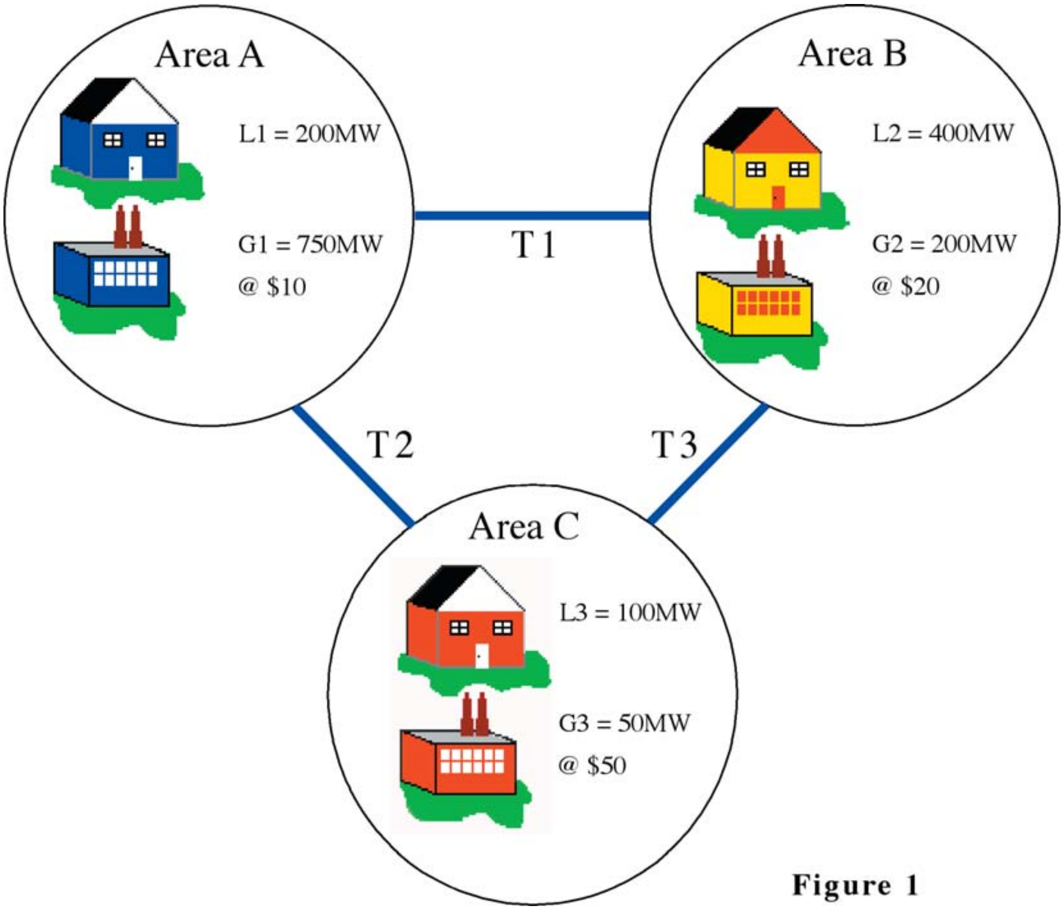

Figure 1

a "bid" that offers a specific quantity of electricity at a proposed price. In a perfectly competitive market, a generator would bid its electricity into the market at its marginal cost of producing that electricity.[2] The auctioneer then starts at the lowest bid and accepts all the bids in ascending order of price until the submitted demand is covered by sufficient supply. This is commonly referred to as "least-cost" or "merit order" dispatch. In the simplest scenario, the price bid by the last generator whose bid is accepted becomes the market-clearing price. In other words, the highest price bid accepted becomes the price for all accepted bids even though the other generators' original bids were below the market-clearing price.[3]

Market Operation – A Simple Market Example

We use an example of a simple market to begin to explain how the market works. The example assumes an auction market under perfect conditions where each generator bids at its marginal cost and there are no conditions that would prohibit the perfectly competitive forces from working.[4] This hypothetical market has three generators (G1, G2, and G3), three loads (L1, L2, and L3), and three transmission lines (T1, T2, and T3). As seen in Figure 1, G1 bids in a quantity of 750 MW at a price of $10 per MW, G2 bids in 200 MW at a price of $20 per MW, and G 3 bids in 50 MW at a price of $50 per MW. The load at L1 is 200 MW, the load at L2 is 400 MW, and the load at L3 is 100 MW. We also assume lines T1, T2, and T3 have unlimited use capabilities.

In this example, shown in Figure 1, total load is equal to 700 MW. To completely cover this load, the auctioneer looks at the bids, sees that G1 will produce the cheapest electricity, followed by G2, then G3. In this example, the auctioneer can fill the 700 MW load demand entirely from G1 with nothing more from the other two generators. Thus, the bid from G1 is accepted, the remaining bids are rejected. G1 supplies 700 MW at $10, the supply equals the demand, and the market-clearing price is $10.

MARKET COMPLICATIONS

We began with a very simple model that assumed a perfect market. The simplified view was necessary to understand the far more complex reality of the actual wholesale electricity market at work. The reality of the wholesale electricity markets and the physical transmission system is that perfection as assumed above is probably impossible to achieve. Generators usually have different asset portfolios**,** which often include multiple generating units. Generating units may differ by size (potential output), the cost of the fuel necessary to operate the units, the location of the units, as well as the type, age and efficiency of the units.

Differences among and between producers and consumers add complications to the market operation. However, the two most common and problematic market complications are transmission congestion and market power.

Congestion

The management and cost assignment of congestion are some of the complications that LMP is intended to assist. Congestion occurs when the transmission lines (T1, T2, and T3 in our example) fill to capacity. Power lines can only carry so many electrons at any given point and time. Once a power line reaches and exceeds its capacity limit safety and reliability become concerns. Power lines are subject to several limits, like voltage and thermal limits. Limits are set to keep lines from overheating and/or sagging which can lead to power outages if a sagging line grounds out by contacting something such as a tree. For example, a given power line may be limited to carrying 250 MW under certain conditions. Any more power across this line could cause this line to overheat and/or sag. Areas with high demand relative to local supply are often subject to frequent and regular transmission line congestion. During a period of active transmission congestion, these areas commonly referred to, as "load pockets," are isolated from the rest of the market by lack of transmission access to more distant generation sources. Simply put, congestion can separate one large geographic market into multiple smaller markets because all available generation within the one larger market cannot get past the transmission constraint into the load pocket.

Load Pocket

An area isolated from outside supply due to transmission congestion.

An over simplified analogy may be roads into a city. During rush hour, the roads fill and no more workers can get into the city. This would create a new market for workers from within the city. In a market where all generators bid at marginal cost, the market operator will dispatch them in merit order until the load is met or the necessary transmission line(s) reaches its physical limit or congests. Once the lines congest, simple least-cost merit order dispatch is no longer possible. Similar to our city traffic example, if congestion inhibits the delivery of electricity from generators outside of the load pocket; the RTO will have to dispatch generation from within the load pocket to meet the demand and alleviate or avoid the congestion bottleneck. It is often the case that the generation within the load pocket

The Hydro Case

The availability and cost of water (which is the fuel) to a hydropower generator on a hydraulically linked system of generators depends upon whether or not other generators on the system are dispatched.

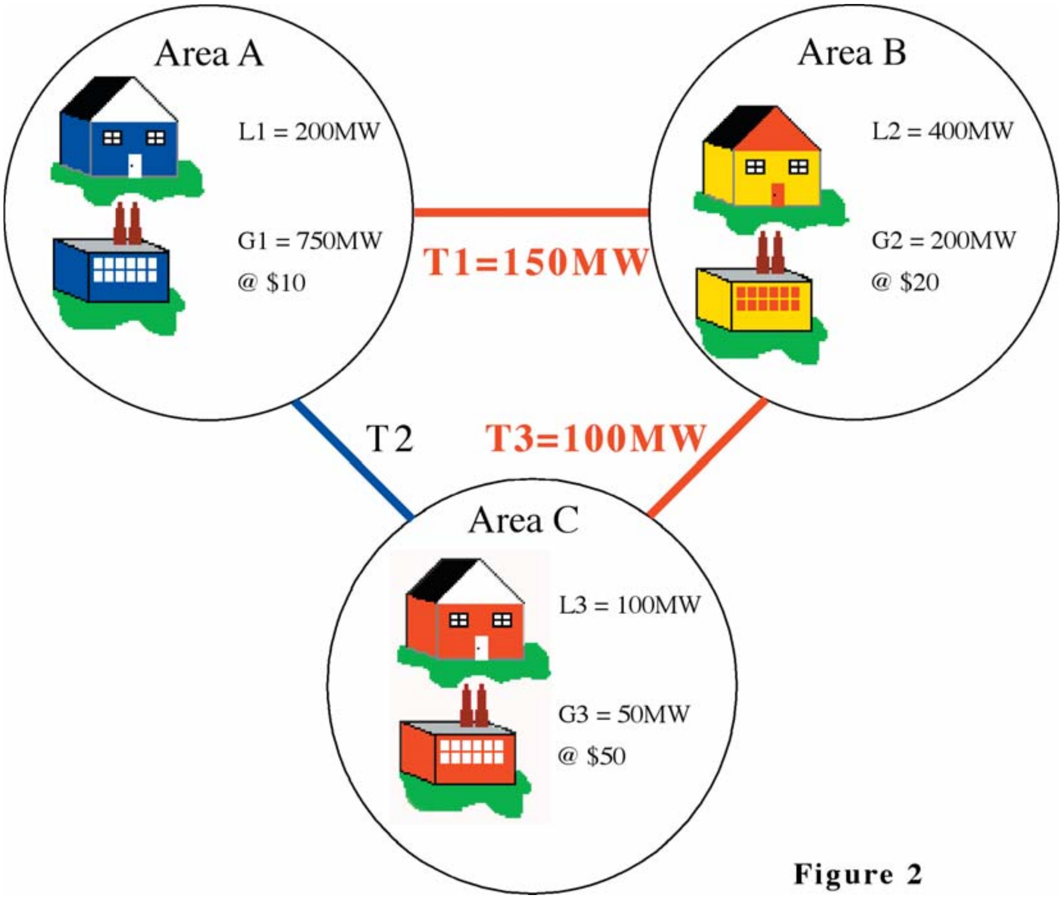

Figure 2

is of higher-cost than some generation that may have been available, absent the congestion, from outside the load pocket.[5] Consequently, the cost of electricity within the load pocket is elevated as a result of the congestion caused by insufficient low-cost generation or transmission constraints.

To expand on the above point, it is useful to return to the simplified perfect market model. In that example we assumed that all power lines had a capacity level that could carry all the necessary supply of electricity to the point of demand. We will now change this assumption. We will keep the same supply and demand assumptions, but now we assume that line T1 is limited to 150 MW and line T3 is limited to 100 MW. This can be seen in Figure 2. The constraint on line T3 is important here because, as mentioned above, power flows in all directions over all available lines. This means that power generated by G1 can get to L2 either by line T1 or a combination of line T2 to T3. In this example, G1 is unable to provide all of the electricity demanded. G1 will be called to supply as much as it can, which is 200 MW for L1, 100 MW for L3, but only 250 MW for L2. L2 receives 150 MW via line T1 before it constrains, and 100 MW from line T3 before it constrains. Now L2 is 150 MW short. In order to fulfill this shortage, G2 will be asked to produce 150 MW. Now, supply equals demand. The interesting question is what the clearing price will be. This question will be addressed below in the discussion of LMP.

Though the concept of congestion seems easy enough to understand, the physics of actual electric congestion are a bit more

Kirchoff's Laws

1. Voltage: The sum of all currents flowing into and out of a node must equal zero. No charge can be lost in the node.

2. Current: For any closed loop path around a circuit, the sum of the voltage gains and voltage drops must equal zero

Remember the Technical Fundamentals

- ✓ Electricity does not follow contracts
- ✓ Electricity flows over all available lines
- ✓ To increase or decrease the flow the generation of electricity must be increase or decreased.
- ✓ Every flow must have a balancing counter-flow
- ✓ Supply must equal demand

complicated. Transmission congestion happens most frequently in times of high demand, but it is possible to have congestion in times of lower demand. This further complication is due to a physical laws of electricity (Kirchoff's Laws) regarding the manner in which electricity flows through transmission lines. Electricity must flow in both directions in balanced portion at all times. Essentially this means that the capacity of the line is not only limited by the amount of power flowing in one direction, but is also affected by the amount of power flowing in the opposite direction. Consequently, if demand is lower in a given location such that there is less generation and less flow in one direction to the low demand location, the constraints of the associated transmission lines are tightened in the opposite direction in proportion to the reduction in flow to the low demand area. This is where our city streets traffic example above ceases to be applicable. Imagine that there is a 12-lane superhighway connecting the city to a suburb. During the morning rush hour the lanes into the city our packed, but lanes out of the city are wide-open. During the evening rush hour this traffic pattern is reversed. However, during the non-rush periods there are still six lanes ready for use at any time in either direction. With electricity transmission, this is not the case. During high-demand periods in one direction the flow must still be balanced in both directions. Imagine that during rush hour, in order to fill all six inbound lanes with traffic, you would need to simultaneously fill the outbound lanes as well.

Market Power

In an open market, if it is known that a specific firm's production will always (or usually) be required to meet market demand, then that firm has significant market power. Many wholesale electricity markets are still in the developmental stages and may be characterized by the presence of pivotal or required generation providers. Consequently, these markets are still subject to significant market power concerns. The high societal value of electricity compounds the concerns of abuse of market power. These concerns are handled by the US Department of Energy's (DOE) Federal Energy Regulatory Commission (FERC), the US Department of Justice, and the Federal Trade Commission. These agencies review complaints and concerns regarding the illegal use of market power.

Market power is simply the ability for one firm to affect price through unilateral or coordinated action. For example, in the competitive market described above, the market determined the market-clearing price. A firm with significant market power knows that the market will demand different amounts of its output at different prices. If that firm reduces output, then, in most other markets, it may see some buyers drop out of the market. However, most buyers in the organized wholesale electricity markets are load-serving entities with strong or unavoidable obligations to provide electricity to its subscribers. Consequently, many buyers will not be able to drop out of the market. Those that still need this output (supply) will now compete for a much scarcer product. In this way a required generation provider may reduce output ("capacity withholding") in order to drive up the price of the good it produces. By doing so, it is able to extract higher profits from the market.

In the strictest sense, G1 has market power in our original example. It knows that the market must take at least some of its output. In order to demonstrate this point we will again change some of our assumptions. In the original problem, the owner of G1 will sell 700 MW at

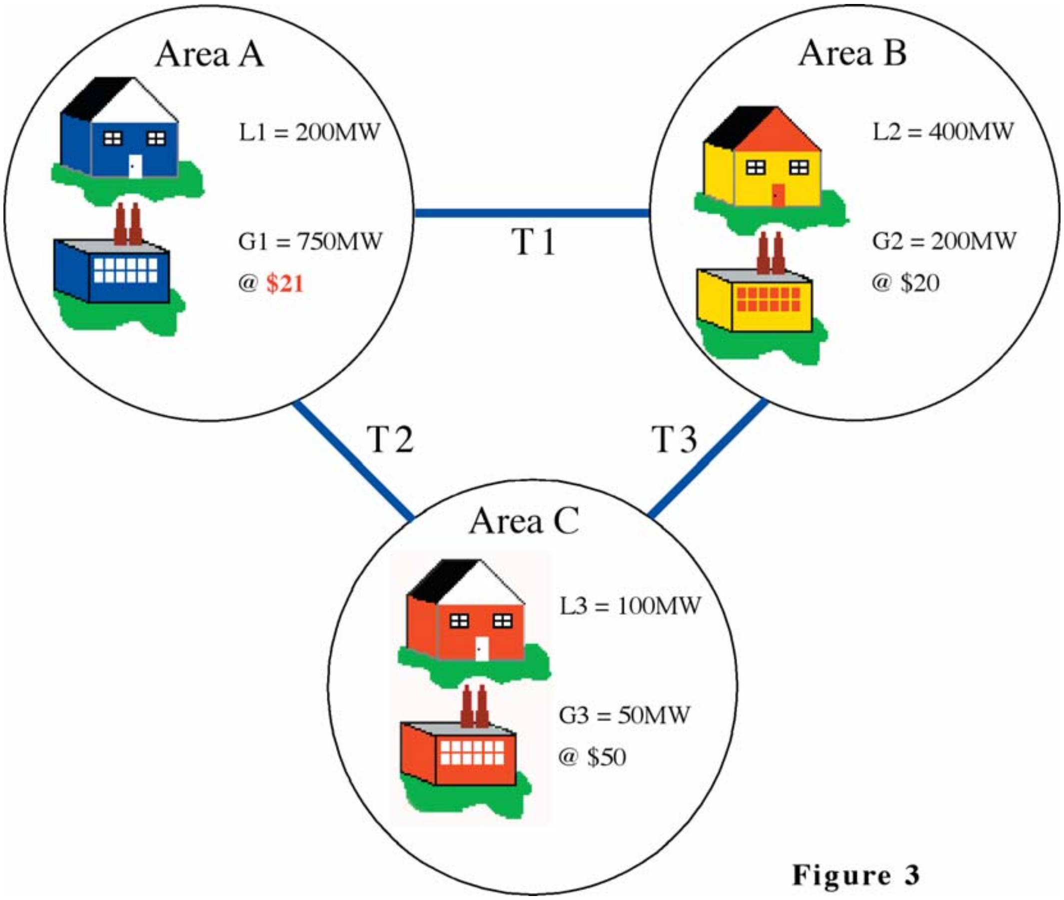

Figure 3

$10 thus giving it $7000 for its output. Now, assume that G1 raises its price to $21. In this new example, as shown in Figure 3, still assuming there is no threat of congestion; merit order is G2, G1, and then G3. Demand is still equal to 700 MW. G2 will be called to produce at full capacity, 200MW. G1 will then be called to produce 500 MW at $21. This sets the clearing-price at $21. So the total revenue for the owner of G1 will be $10,500. This increase in revenue is a result of economic withholding. Economic withholding occurs when a plant bids its generation into the market at an exceptionally high price.[6] In this example, such withholding resulted in raising the market-clearing price and providing the owner with higher revenues.

Economic withholding is not the only means used to exercise market power. It is also possible for a firm to physically withhold its output from the market. We will again go back to the original example, and change some of the assumptions. In this example, as shown in Figure 4 we have all plants owned by the same firm.[7] We will also assume that G1 produces 650 MW. Demand is still 700 MW.

Suppose that G2 has been taken down for repairs and is not available. G3 must be called to fulfill demand. The clearing price will now be $50 instead of $20 if G2 had been in service. To emphasize the difference, with G2 in service, the firm makes $14,000, without G2, it makes $35,000.

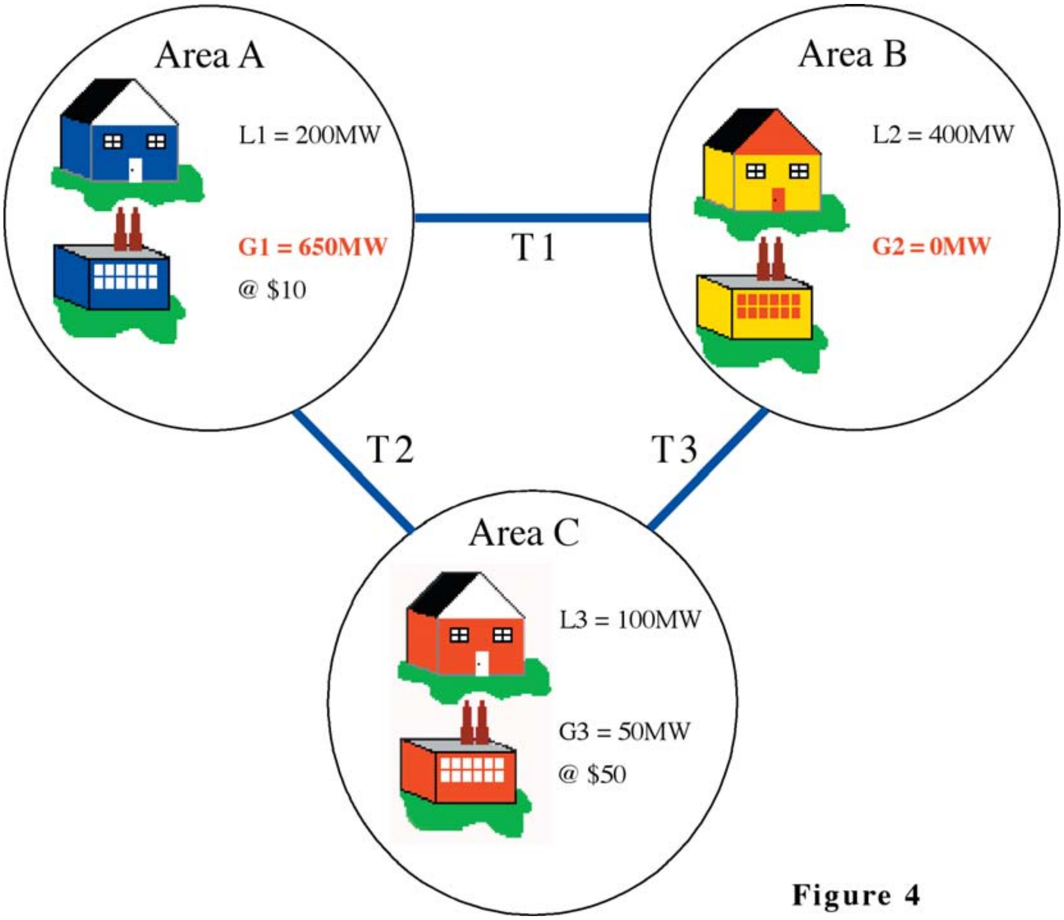

Figure 4

Congestion and Market Power in Wholesale Electricity Markets

Now that the basic ideas of congestion and market power have been explained, we combine them to see how they can be used in the context of a wholesale electricity market. It has already been demonstrated how each of these complications work separately, but they can also be used in conjunction with one another. In Figure 1, G2 had no market power. However, when faced with congestion as in Figure 2, G2 will be put into a position of market power. The congestion means that area B becomes its own market for the final 150 MW. Since no one else can serve the load, G2 bids in its capacity for $80, as shown in Figure 5. Only 150 MW are taken, but it generates $12,000 in revenue, which is three times more than if it had sold all 200MW of capacity at $20.

Another way in which a generator might abuse market power is to “create” congestion using the generator’s location and the physical laws of electricity. Recall that the capacity of a transmission line is affected by counter flow out of a load pocket, as well as the flow into it. Using a combination of assets, a firm with generation assets inside and outside a load pocket may find a set of market and transmission conditions wherein it becomes beneficial to bid an exceptionally low price from one generation unit outside the load pocket and a relatively high price from a generation unit within the load pocket. The hope being that the low cost unit is dispatched and thereby causes a line to congest blocking further in-flow from other non-affiliated generators. As a result, a new market is created within the load pocket and the high- priced generation is also dispatched.

By congesting the lines at a known price, the generator may be able to remove uncertainty regarding actions within that load pocket, and thus bid higher prices knowing that it would be taken to meet the load requirements.

Congestion can also be created using inappropriate physical and/or economical withholding.[8] If a generator in a load pocket chooses to withhold electricity, it effectively reduces the amount of energy able to flow into the pocket. By doing so, the firm may block lower cost power from entering, thus creating a load pocket in which they have market power. This generator may then be paid the higher amount due to the congestion created by its exercise of market power.[9]

WHAT IS LMP?

LMP is commonly defined as the cost of providing the next MW to a specific location in the least-cost manner given transmission constraints. Though some regions use slightly different terminology, like Locational Based Marginal Pricing or Locational Margin Pricing, the principle behind all of these methods is fundamentally the same. To fully understand this definition, we can break it down into parts starting with the last part:

- "Given transmission constraints" – Transmission constraints can prevent power from flowing freely to all loads. Therefore, the market-clearing price may be impacted.

LMP

The cost of providing the next MW to a specific location in the least cost manner given transmission constraints.

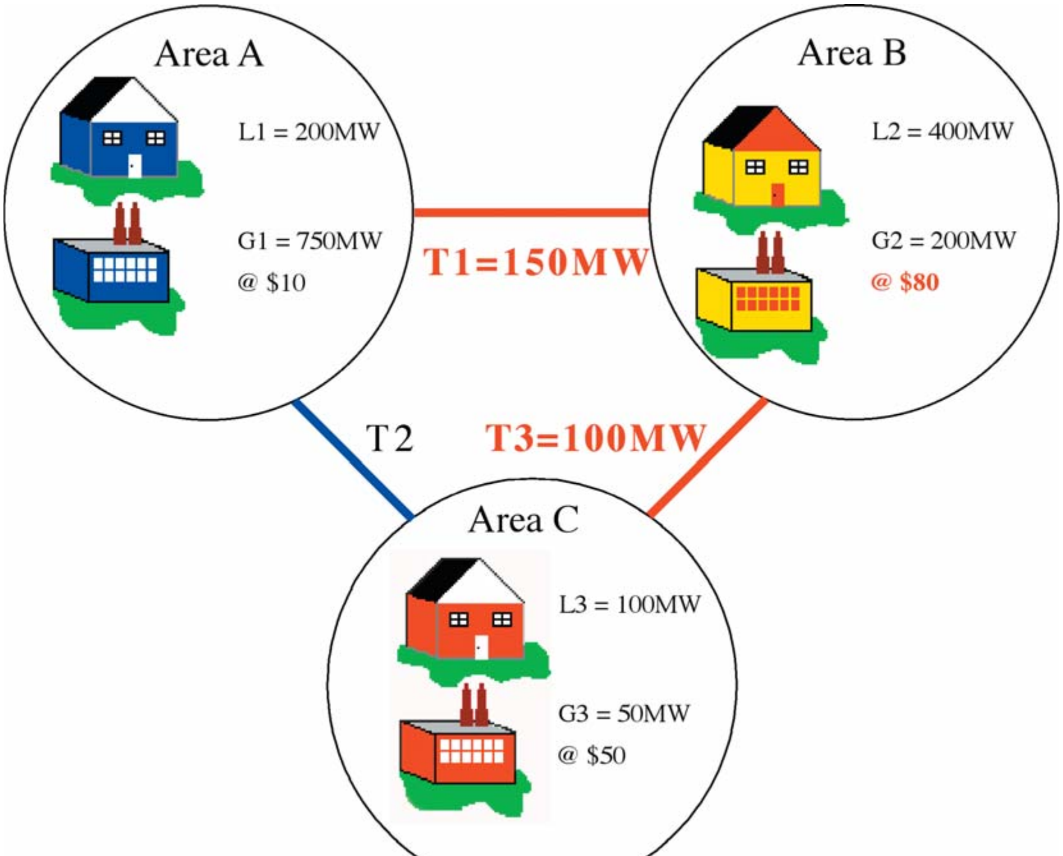

Figure 5

- "In the least-cost-manner" – Even in the face of congestion, there is an order of dispatch that will meet load with the least-cost possible. This least-cost dispatch will likely be higher when there is a need to adjust dispatch for congestion than if there were no congestion.

- "To a specific location" – Just as its name suggests, LMP is determined at a location. The location of interest is referred to as a node. The concept of nodes, how they work, and when they are important is be discussed in greater detail below.

- "Cost of providing the next MW" – This is a concept similar to a clearing price.

Putting these ideas back together, we start to get an idea of how LMP works. When there is congestion, each location affected by the congestion will have its own clearing price that reflects the least-cost means of meeting demand through an adjusted dispatch order.

Nodes

Points in transmission grids at which an LMP price can be calculated.

In an LMP structure, nodes define locations. Nodes are simply points in the transmission grids at which a LMP price can be calculated. There can be thousands of nodes in a system. However, most nodes are not of immediate LMP interest. Interest is generally focused on nodes between which there is a price difference. When a price difference exists between two nodes, each of these nodes could be in a different market. LMP prices vary between locations in a transmission system because the least-cost energy dispatch is constrained by physical properties of the transmission system. Congestion, market power, planned and unplanned outages, line losses, fuel source, and generation location, can all cause price differences. Nodes of interest can change as supply, demand, and congestion changes. Just like the city traffic, we do not always know where, when, and/or to what degree congestion will occur. The road can become congested because of planned construction or an accident. Accidents and construction are not always at the same place, but they are most frequent on heavily traveled highways. We can also see patterns in electrical grids. Like busy intersections, we expect congestion to happen at certain points more frequently than at others.

To help further understand what happens with LMP, it is easiest to go back to the congestion example in Figure 2. In this example, we had limits on lines T1 and T3. L2 then becomes isolated. In LMP, L2 is now a separate market. So now there are two markets with different prices. L1 and L3 will be one market and have the same price, while area L2 will be a new market with a new price. The market-clearing price for L1 and L3 will be $10, while L2 will be $20. G1 will receive $10 for 400 MW for load served in L1 and L3 and $20 for the 150 MW serving load in pocket L2. Meanwhile, G2 will receive $20 for the 150 MW used to serve load in L2. In theory, this is a desirable outcome because the higher cost of energy in L2 was borne by L2, while L1 and L3 continued to enjoy least-cost pricing for their particular markets.

In the model, every market gets least-cost pricing based on the specific conditions of supply, demand, and congestion within each market.[10] Of course in reality, the electricity system is not as simple as our three-node model. LMP prices at a given node are affected by the offer prices of all generators on the grid.

What Does LMP Attempt to do?

Among the goals of LMP is ensuring a least-cost or merit order dispatch of wholesale electricity, increasing the reliability of the electric transmission grid, and mitigating the occurrence and potential for market power abuse. The use of nodes means that at any given location, the price paid should reflect the marginal cost to produce and transmit to that node. This means that every node should be paying for the electricity demanded at that node.

Another intended goal of LMP is to provide clear market signals that identify areas where market participants could or should take certain actions. The signals should be transparent to all, regulators and market participants alike. A market participant should be able to see if it is being blocked out of markets. At least in the design theory, transparent LMP nodal prices are intended to encourage the development of new transmission lines or generation by identifying locations where system limitations lead to higher prices, and therefore, the locations where the expansion or addition of generation and/or transmission would be a financially positive investment.

LMP might also be an indicator to market monitors that a market participant(s) in an organized regional market is behaving questionably. The signals come from the difference in prices between two or more nodes. In the congestion example, LMP would send a signal that there is insufficient transmission capacity into or insufficient generation within the load pocket. This signal can be seen without any knowledge of how the transmission lines are used. If a market monitor were to look at the congestion example without the lines, assuming that our firms bid in a fair fashion, the monitor would see that there had to be insufficient transmission or local generation, simply by noticing that the prices in L1 and L2 are different.[11] In a similar manner, armed with only basic plant characteristics, the same monitor could identify the exercise of market power. For example, if our market monitor knows that G1 is a low cost coal plant, and G2 is a higher cost gas plant, and sees that G1 has a higher bid price than G2, the market monitor should be suspicious.[12] However, to see inappropriately created congestion, the market monitor would need to examine more detailed information about the network and market participants.

SUMMARY

The nature of electricity and the significant regional variations in supply and demand around the country make the operation of the wholesale electricity markets exceedingly complex. By first understanding the theoretical principals of wholesale market design it is easier to understand and monitor the factors that complicate the operation of the markets.
LMP is intended to enhance the efficient and reliable operation of the organized wholesale generation and transmission systems while insuring least-cost dispatch. LMP is also suppose to identify the best places to improve and/or expand transmission and generation facilities and locate areas in need of greater market mitigation by creating transparent market signals in areas of repeated supply shortages or transmission constraints.

LMP is still a new model and only time will definitively demonstrate its successes or failures. LMP will probably never be a perfect solution for all wholesale market concerns. It has its limitations. At this time, LMP is largely a supply-side focused approach to organized markets. Integration of demand-side factors to such issues as transmission congestion or generation shortages remains to be

Time Will Tell

One difficulty of LMP acting as a real-time price signal to encourage new plant investment is the inevitable passage of much time between such a signal and when new plant could be operational. The siting and construction of new transmission lines is often an endeavor of three or more years. A new generation plant may be considerably longer. Consequently, it is not yet clear that the value of time and the risk that the real-time signal will still be there several years later do not in combination outweigh the incentive of the current high LMP price in a given location.

considered. LMP is data intensive and requires sufficient access to producers in order to assure least-cost dispatch and to prevent inappropriate market behaviors.

The operation of the all electricity wholesale markets, and in particular the wholesale prices paid by retail electric service providers, has a direct impact on the retail services provided in every state regardless of whether a state has a restructured or traditionally regulated retail system. State utility commissions must continue to be vigilant in their attention to wholesale electricity markets. The implementation of market protocols such as LMP may provide additional safeguards and market-based controls to organized regional wholesale markets; however, market abuses are still possible with LMP. Additionally, LMP should not be seen as only a way to encourage new generation and transmission development, but also to identify locations where the mitigation effects of demand-side measures should be considered.

Disclaimer

This is the first in a planned series of Commissioner Primers intended to provide objective, readable introductions to current utility subjects.

The Primers are not intended to be policy endorsements or criticism but resources for Commissioners as they engage in policy debates and deliberations.

Notes

[1] In some instances the consumer in the wholesale market may be a large industrial consumer that is able to participate directly in the wholesale market, self-supplying or contracting necessary services from another provider, possibly bypassing the distribution service provider.

[2] In a perfectly competitive market, a generator bidding above marginal cost runs the risk of bidding too high, and thus not selling its supply into the market.

[3] Some regions may be using the price of the next MW that would be taken after the last MW that was actually taken.

[4] Factors such as line losses; unforced or unplanned outages; impedance; load service obligations; affiliations between suppliers and consumers; and other factors have been ignored for the sake of simplicity.

[5] Though rare, it is sometimes the case that local generation, or generation inside the load pocket, is the least-cost dispatch.

[6] This exceptional price is determined relative to others comparable bidders, current market conditions, the generator's bid history, the operating characteristics of the physical plant, and/or other externalities.

[7] In this problem we will ignore the economic withholding behavior discussed above. This example could also work if the same firm owned only G2 and G3.

[8] Withholding generation is not by default inappropriate. A generator may physically withhold a unit that is undergoing maintenance or repairs. In an open market, a generator may simply decide that market conditions are such that generation would not be cost effective at a particular point in time. Inappropriate physical or economic withholding is when it is done with the intention of affecting market to the advantage of the withholding firm.

[9] This is somewhat offset by the reality that whenever generation or load changes, the entire grid is redispatched to determine the LMP at any point.

[10] Least-cost pricing in the wholesale market is not a de-facto guarantee of least-cost pricing in the retail market. Furthermore, it is not a given that marginal costs of generation are always lower than the average cost.

[11] There are other reasons for price differences, but we have looked past more complex reasons for LMP price separation differentials.

[12] This is a clear case of a red flag regardless of an LMP market structure, but it fits accurately into the example.

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