# Locational Marginal Pricing (LMP)

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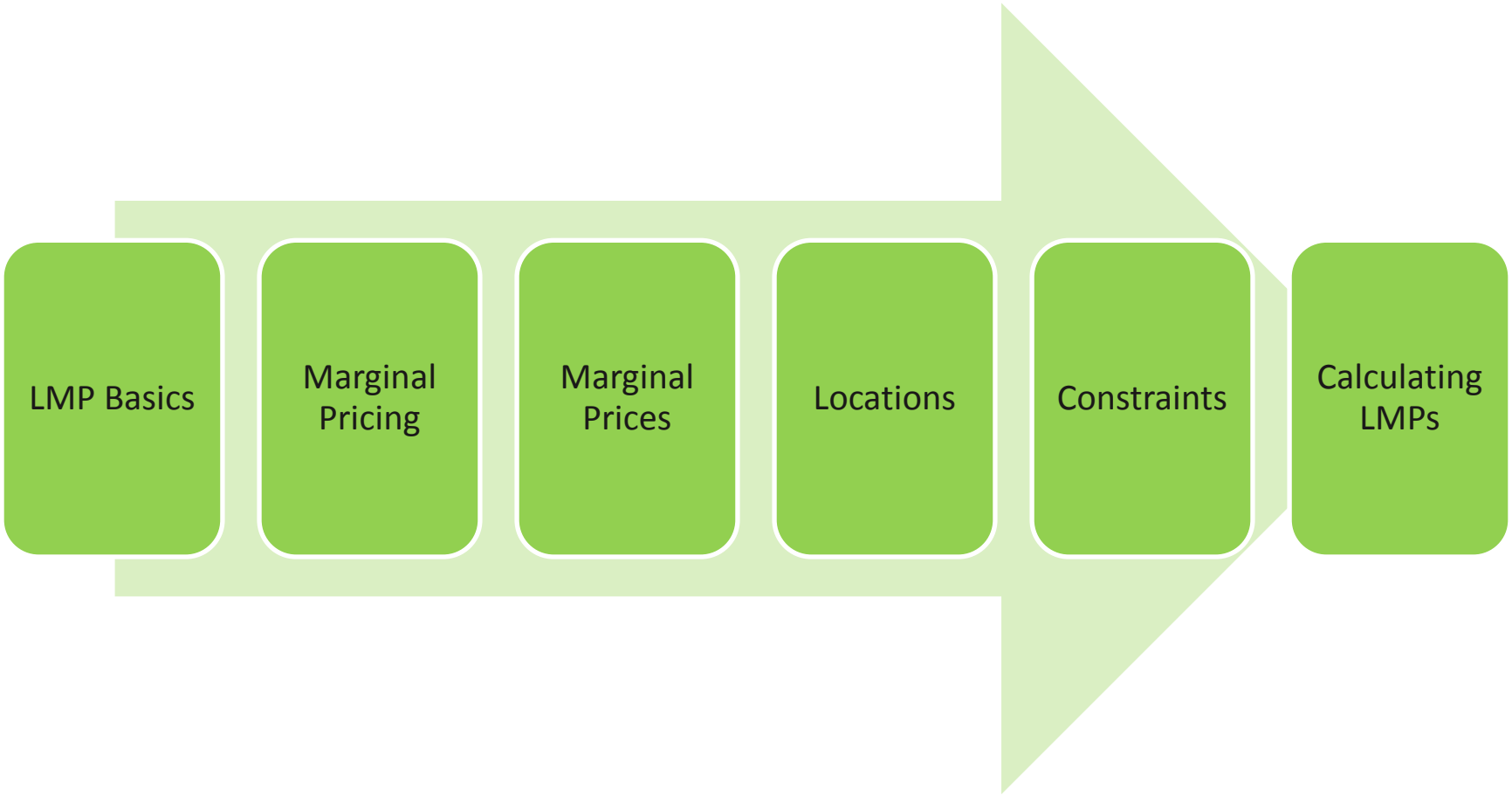
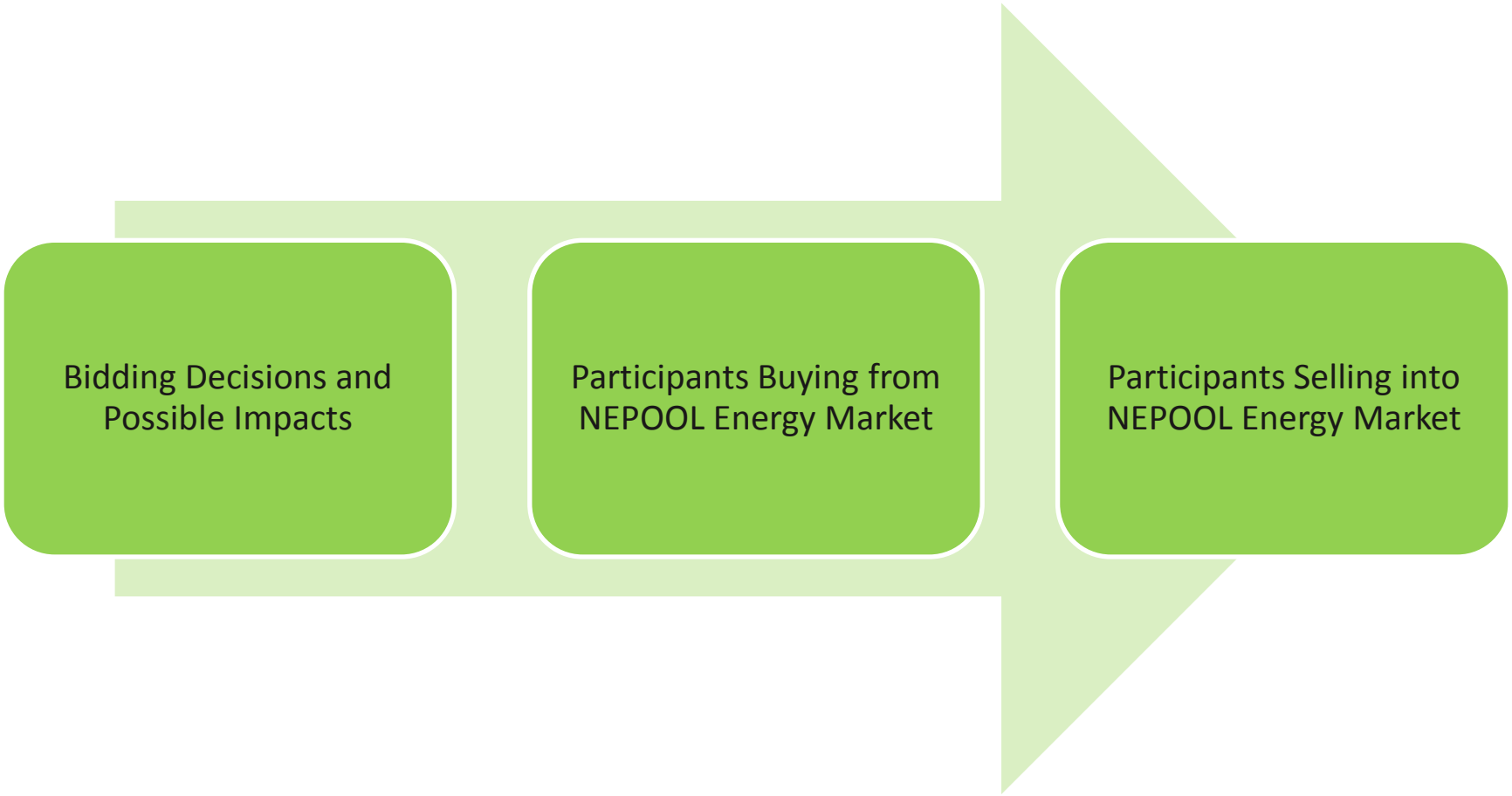
# Module Objective

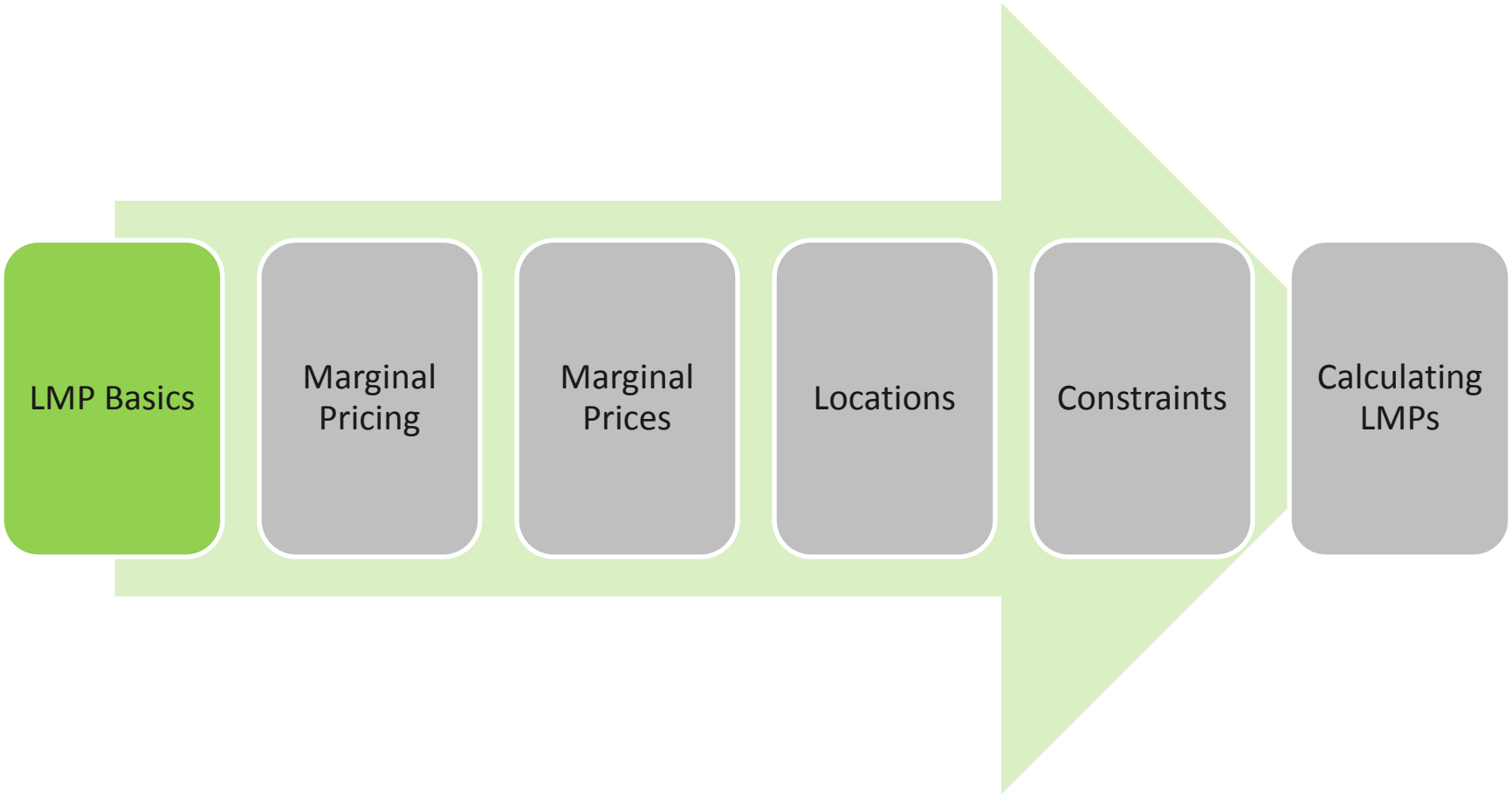
- To present a foundational knowledge of Locational Marginal Pricing (LMP) using examples
- Explain Bidding/Offer impacts on LMP

# Topics Covered in this Module



# Topics Covered in this Module (cont.)





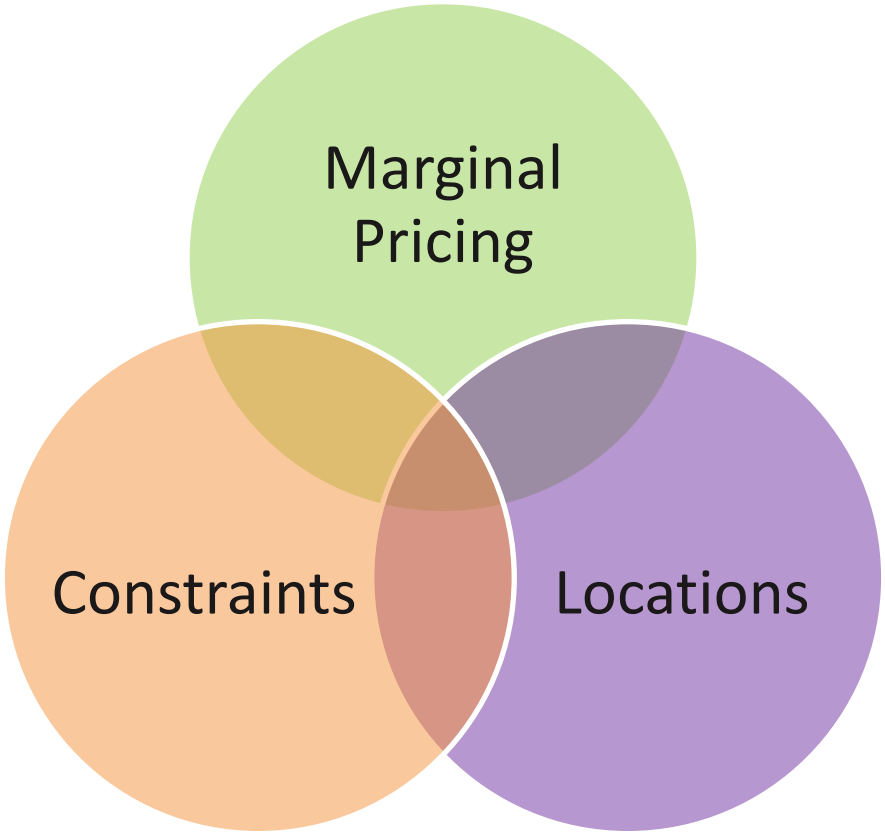
# LMP Basics

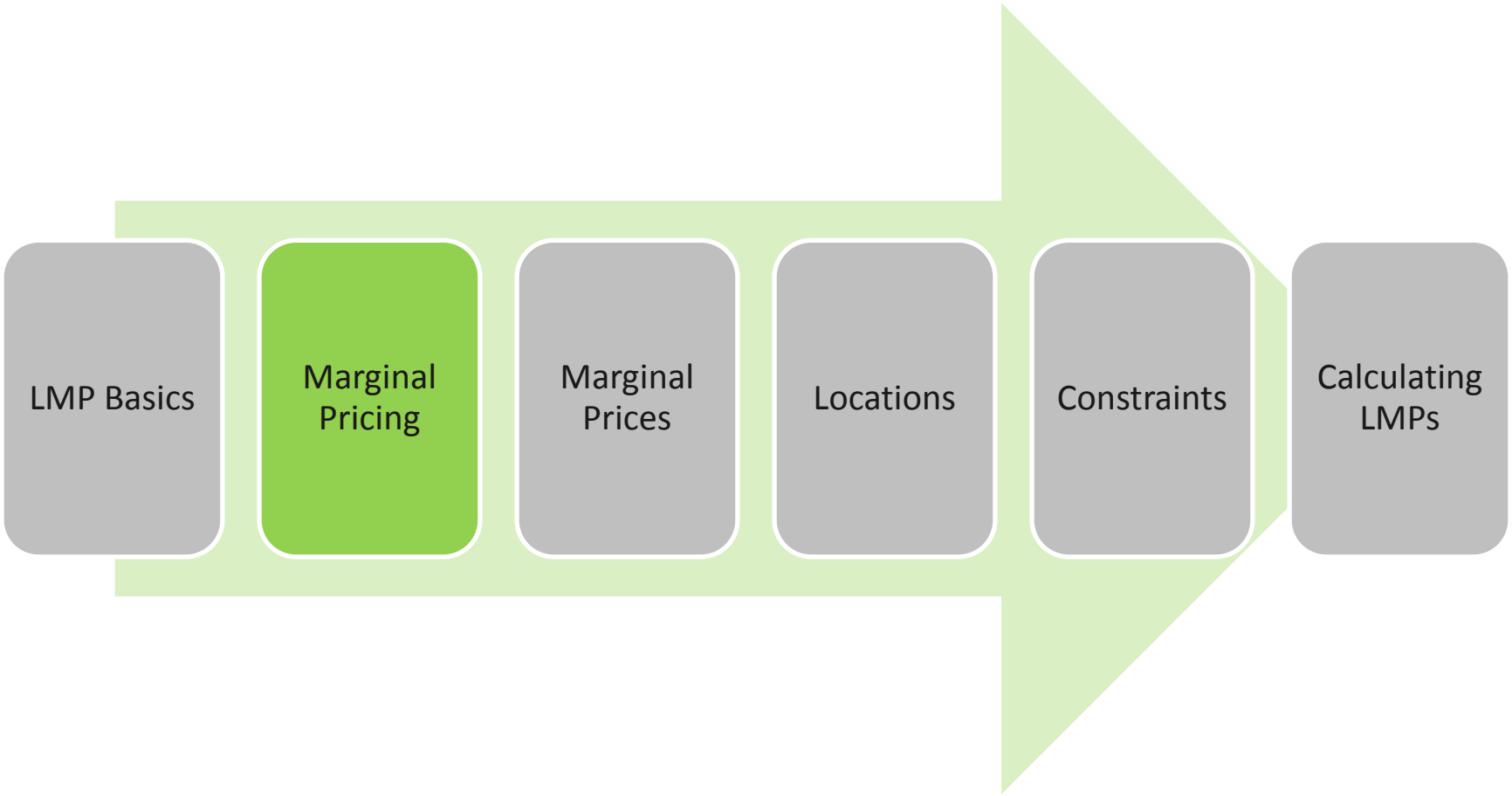
- Uses of LMPs
- Locations
  - Node, Zone, Hub
- LMP Pricing concepts
- Economic Dispatch
- Power Transfer Distribution Factors (PTDF)
- Using PTDFs to Calculate LMPs

# What are LMPs Used For?

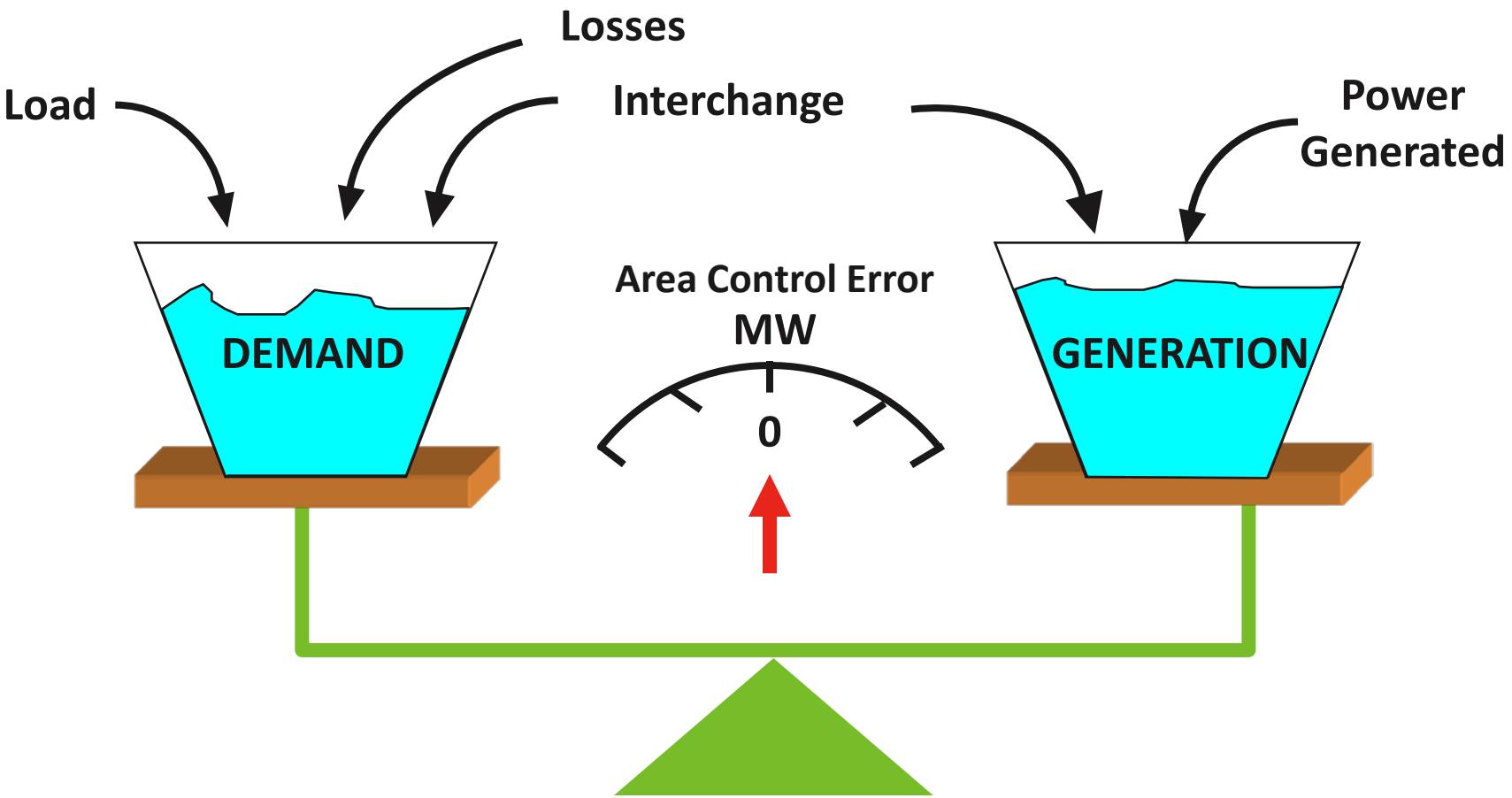
- Pricing Method used to:
  - ✓ Establish the price for Energy purchases and sales at specific locations throughout the New England wholesale electricity market
  - ✓ Pay Generators (Suppliers)
  - ✓ Charge Load (Consumers)
  - ✓ Collect Transmission Congestion Charges
  - ✓ Determine compensation for FTR Holders

# What are the Elements of LMPs?





# The Energy Balance



# Power System Normal Operation Control

- One of the most important power system control objectives is to keep the balance in the system.
- At any moment, the sum of all generation must meet all loads, losses and scheduled net interchange.
- There are three processes that achieve this goal under normal operations: Automatic Generation Control (AGC), load following, and optimal/economic dispatch.

# Economic Dispatch

- It is the least expensive way of supplying load in the system.
- Dispatching generators means changing their output to keep the system in balance.
- Economic dispatch is part of the load following control and is being run every five (5) minutes in ISO New England (ISO-NE) to re-optimize the generation to meet load at minimum cost.
- The result of the dispatch is asset output levels (Desired Dispatch Points - DDP) in MW, and LMPs at each generator node, which are nodal dispatch rates.

# Economic Dispatch – Marginal Pricing

Cost to serve the next MW sets price.

**C**
**$20/MW**
Capacity:
200 MW

**B**
**$15/MW**
Capacity:
200 MW

**A**
**$10/MW**
Capacity:
300 MW

**Not dispatched**

**199 MW @ $15**

**300 MW @ $10**

**Dispatcher**

**Load**

**499 MW**

**$15**

*Marginal price of Energy*

# Economic Dispatch – Marginal Pricing (cont)

Cost to serve the next MW sets price.

**C**
**$20/MW**
Capacity:
200 MW

**B**
**$15/MW**
Capacity:
200 MW

**A**
**$10/MW**
Capacity:
300 MW

**10 MW @ $20**

**200 MW @ $15**

**300 MW @ $10**

**Dispatcher**

**Load**

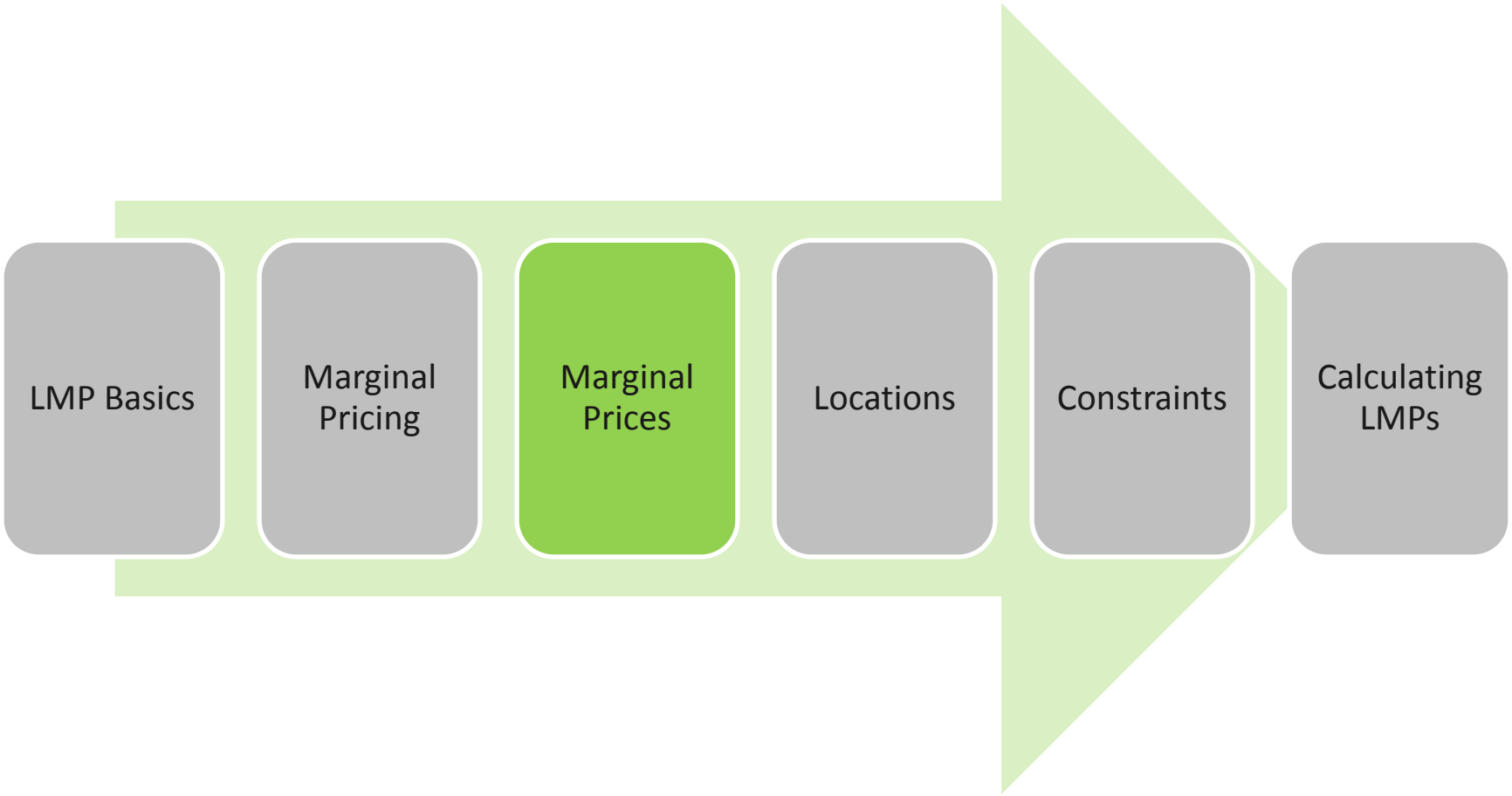
**510 MW**

**$20**

*Marginal price of Energy*

# Economic Dispatch

- In case of economic dispatch, the objective is to minimize the total cost of producing electricity while keeping the system in balance.
- Each asset submits offers that specify the incremental cost of producing energy.

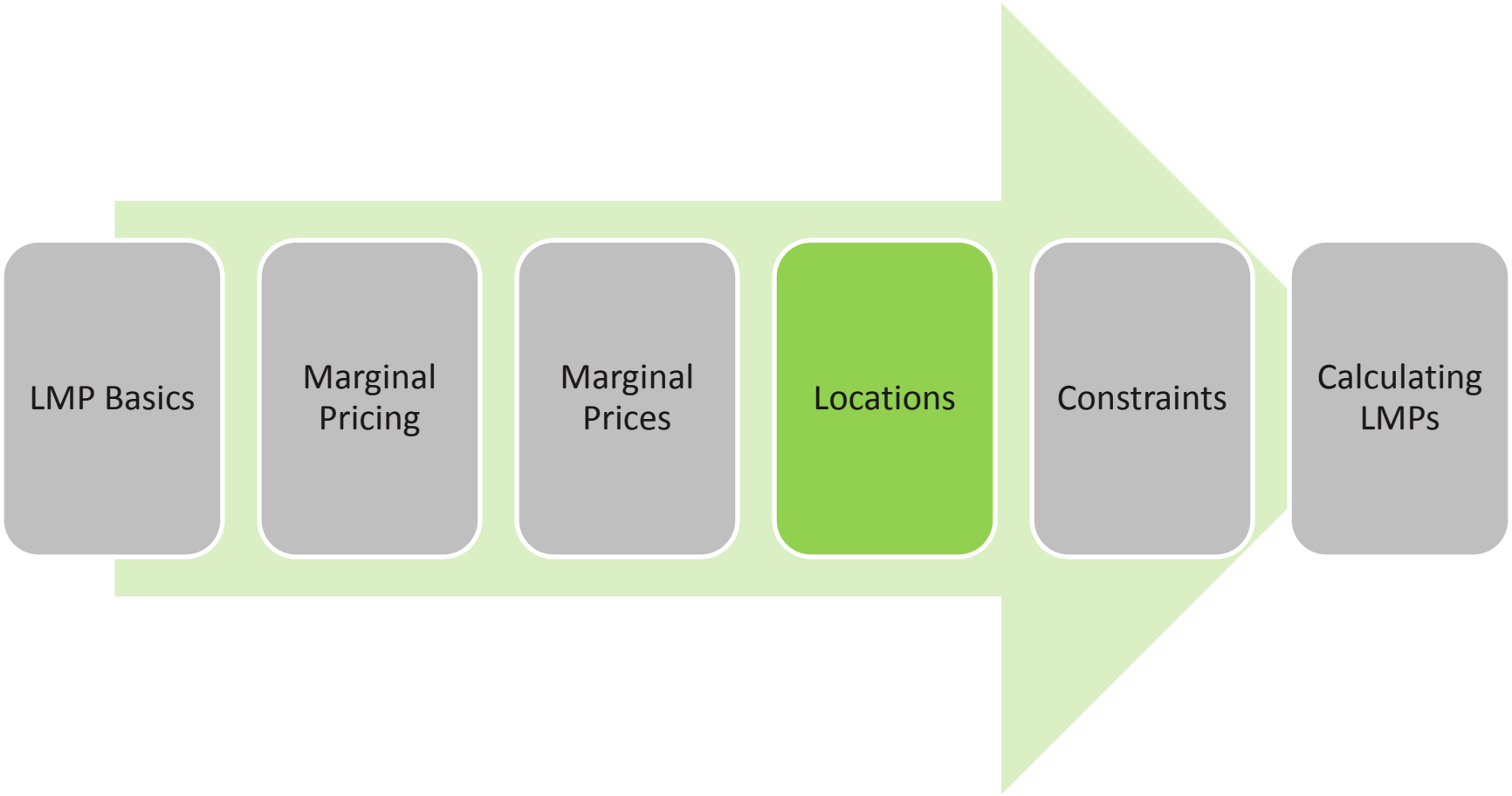


# Marginal Pricing

- Marginal Pricing reflects the cost to serve the next increment of load in a system that is economically dispatched.
- This method of pricing is the same method that has been in place since May of 1999 (formerly known as Energy Clearing Prices (ECPs) prior to March 2003).

# Marginal Price Calculation

- While dispatched, all assets will end up in one of three groups:
  - At the maximum limit
  - At the minimum limit
  - Between minimum and maximum
- The maximum and minimum can be ramp rate constrained limit, regulation limit, etc.
- The third group of assets is called Marginal Assets. These are the assets that determine LMPs at ALL locations.



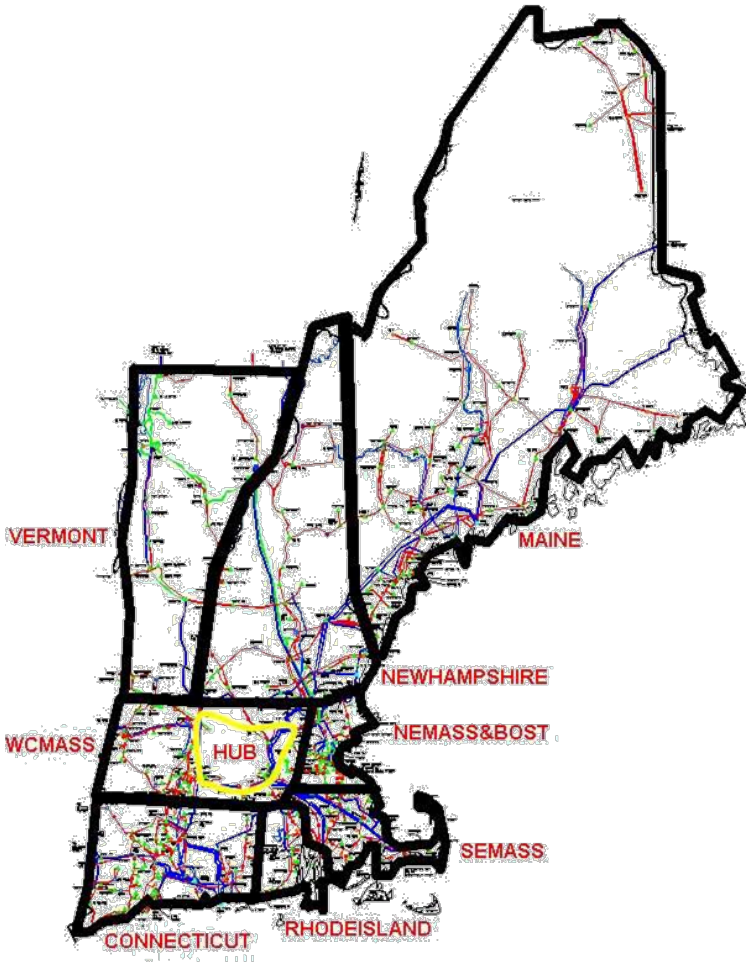
# What Makes Marginal Pricing (ECPs) Become LMPs?

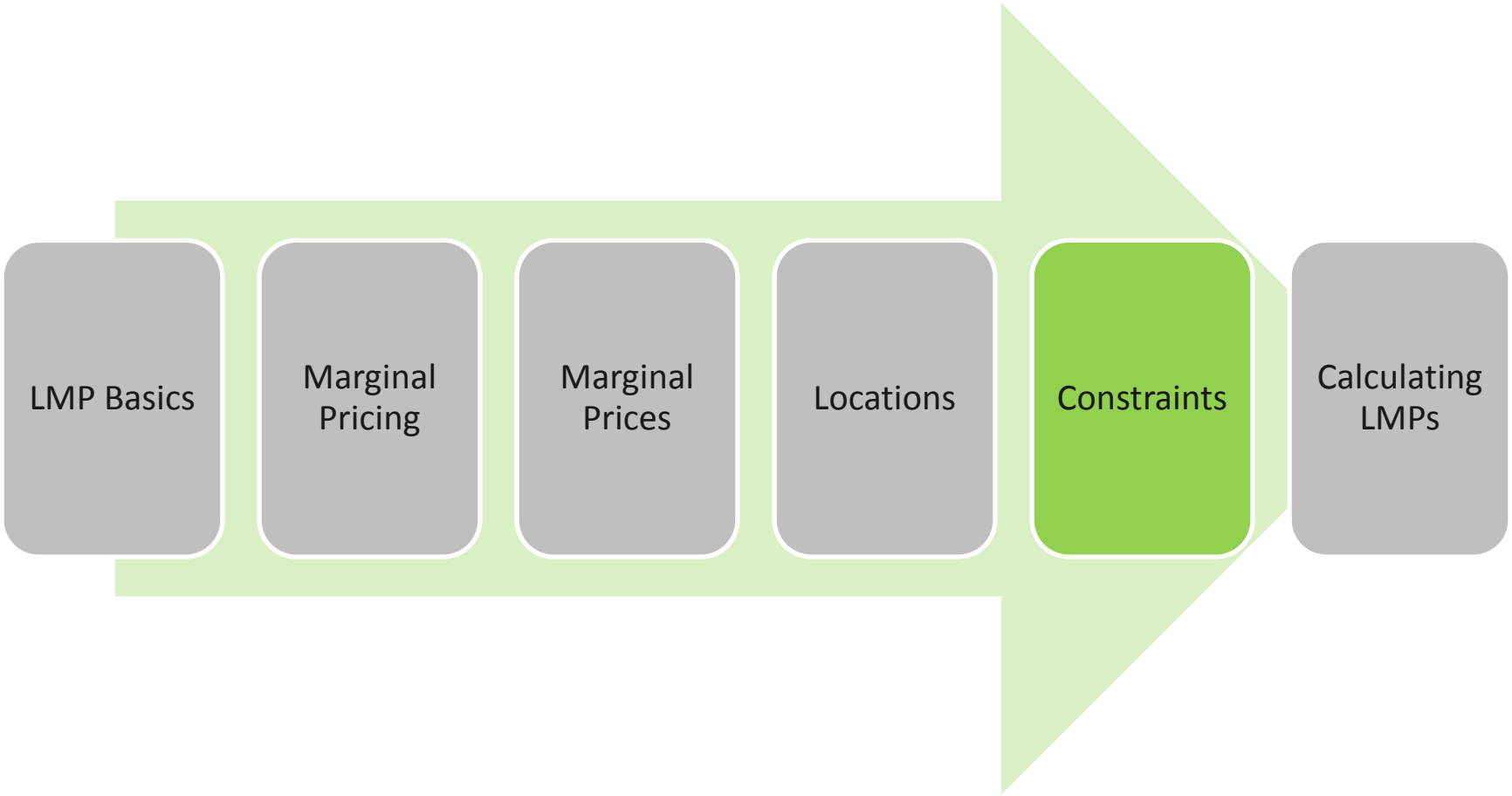
- Locations
- Constraints between Locations

# Locations of LMPs

| Node | Load Zone | Hub | External / Proxy Node |
|---|---|---|---|
| Corresponds to a physical bus or collection of buses within the network – every generator and load has a node | Aggregation of nodes. Zonal price is the load-weighted average of the prices of all nodes in the zone | Representative selection of nodes to facilitate long-term commercial energy trading. The hub price is a simple average of LMPs at all hub locations. | Location that serves as a proxy for trading between ISO-NE area and its neighbors |

# NEPOOL Control Area and Pricing Hub





# Three Factors of LMPs

- LMPs depend on:
  1. Marginal cost to operate generation
  2. Total load
  3. Cost of delivery on the transmission system
  - Cost of meeting Reserve Constraints (explained in detail in LMP 201 and LMP 301)

# Location-based Marginal Price (LMP)

- LMP is the cost of supplying an increment of load at a particular location.
- One can think of the LMP as a change of the total production cost to deliver an additional increment of load to a location (We will show this in later examples), while respecting all constraints.
- LMPs are usually produced as a result of economic dispatch.
- LMPs can be calculated looking ahead – ex-ante LMPs or after-the-fact – ex post LMPs. Ex-ante LMPs for generation locations are also called Nodal Dispatch Rates (NDR).

# LMP & Economic Dispatch

- Dispatch Rate (ex-ante)
  - Where ISO-NE wants the asset to be loaded economically
- LMP (ex-post)
  - Based on actual loading of each asset

# Calculation of LMPs

LMPs are calculated for all locations:

**Day-Ahead Market (DAM)**

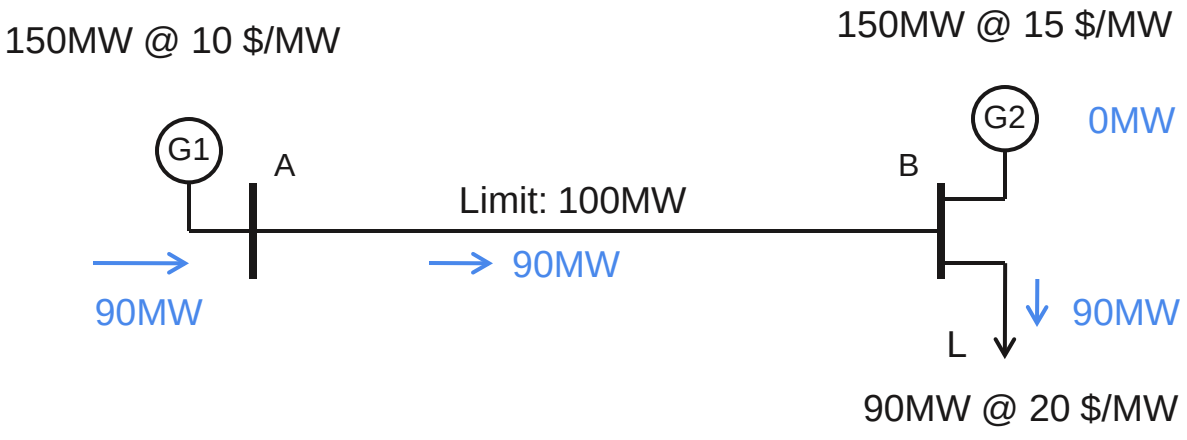
Hourly basis

**Real-Time Market (RTM)**

Every five (5) minutes during the Operating Day

*Reference Market Rule 1, Section 2.1.*

# System With No Constraints




$LMP_A$ = 10 $/MW

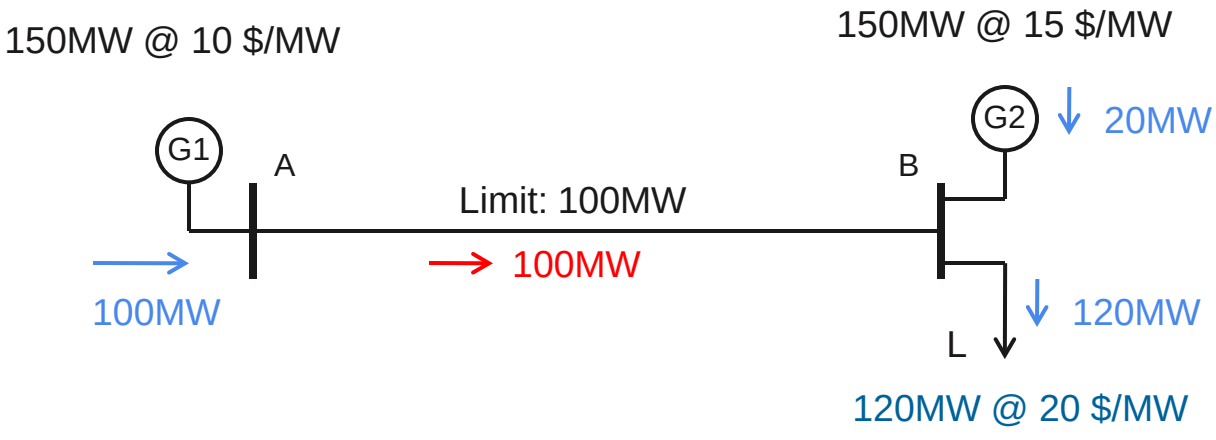
$LMP_B$ = 10 $/MW

G1 is the ***marginal asset***– would supply next increment of load at either location A or B. Its offer price determines LMP at both locations!

# LMP Calculation – Fundamental Properties

- The price at the location of each marginal asset is always equal to its offer price.
- n+1 Rule: For n binding constraints, there is at least n+1 marginal assets.
- In the case of no congestion, there is at least one marginal asset.

# System With a Binding Constraint



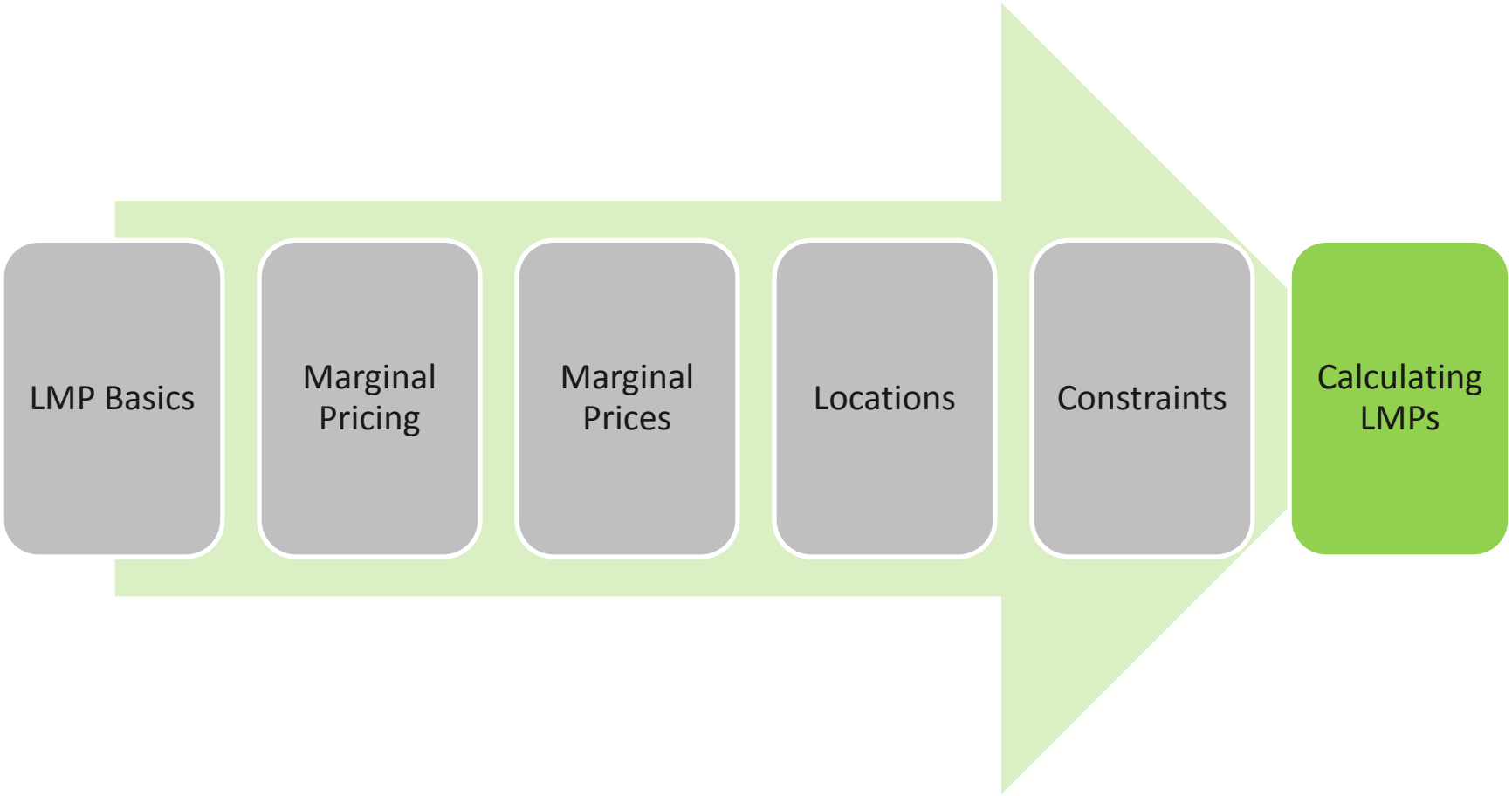

$LMP_A$ = 10 $/MW

$LMP_B$ = 15 $/MW

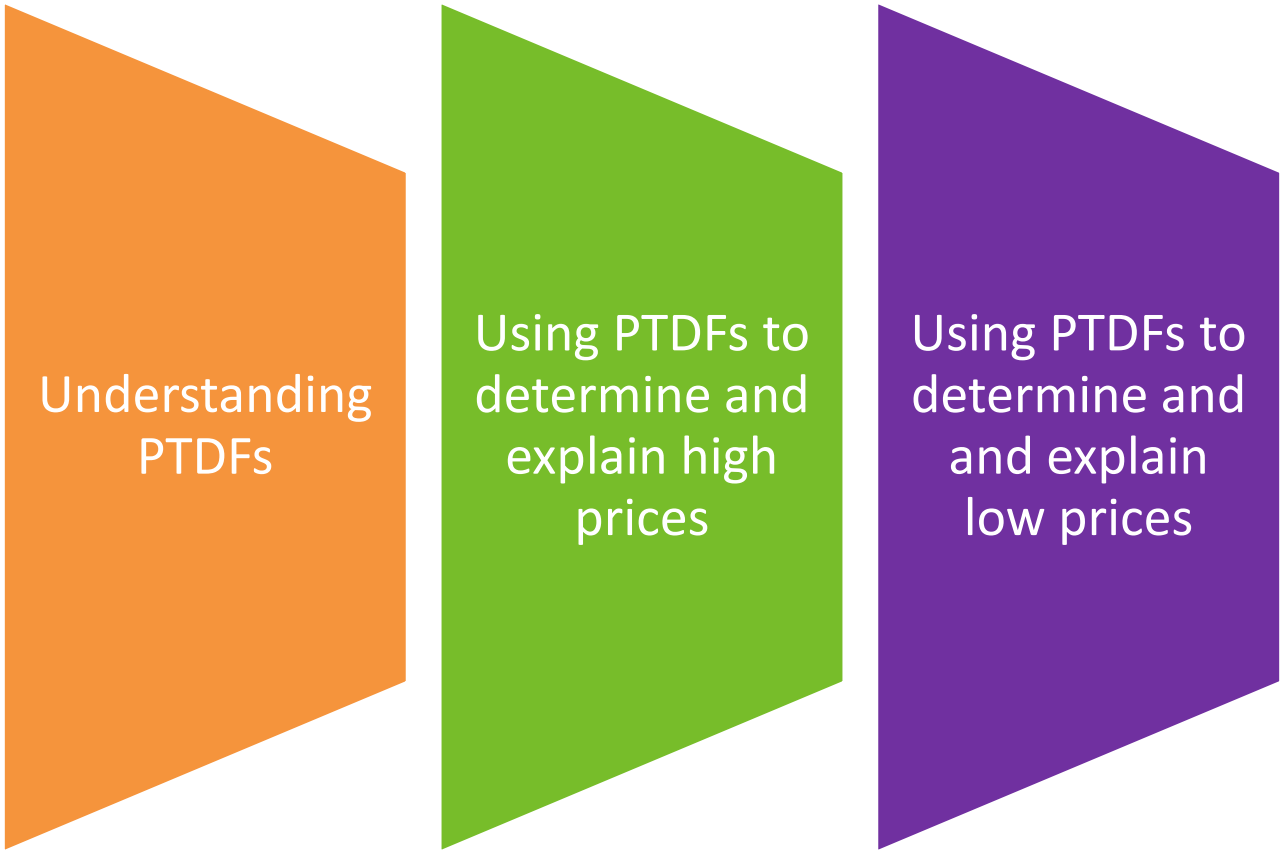
There are two ***marginal assets*** – G1 and G2.
G1 would supply next increment of load at the location A and G2 would supply it for the location B.
Therefore, there are different LMPs at different locations (due to binding constraint - congestion in the system)

# Elements of LMPs – Review

- ✓ Marginal Pricing
- ✓ Locations
- ✓ Constraints



# Calculating LMPs



# LMP Calculator

- Binding Transmission constraints converted to Sensitivities, one type of which is Power Transfer Distribution Factors (PTDF)
- PTDF determines a change in the power flow at each line when one (1) (or more) MW is transferred from one bus of the network to another.
- When a MW is transferred from one bus to another, it affects every single flow in the network.

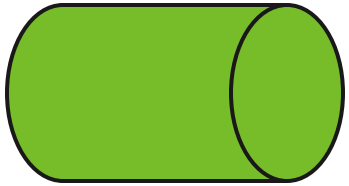
# How Does Energy Get from Generator to Load?

- Two things have a major impact on flow:
  1. Impedance
  2. Resistance

# How Does Energy Get from Generator to Load? (cont.)

- Think of it as two pipes:
  - one very narrow pipe (high impedance)

  - One wider pipe (low impedance)



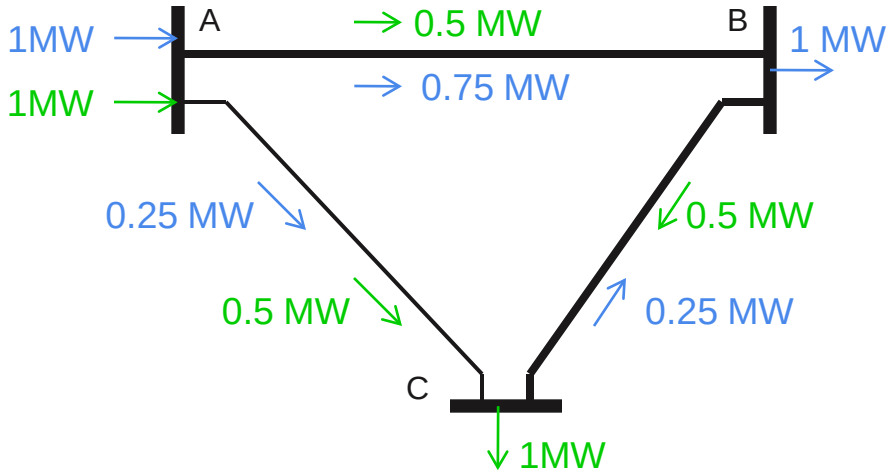
Which can more volume of water flow through?

# How Does Energy Get from Generator to Load? (cont.)

- Resistance impacts Losses during the flow – friction in the pipe.
- Impedance can be thought of as determining how much will flow – size of the pipe.

# Power Transfer Distribution Factors (PTDF)

*Example*




Lines A-B and B-C have the same impedance.

Line A-C has 2 times higher impedance than lines A-B and B-C.

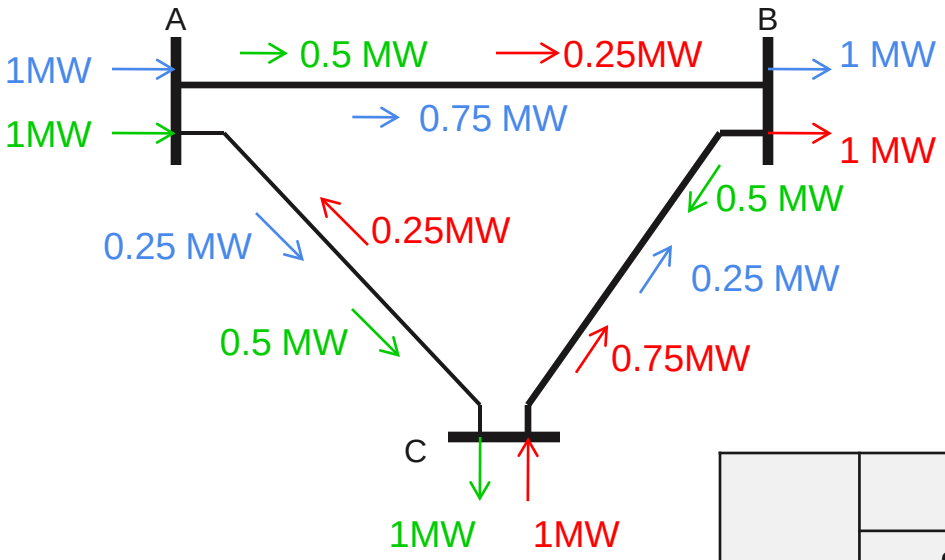
$PTDF^{A\ to\ B}_{A\text{-}C} = 0.25$

Flow on line A-C, when 1 MW of power is transferred from location A to location B

$PTDF^{A\ to\ C}_{A\text{-}C} = 0.50$

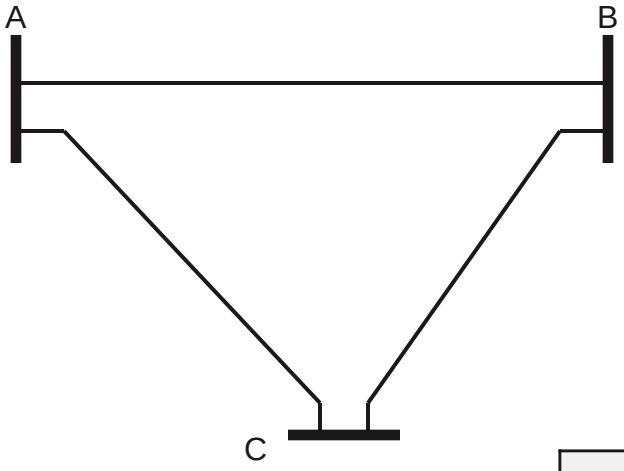
Flow on line A-C, when 1 MW of power is transferred from location A to location C

# PTDF




| Line | Power transfer from-to location | | | | | |
|---|---|---|---|---|---|---|
| | from A | | from B | | from C | |
| | to B | to C | to A | to C | to A | to B |
| A-B | 0.75 | 0.5 | -0.75 | -0.25 | -0.5 | 0.25 |
| B-C | -0.25 | 0.5 | 0.25 | 0.75 | -0.5 | -0.75 |
| A-C | 0.25 | 0.5 | -0.25 | 0.25 | -0.5 | -0.25 |

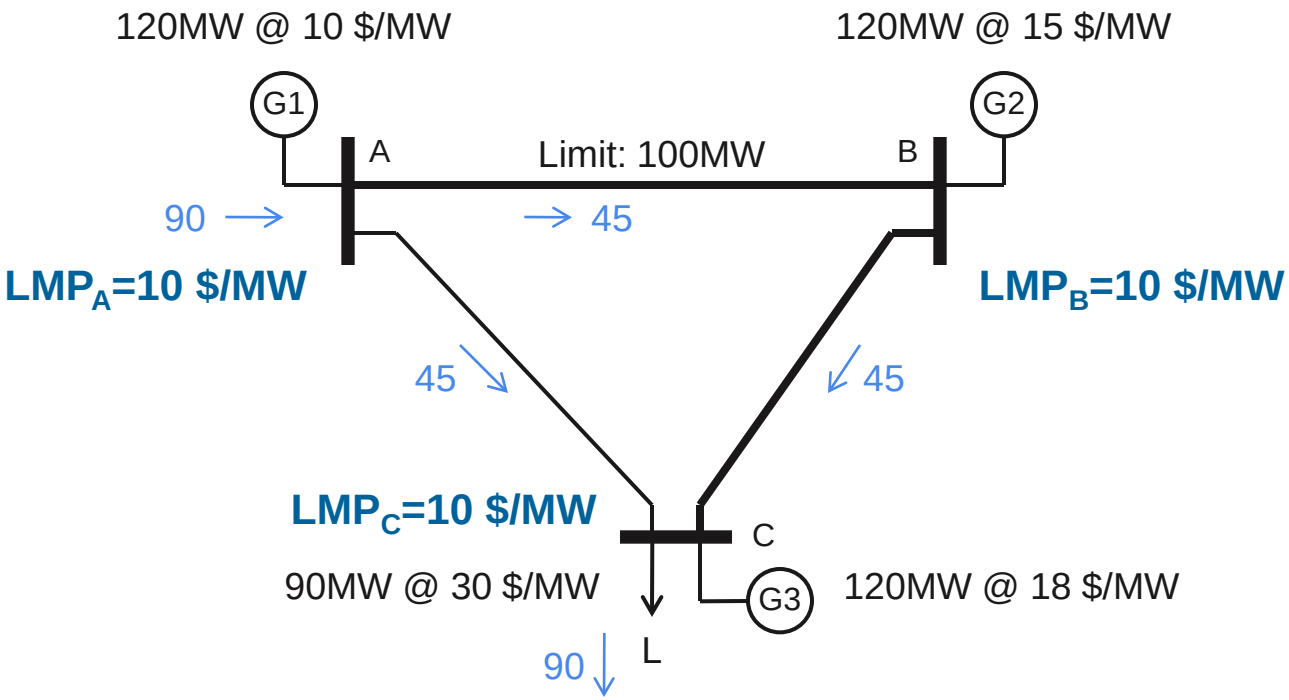
# PTDF - Exercise




All lines have the same impedance

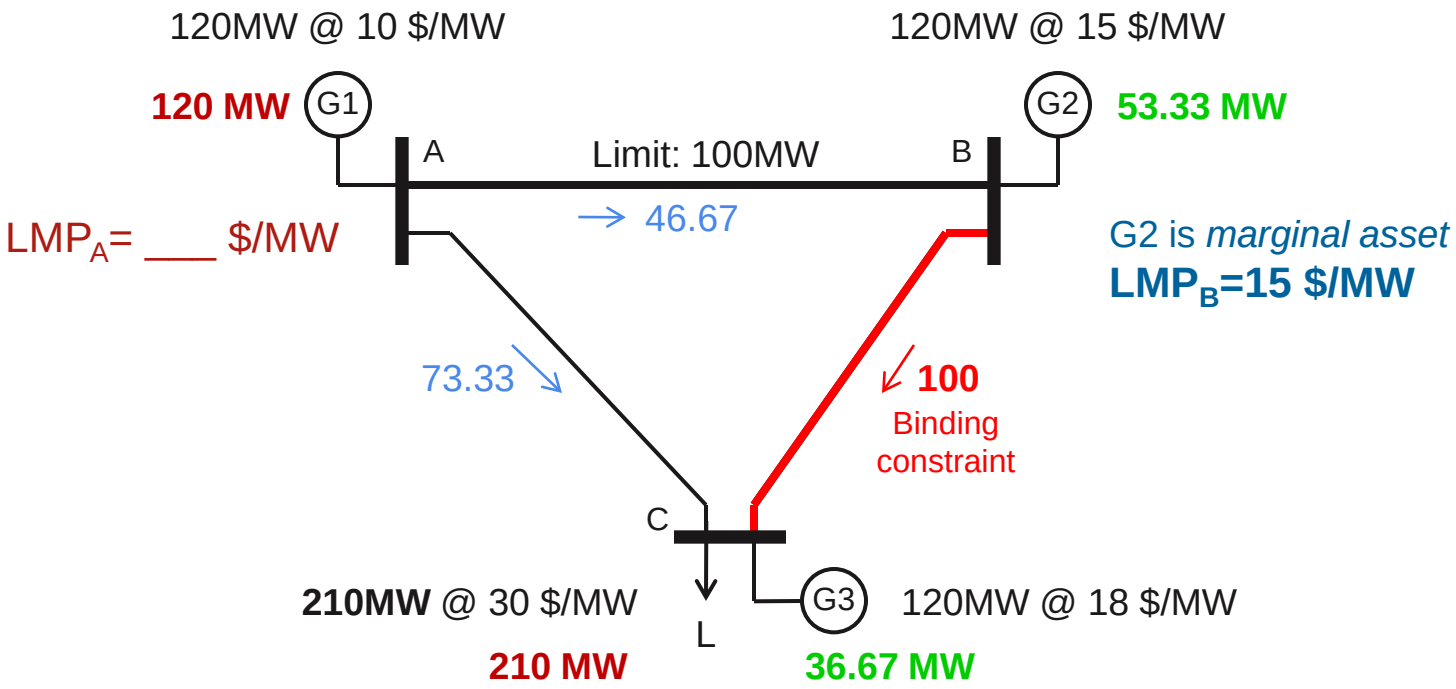
| Line | Power transfer from-to location | | | | | |
|---|---|---|---|---|---|---|
| | from A | | from B | | from C | |
| | to B | to C | to A | to C | to A | to B |
| A-B | | | | | | |
| B-C | | | | | | |
| A-C | | | | | | |

# Using PTDF to Calculate the Prices …



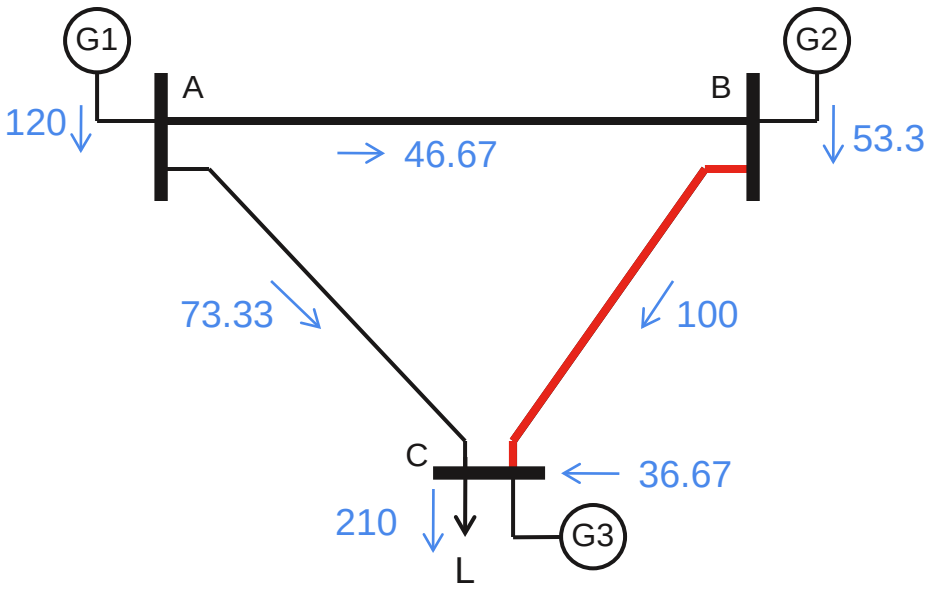

G1 is the *marginal asset*: would supply next increment of load at any location: A, B or C.
*No binding constraints* => All LMPs are the same, equal to G1 offer price (**10 $/MW**)

# Using PTDF to Calculate the Prices …




G3 is *marginal asset*
**LMP$_C$=18 $/MW**

# Using PTDF to Calculate the Prices …

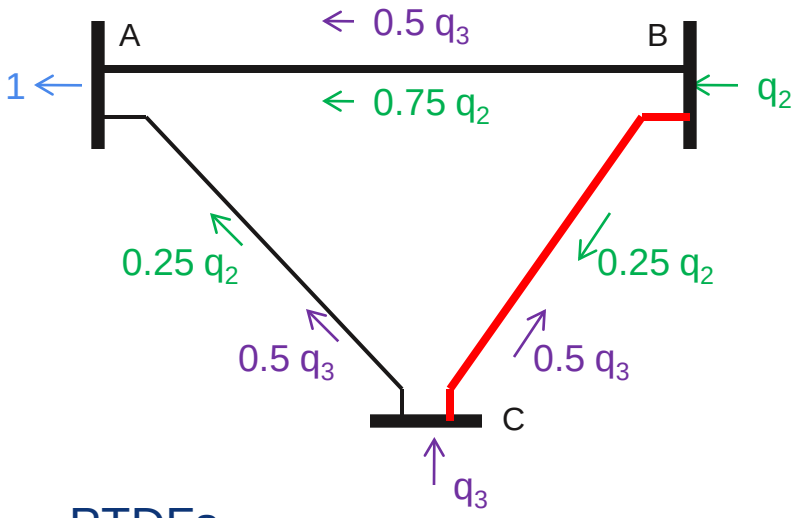



LMP at the location is equal to the change in a production cost to supply the increment (e.g. 1MW) of load at that location.

Additional load at location A can be supplied from assets $G_2$ (at location B) and $G_3$ (at location C)

Line B-C flow is at the limit, and cannot change.

# Using PTDF to Calculate the Prices …




PTDFs

| Line | Power transfer from-to location | | | | | |
|---|---|---|---|---|---|---|
| | from A | | from B | | from C | |
| | to B | to C | to A | to C | to A | to B |
| A-B | 0.75 | 0.5 | -0.75 | -0.25 | -0.5 | 0.25 |
| **B-C** | -0.25 | 0.5 | **0.25** | 0.75 | **-0.5** | -0.75 |
| A-C | 0.25 | 0.5 | -0.25 | 0.25 | -0.5 | -0.25 |
| | | | $q_2$ | | $q_3$ | |

$$q_2 + q_3 = 1$$

$$0.25q_2 - 0.5q_3 = 0$$

Increase output of $G_2$ by 2/3 MW and output of $G_3$ by 1/3 MW:

$$q_2 = 2/3,\ q_3 = 1/3$$

Production cost change:

$$(2/3)x15 + (1/3)x18 = 16$$

$$LMP_A = 16\ \$/MW$$

# Using PTDF to Calculate Price

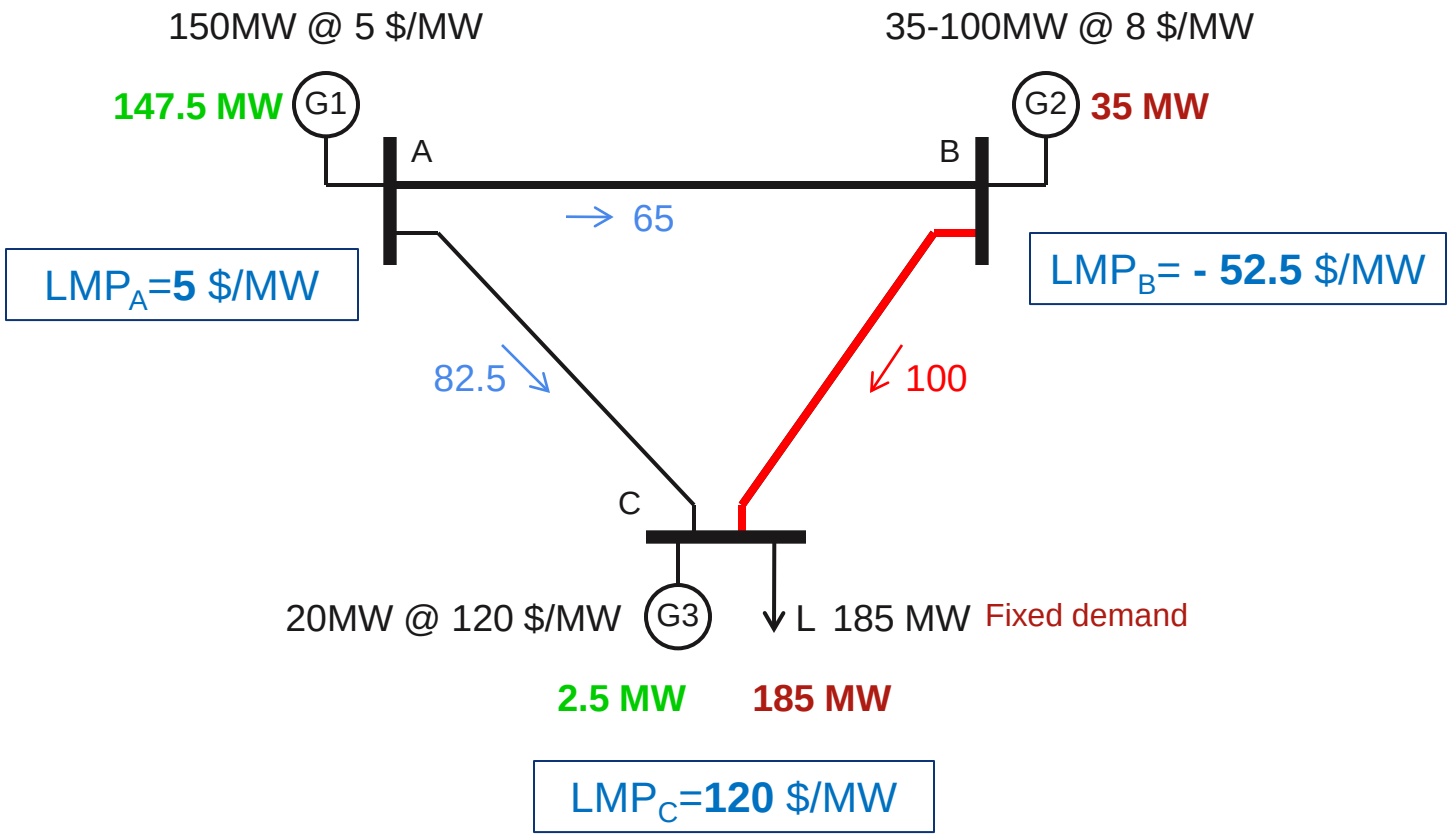
- PTDF can determine the MW dispatch to solve the additional increment.
- So PTDF can be used to calculate LMP by using prices in the calculation.

| Asset | MW Change | Cost Change ($/MW x MW Change) | PTDF (B-C Path, power transfer to location A) | Change Flow Over B-C Path |
|---|---|---|---|---|
| $G_2$ | 2/3 | 15x(2/3) = 10.00 | 0.25 | -1/6 |
| $G_3$ | 1/3 | 18x(1/3)= 6.00 | -0.50 | 1/6 |
| $\sum$ | 1.00 | 16.00 | | 0 |

# Simple Arithmetic

- Need to serve one (1) MWh @ A
- 25% (0.25) of one (1) MWh from B ($G_2$) will flow over constrained line (B-C).
- -50% (-0.50) of one (1) MWh from C ($G_3$) will flow over constrained line.
- What does this mean? It means that if we serve the additional increment of load in A with the $G_3$ asset, the constrained line will become less constrained so we can use more of the cheaper energy from asset $G_2$, at the same time reducing usage of more expensive $G_3$ asset.

# High and Negative LMP Prices

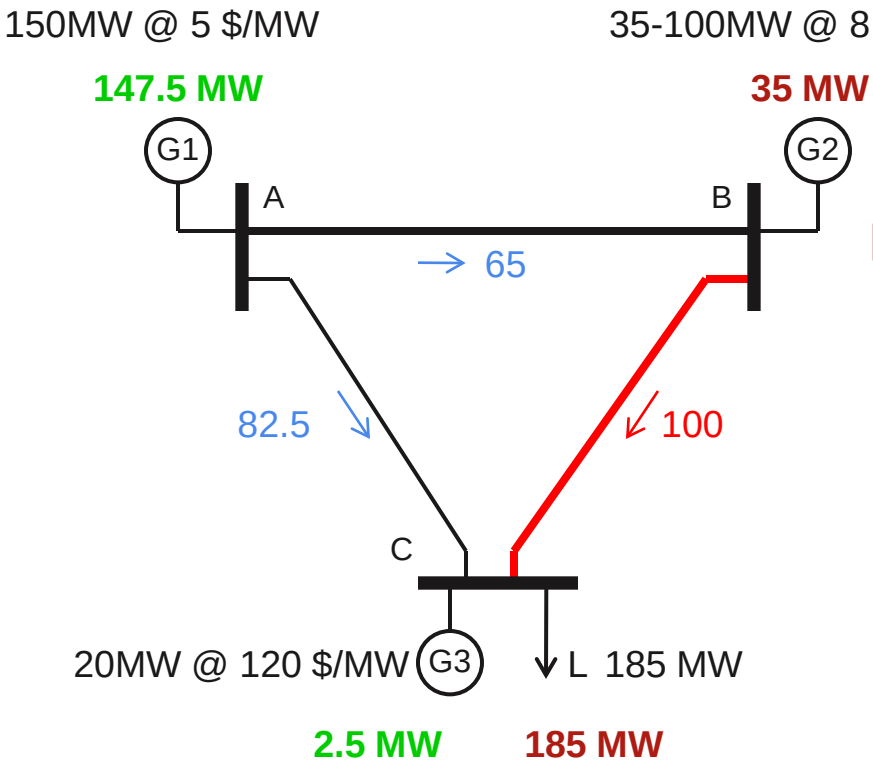


# PTDF

| | Power transfer | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | From A | | | From B | | | From C | | |
| | to A | to B | to C | to A | to B | to C | to A | to B | to C |
| A-B | 0 | 0.75 | 0.5 | -0.75 | 0 | -0.25 | -0.5 | 0.25 | 0 |
| B-C | 0 | **-0.25** | 0.5 | 0.25 | 0 | 0.75 | -0.5 | **-0.75** | 0 |
| A-C | 0 | 0.25 | 0.5 | -0.25 | 0 | 0.25 | -0.5 | -0.25 | 0 |

Note: Line A-C has two times higher impedance than lines A-B or B-C

# How the Negative Price is Determined




**$LMP_B$ = -52.5 $/MW**

$q_1 + q_3 = 1$

$-0.25q_1 - 0.75q_3 = 0$

$q_1 = 1.5;\ \ q_3 = -0.5$

$LMP_B = 1.5x5 + (-0.5)x120$

$LMP_B = 7.5 – 60 = -52.5$

# Using PTDF to Calculate Price

- To allow additional MW to be delivered to certain location (i.e. B), we need to decrease an output at location (i.e. C – $G_3$) that has higher PTDF for a constrained path (i.e. B-D), and increase output at location (i.e. A – $G_1$) that has lower PTDF for a constrained path.

| Asset | MW Change | Cost Change ($/MW x MW Change) | PTDF (B-D Path, power transfer to location D) | Change Flow Over A-C Path |
|---|---|---|---|---|
| $G_1$ | 1.50 | 1.5 x 5.00 = 7.50 | -0.25 | -0.375 |
| $G_3$ | -0.50 | 120 x (-0.50) = -60.00 | -0. 75 | 0.375 |
| $\sum$ | 1.00 | -52.50 | | 0 |

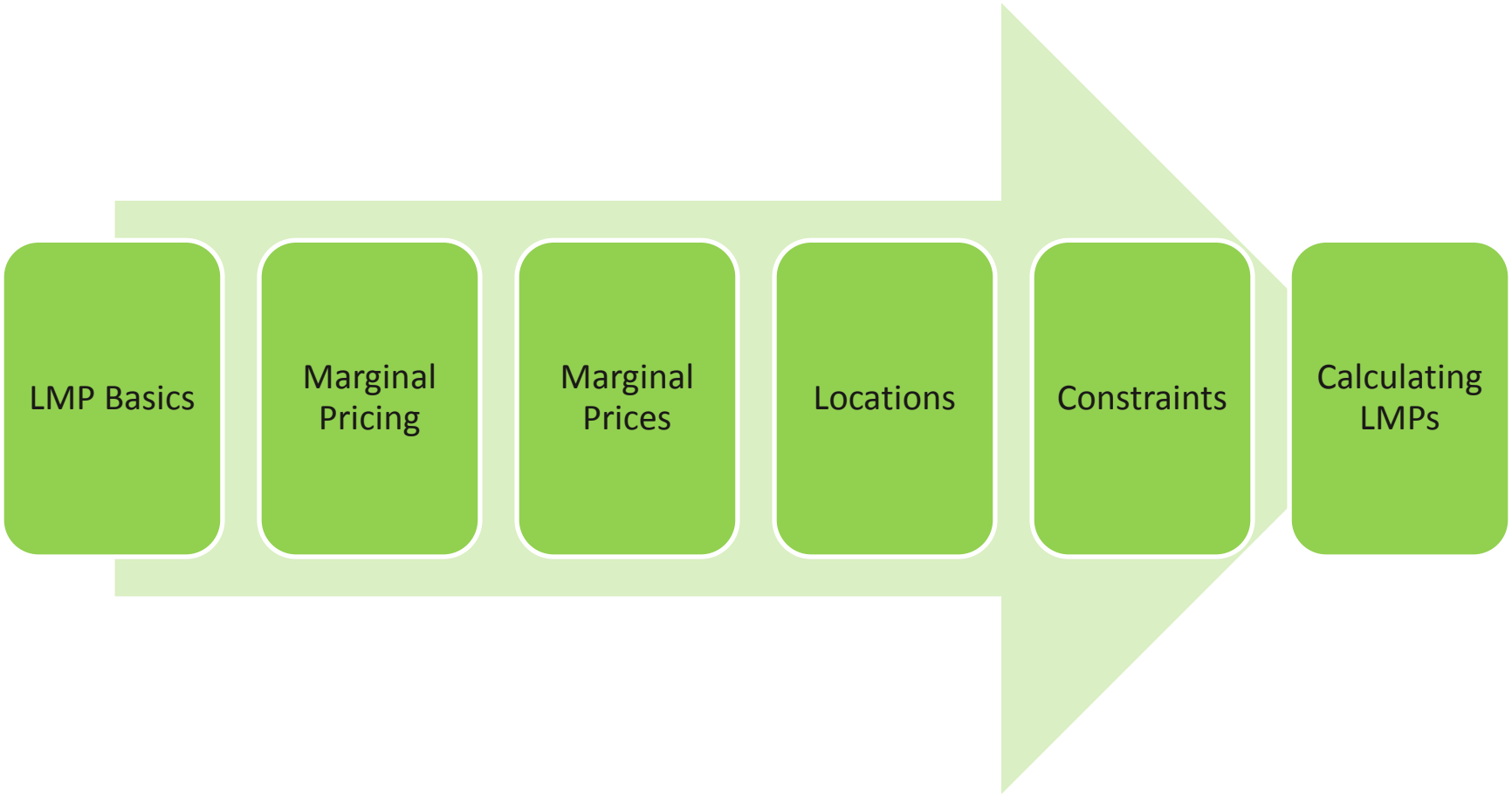
# LMP Components

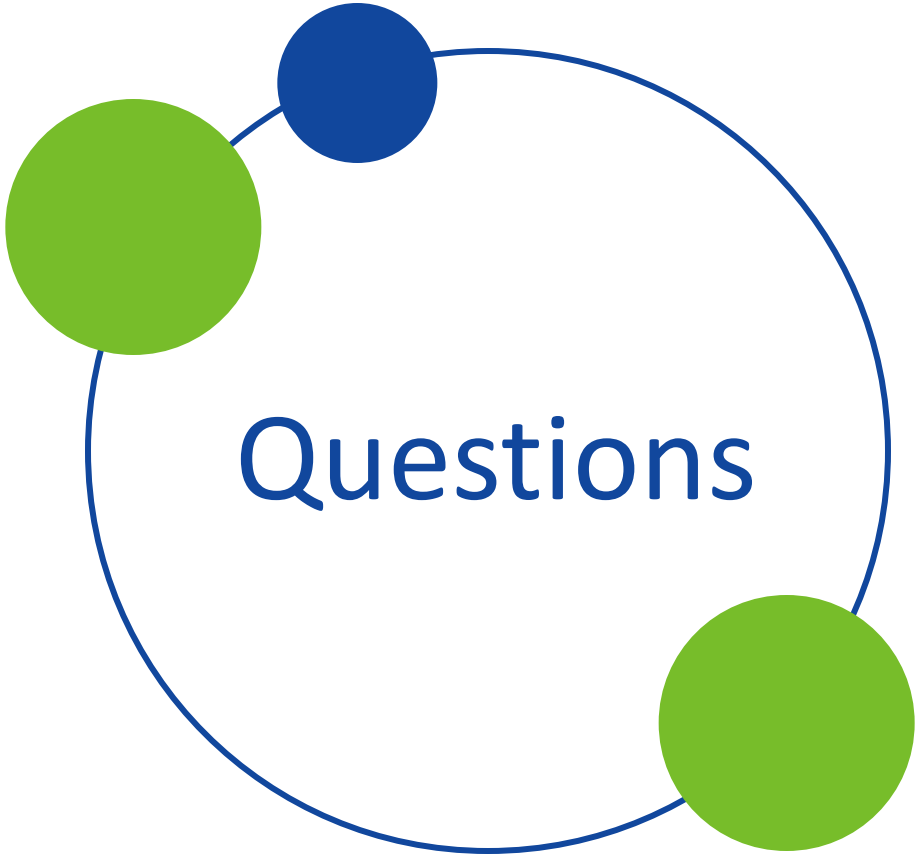

Each LMP can be **split** into three components.

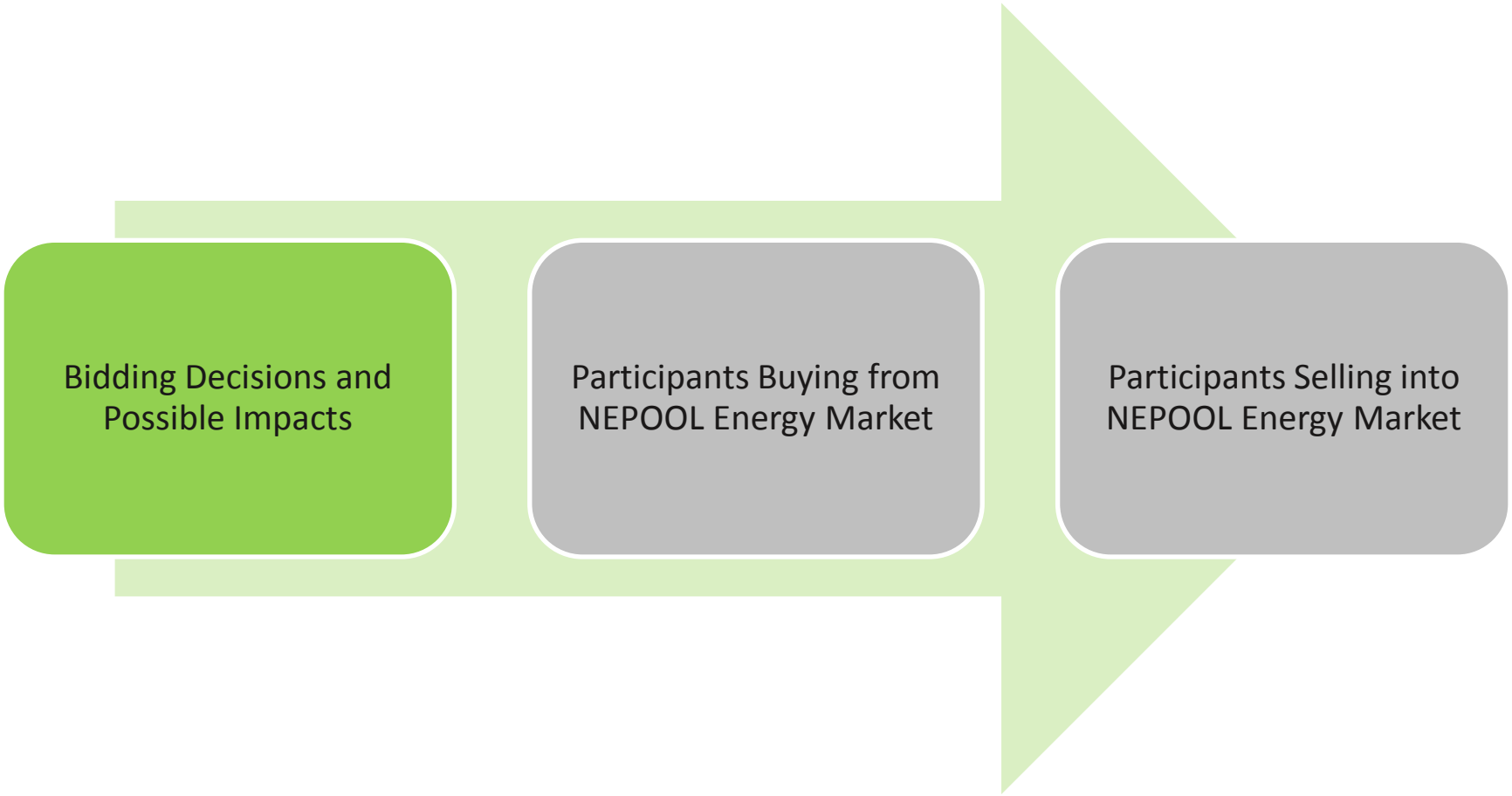
# LMP Components

- LMP is calculated at each location as the cost to serve the next MW of load at that location
- LMP is all that is needed to charge load and pay generators
- The only reason to break down the components of LMPs is for FTRs to determine how much of the difference in LMPs at one location versus another location is due to transmission congestion and how much is due to loss impacts
- The breakdown depends on the determination of the “reference” location which defines the energy component

# Section Review: Topics Covered



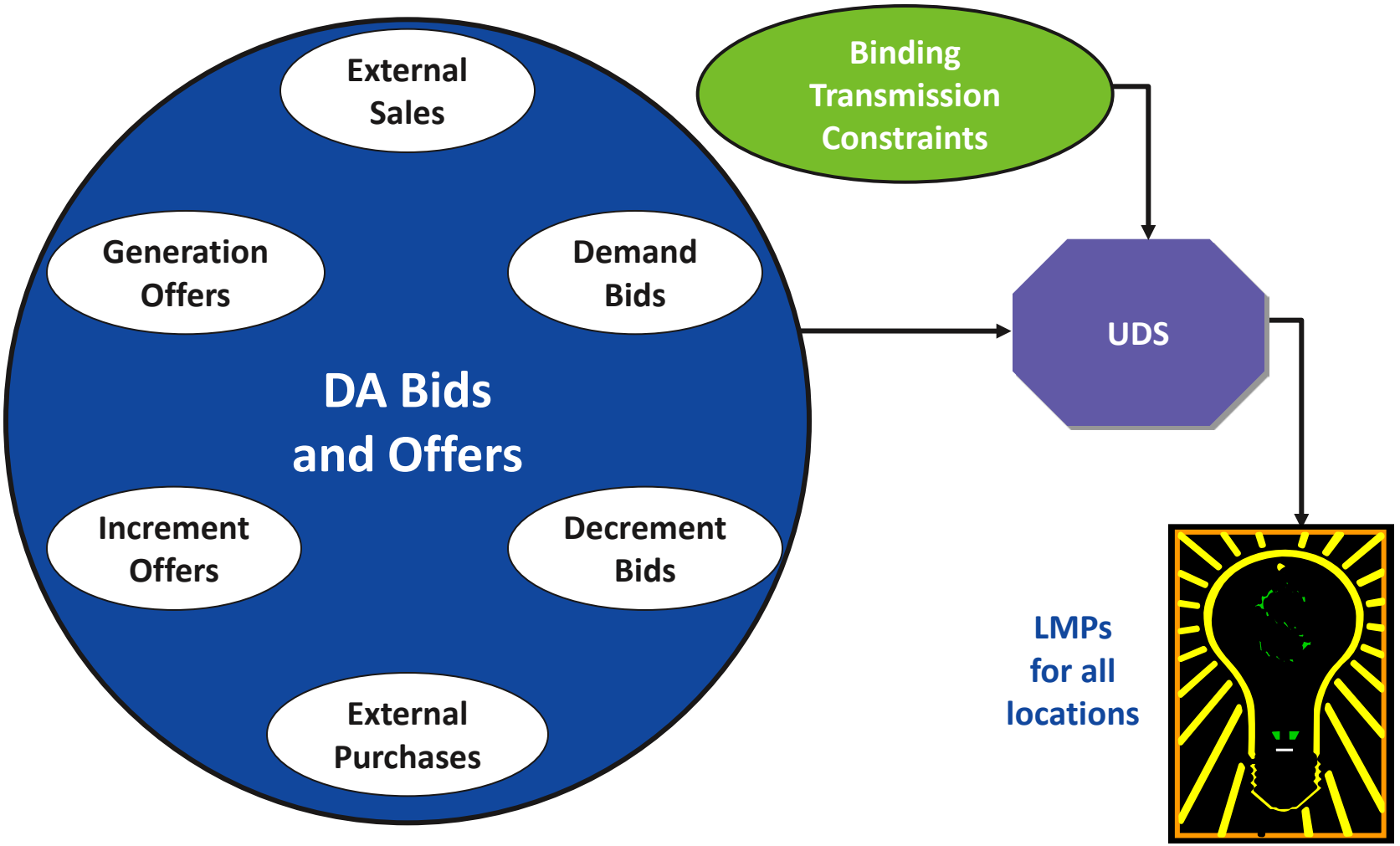




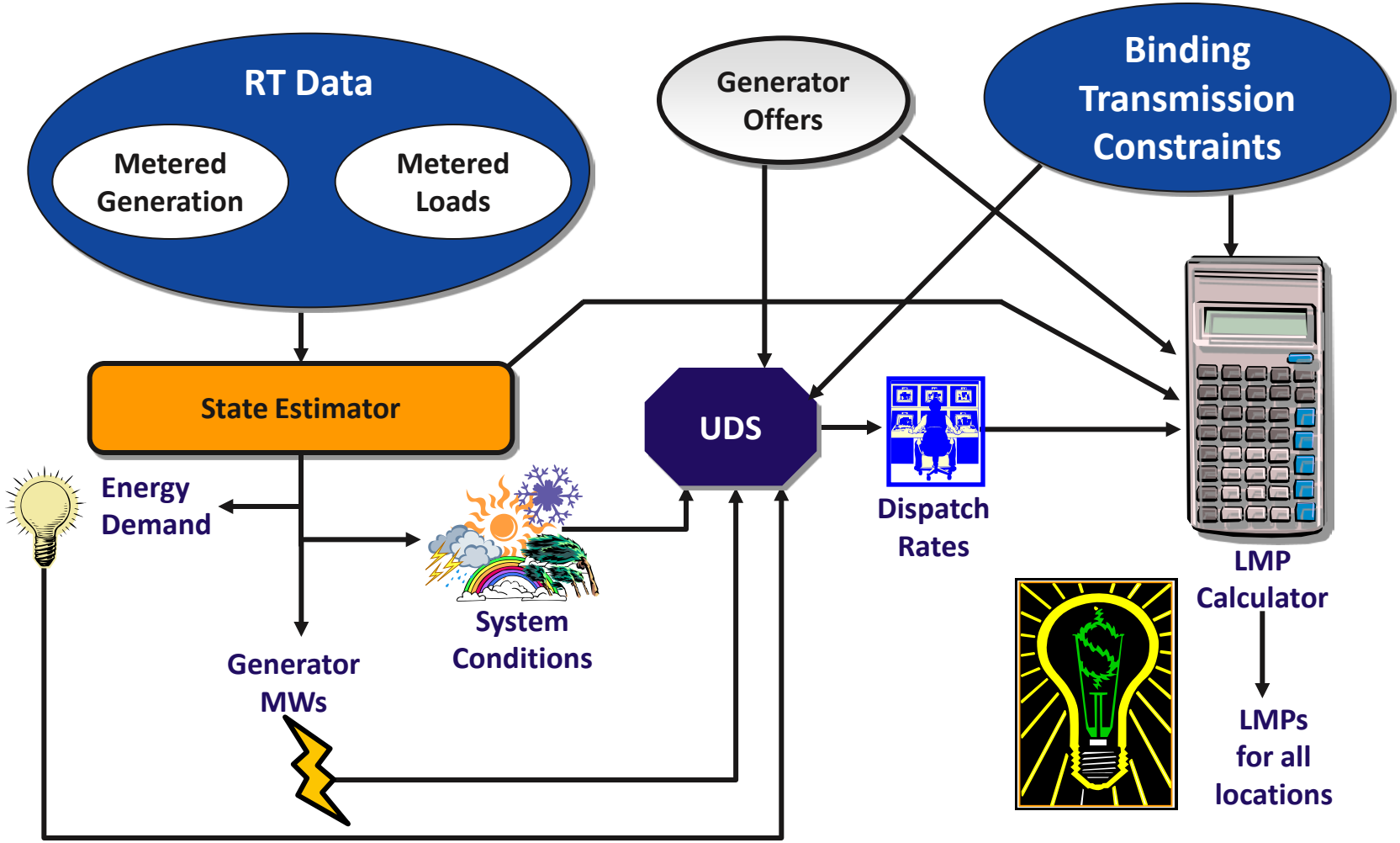
# What We Will Cover

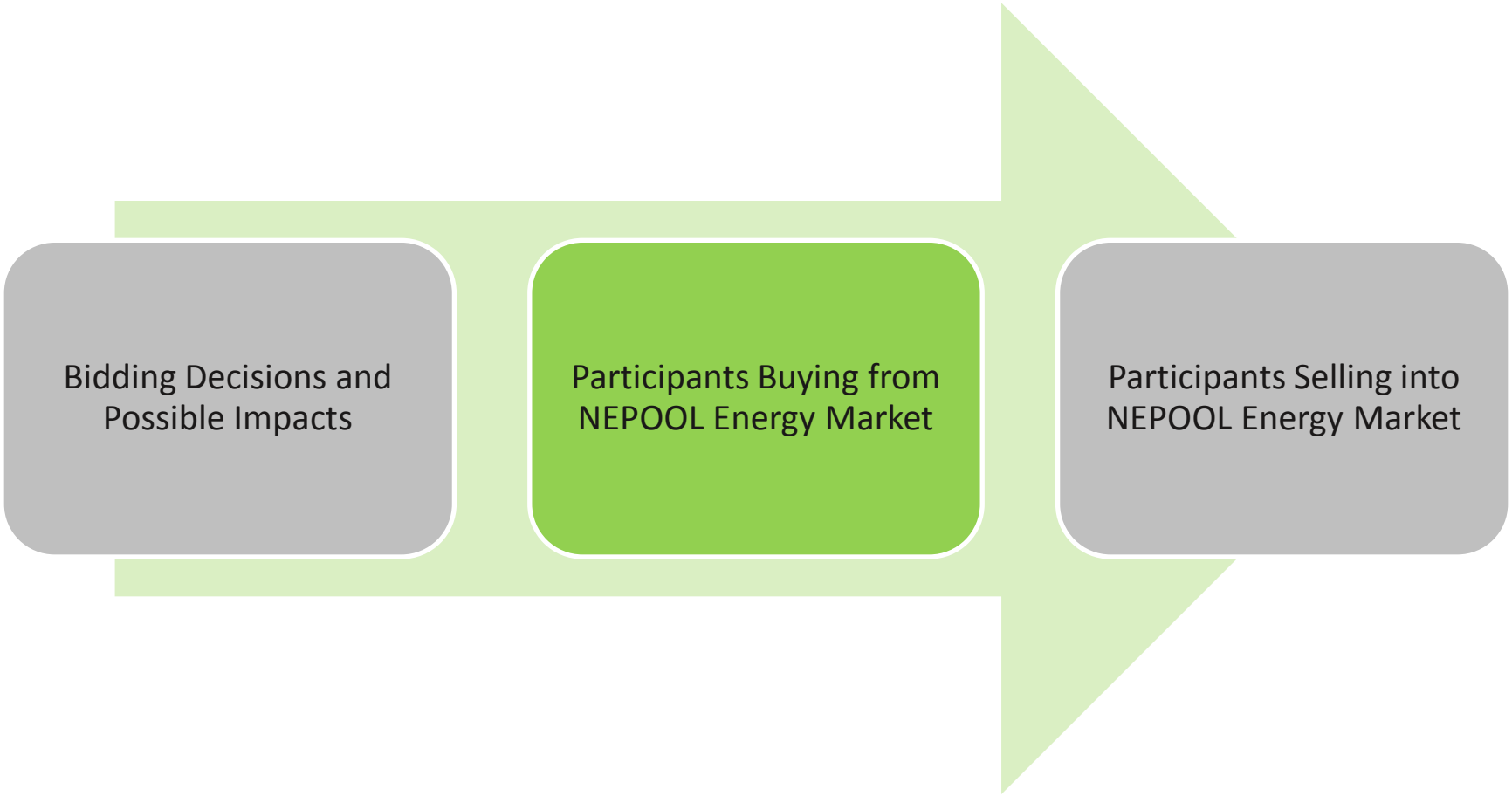
- This section is designed to:
  - Discuss how these tools interact with other inputs in impacting the Day-Ahead Market LMPs
- The topics we will cover are:
  - Fixed Demand
  - Price Sensitive Demand
  - Self Scheduled Generators (and Generator minimums)
  - Why wasn't my Generator Committed and Dispatched?

# DA LMP Process



# RT LMP Process

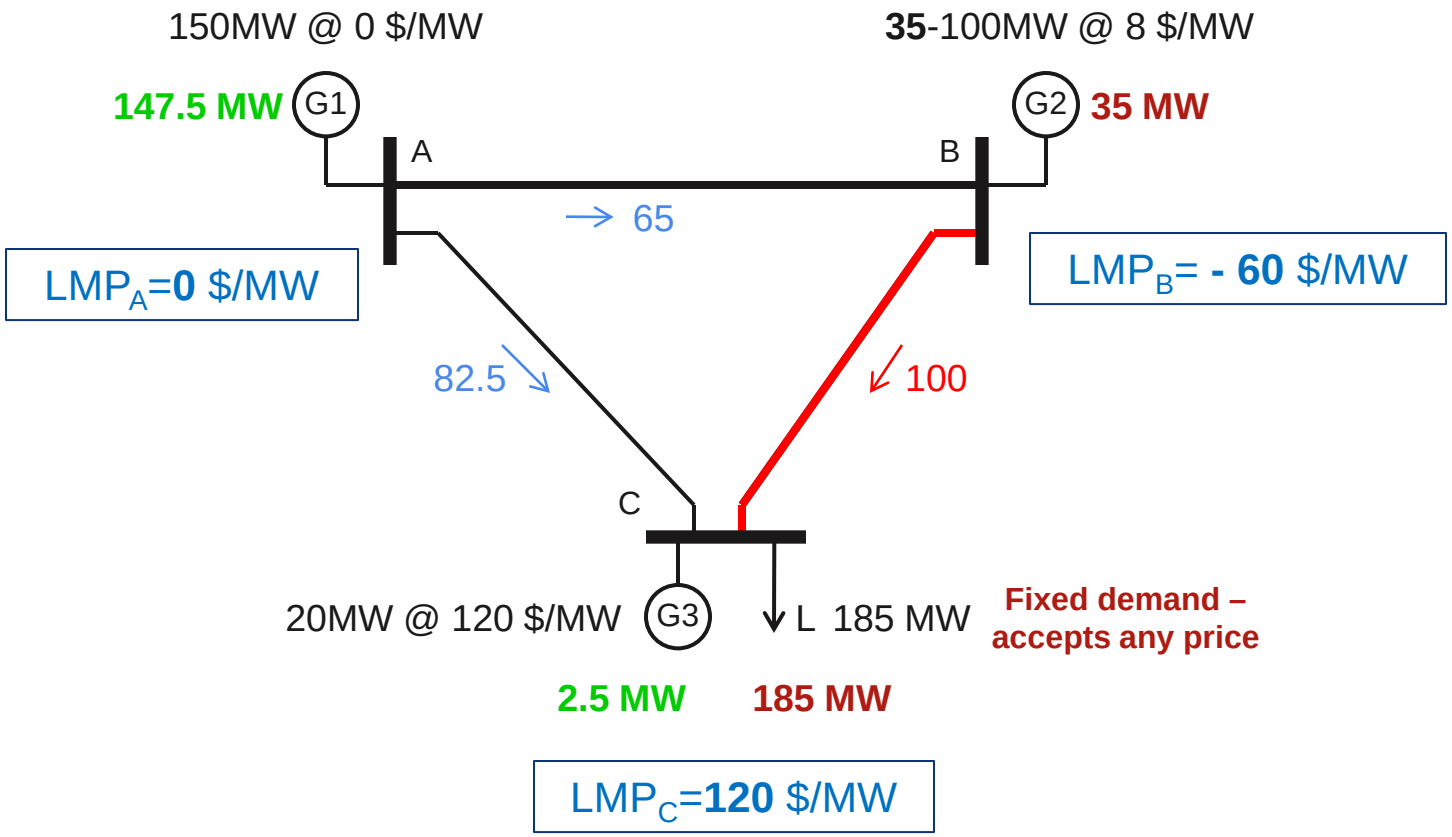




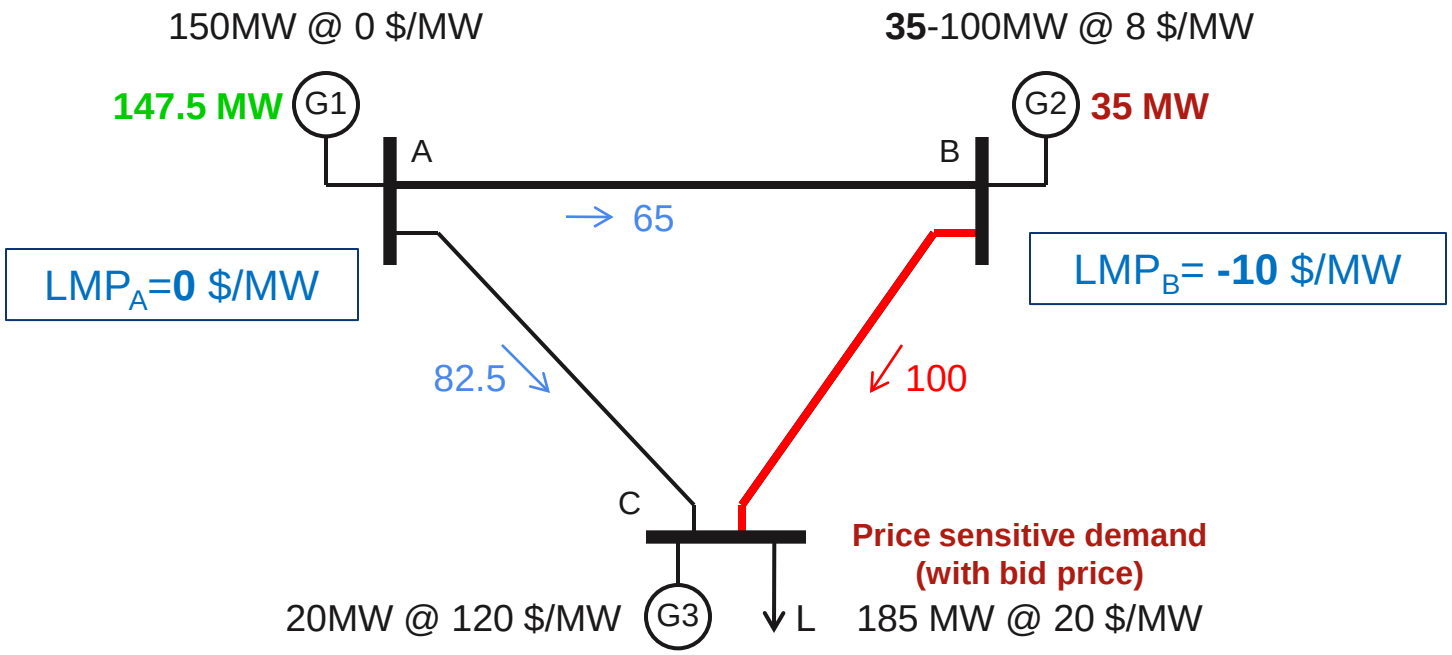
# Clearing Fixed Demand Bids

- Submitted at the zones
- Software distributes the amount bid to each of the load nodes within the zone pro-rata to the seven day average nodal weighting.
- Software will attempt to re-dispatch without regard to cost to meet fixed demand. This can create extremely high LMPs in local areas.
- Nodal LMP can far exceed bid/offer caps because there is no cost associated with fixed demand bid.
- A small amount of “fixed” load at a location may impact the nodal price dramatically.

# Fixed Demand Bid

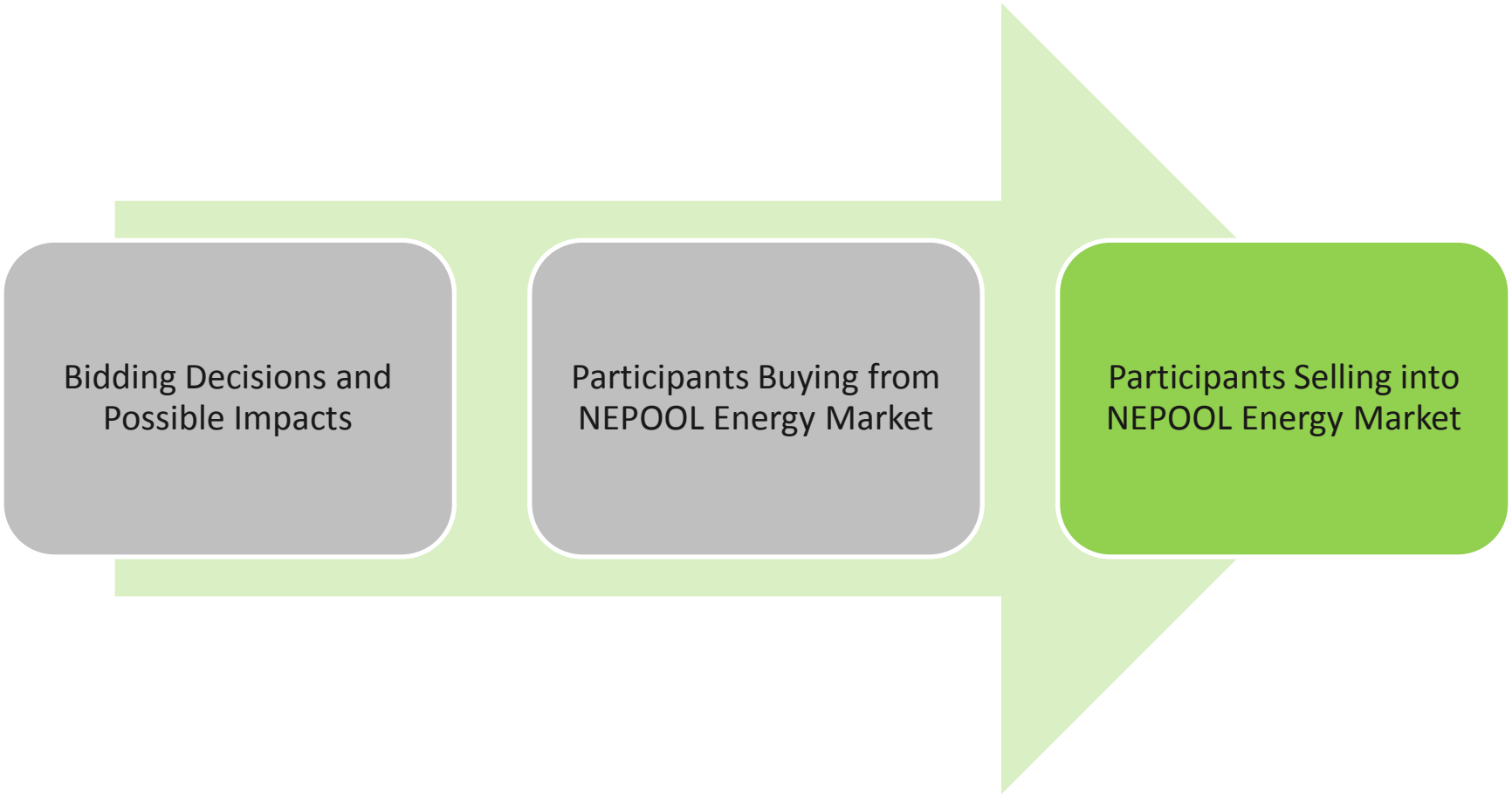


# Changed Fixed to Price Sensitive



# Clearing Price Sensitive Demand Bids

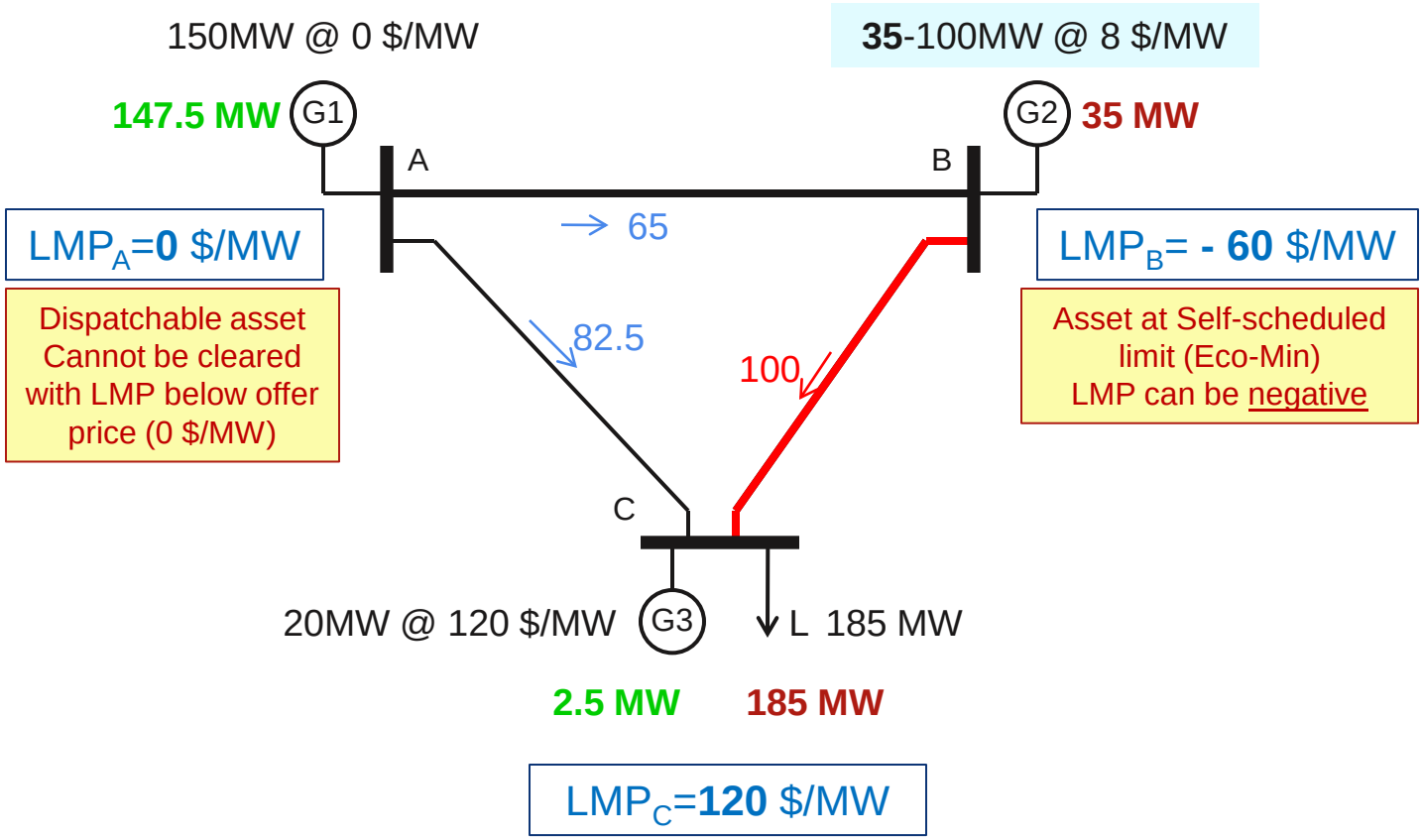
- Submitted at the zones, nodes, hub or interfaces
- Software will distribute zonal bids to the nodes using same weighting as fixed bids.
- Will lessen the impact of nodal constraints
- If bid at the zone, some of the individual nodes may exceed the bid price, but the zonal price will not exceed bid. Depending on the bid price and nodal weighting, an individual node LMP may still exceed bid/offer caps.



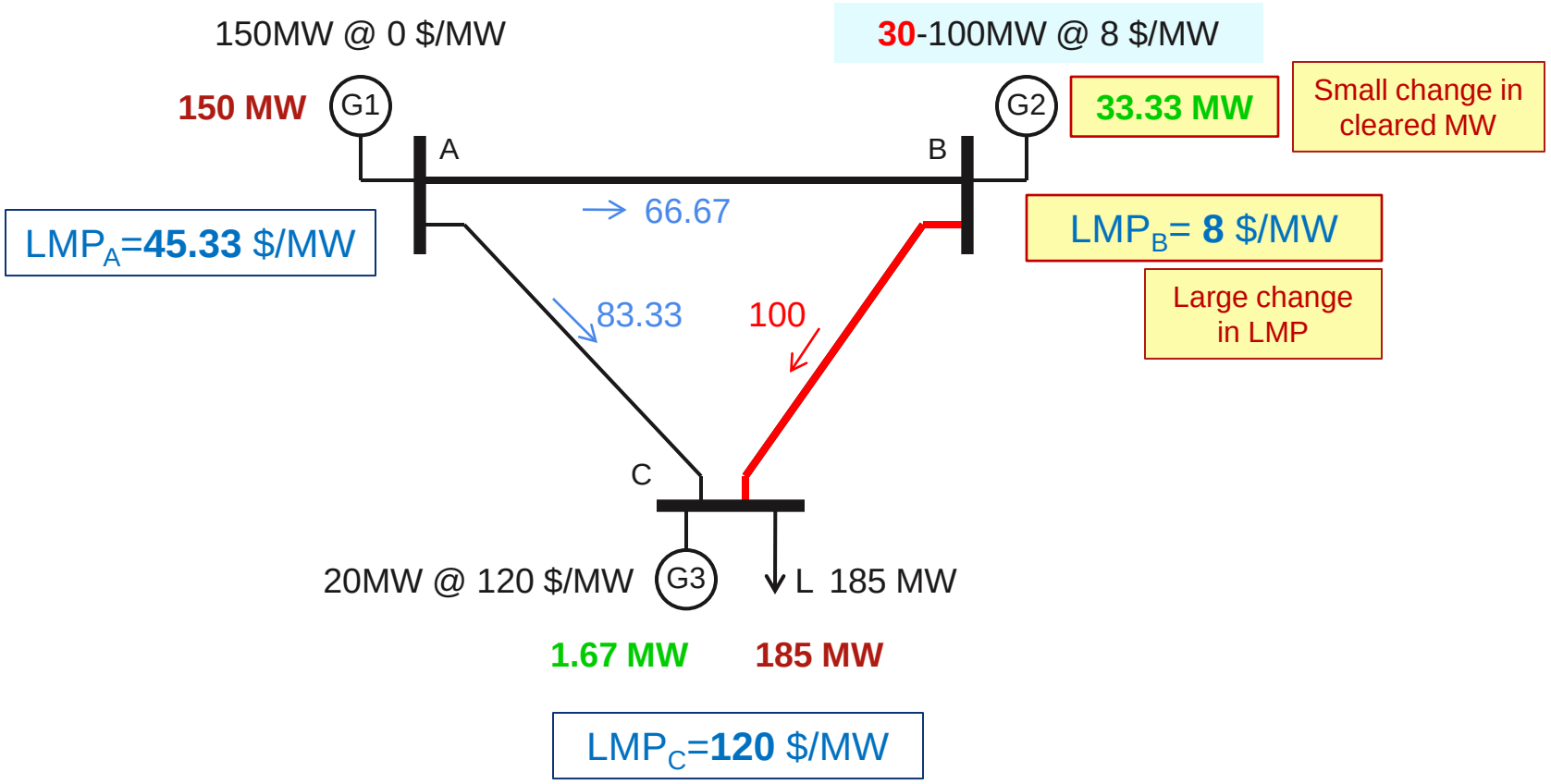
# Clearing Fixed Supply Offers (Self-Scheduled)

- Submitted by Generators
- Software will attempt to re-dispatch without regard to cost to clear fixed supply offers. This can create extremely low LMPs in local areas.
- Nodal LMP can go negative because there is no cost associated with fixed supply offer.
- A small change in the amount of “fixed” Generation at a location may impact the nodal price dramatically.

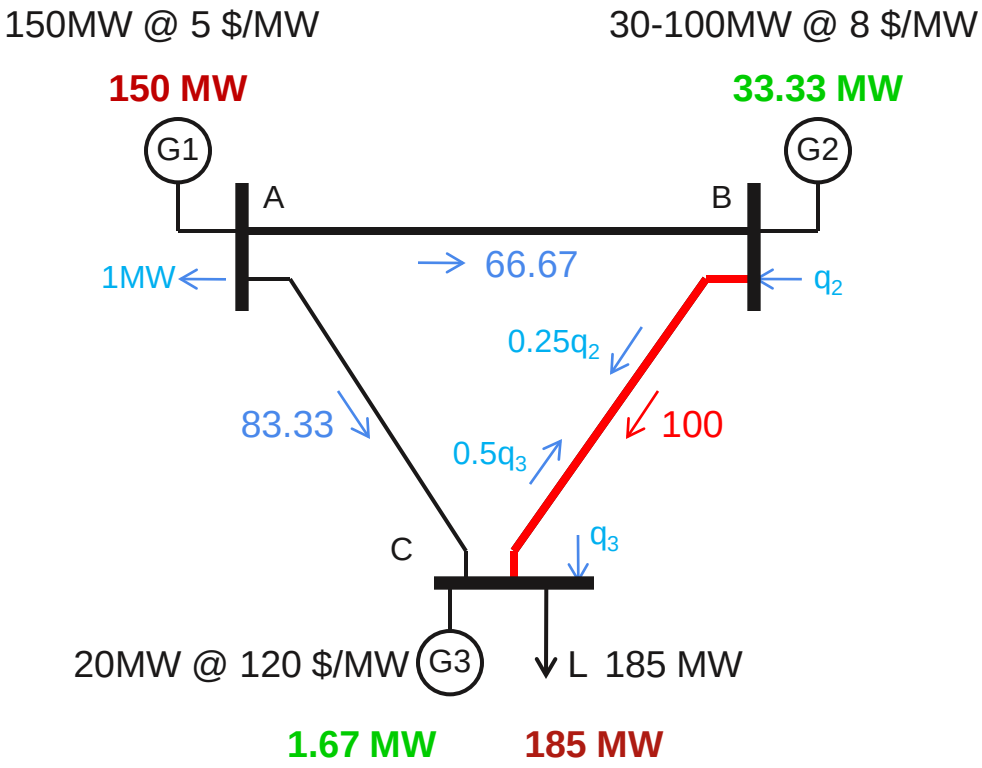
# Example of Extremely Low Price Due to Self-Scheduling



# Remove (or lower) Eco Min of Single Asset



# Refresher: How $LMP_A$ is Determined




$q_2 + q_3 = 1$

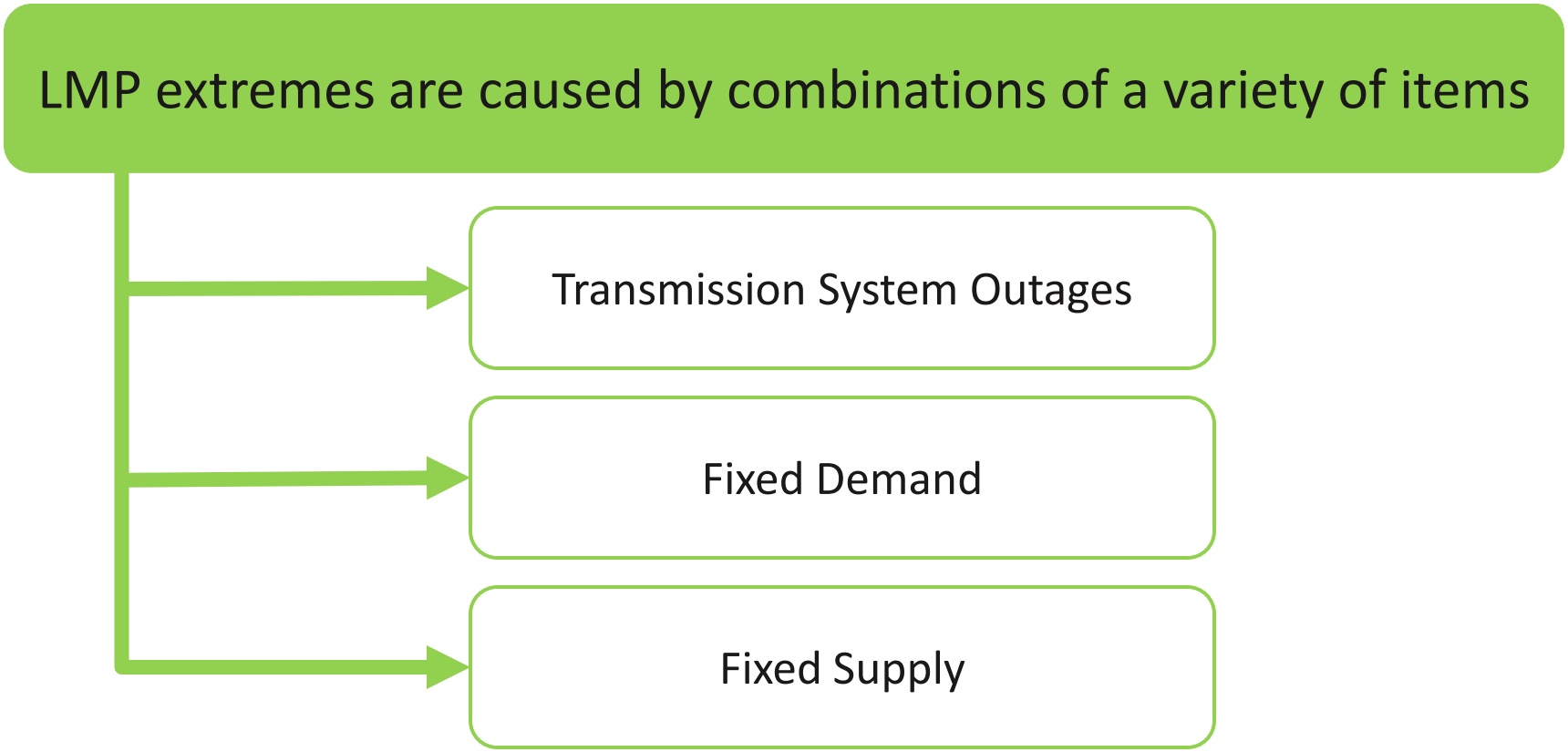
$0.25q_2 - 0.5q_3 = 0$

$q_2 = 2/3;\ \ q_3 = 1/3$

$LMP_A = (2/3)x8 + (1/3)x120$

**$LMP_A$ = 45.33 $/MW**

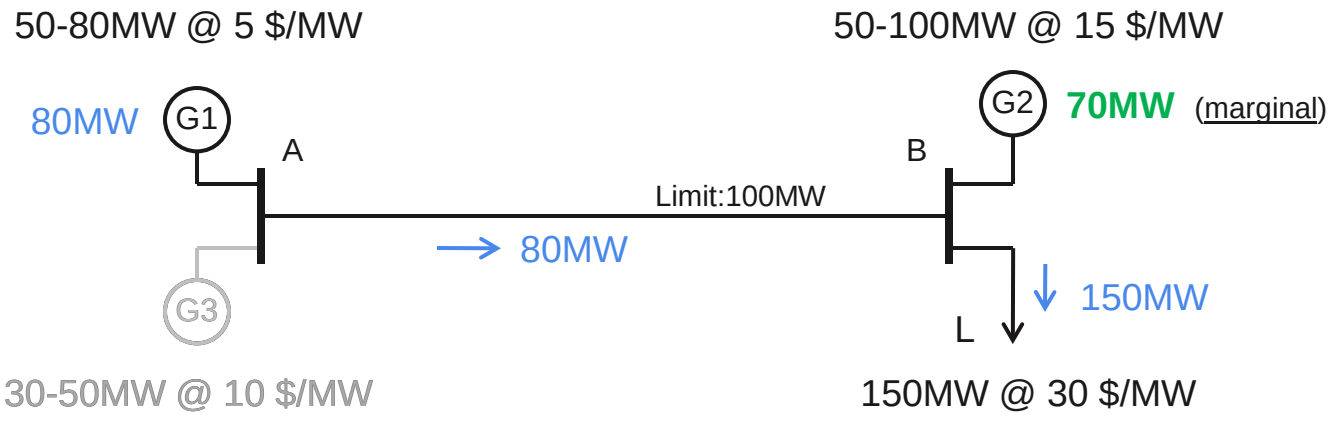
# Extremes in LMPs



# Commitment Decisions in Day-Ahead Market

- Common issue in DA Market is “Why is my asset not running when its offer is below the LMP?”
- The answer in many cases is that by running this asset, it will cause the price to fall below the asset’s bid and put that asset out-of-rate.

# Asset Commitment Example

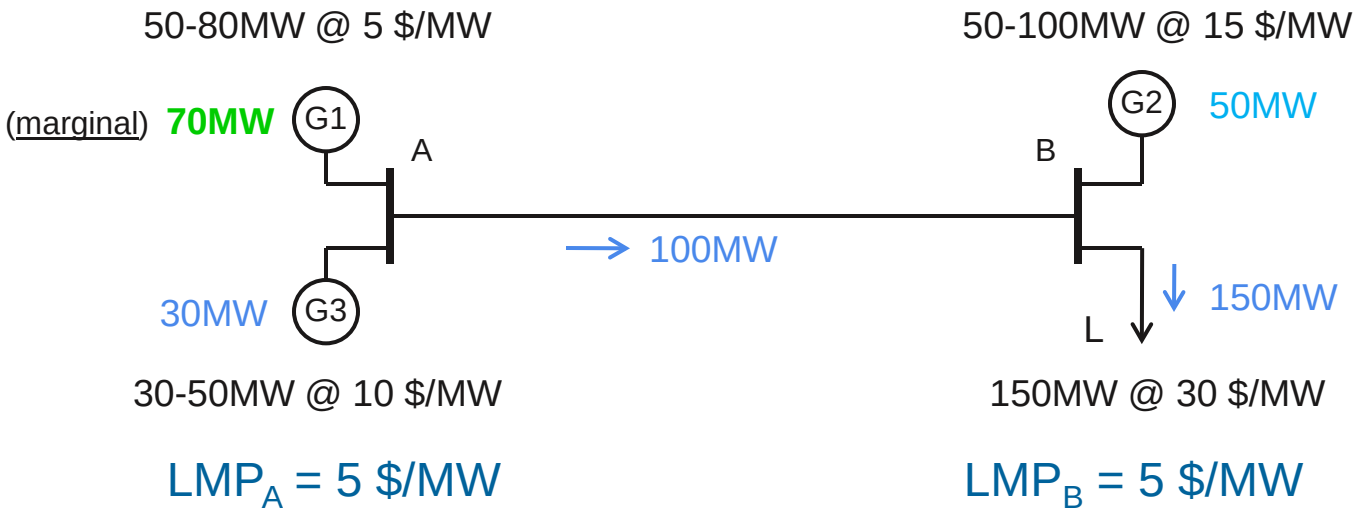



$LMP_A$ = 15 $/MW

$LMP_B$ = 15 $/MW

Why isn't asset G3 committed? It's offer price is below LMP!!!

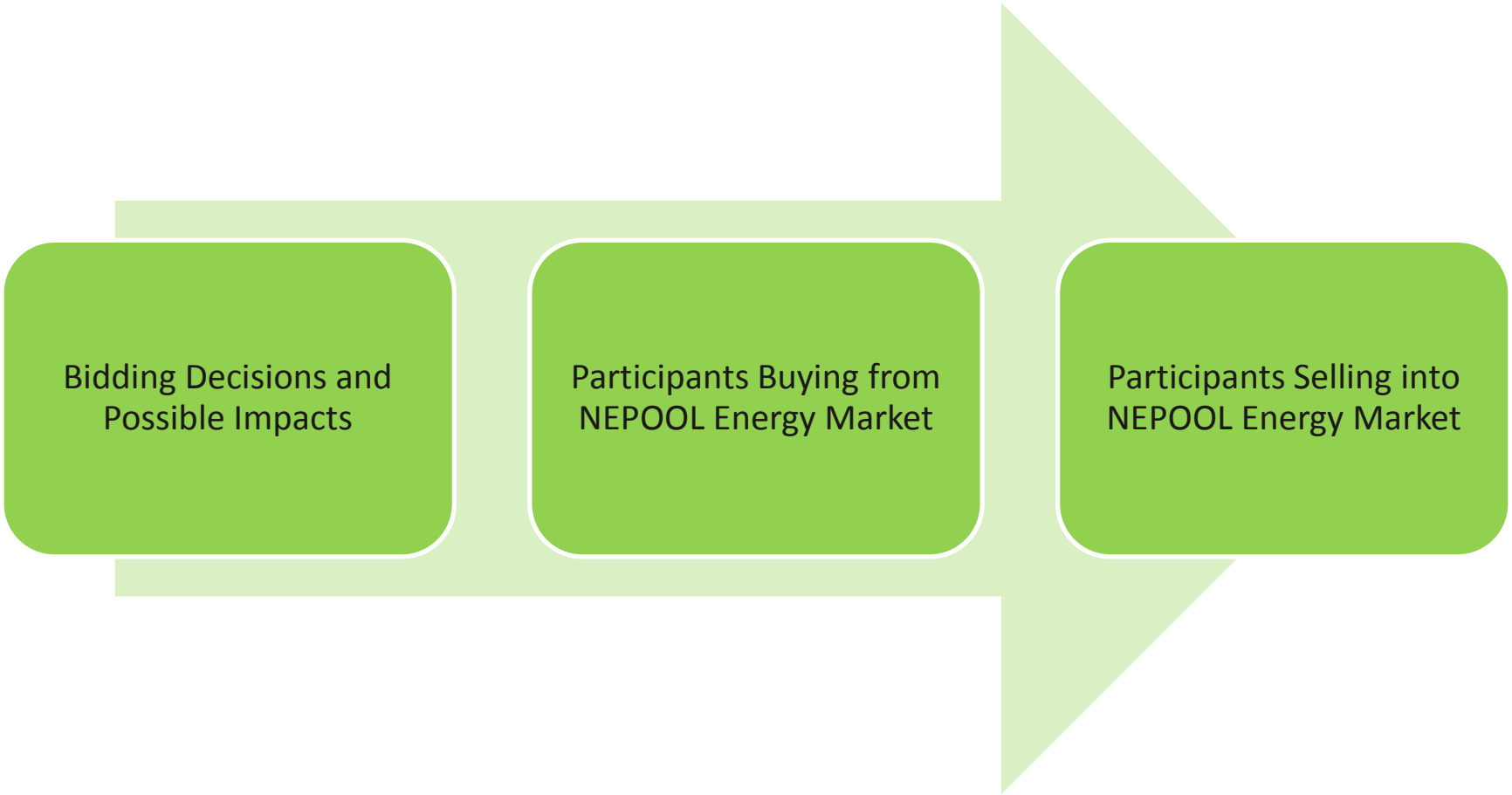
# Asset Commitment Example




**If asset G3 was committed, LMP would be 5 $/MW.**

Now G3 questions is: *Why have you committed me when my offer price is above LMP?*

# Section Review: Topics Covered



# What We Covered

- ✓ Discuss how these tools interact with other inputs in impacting the Day-Ahead Market LMPs
- ✓ Fixed Demand
- ✓ Price Sensitive Demand
- ✓ Self Scheduled Generators (and Generator minimums)
- ✓ Why wasn't my Generator Committed and Dispatched?

# Wrap-Up

- To present foundational knowledge of LMP using examples
- Explain Bidding/Offer impacts on LMP
- *LMP 201 class allows more time to fully explore all of these subjects*