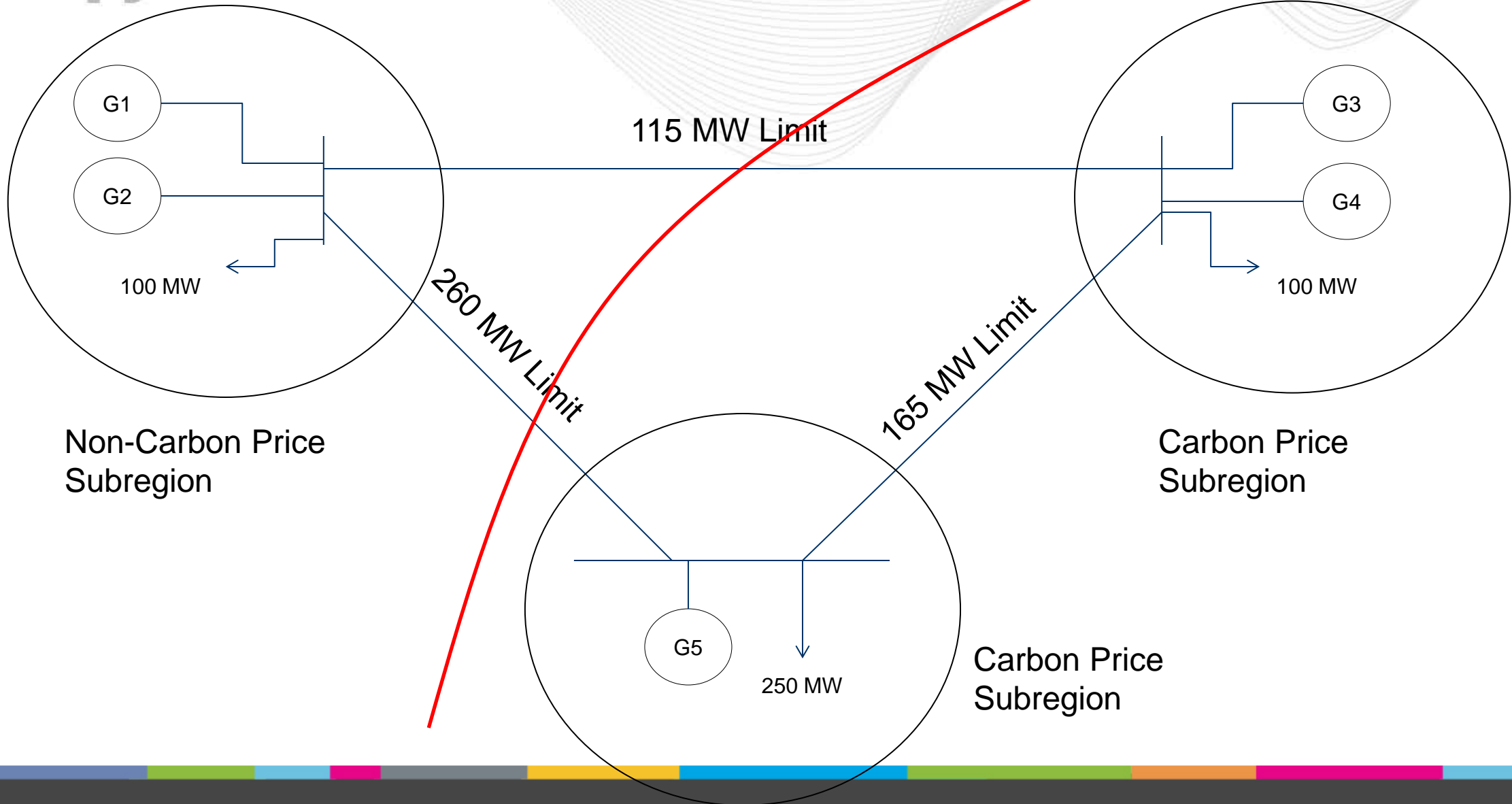


Appendix: Advancing Zero Emissions Objectives through PJM's Energy Markets Additional Examples



- Subregional Carbon-Pricing Example
- Base Case
- Base Case with Carbon Price Subregion Adjusted Offers
- Two-Pass Method
 - Example 1 – Carbon Price
 - Example 2 – Carbon Price with Congestion
 - Example 3 – Regional Pricing Impacts

Subregional Carbon-Pricing Example

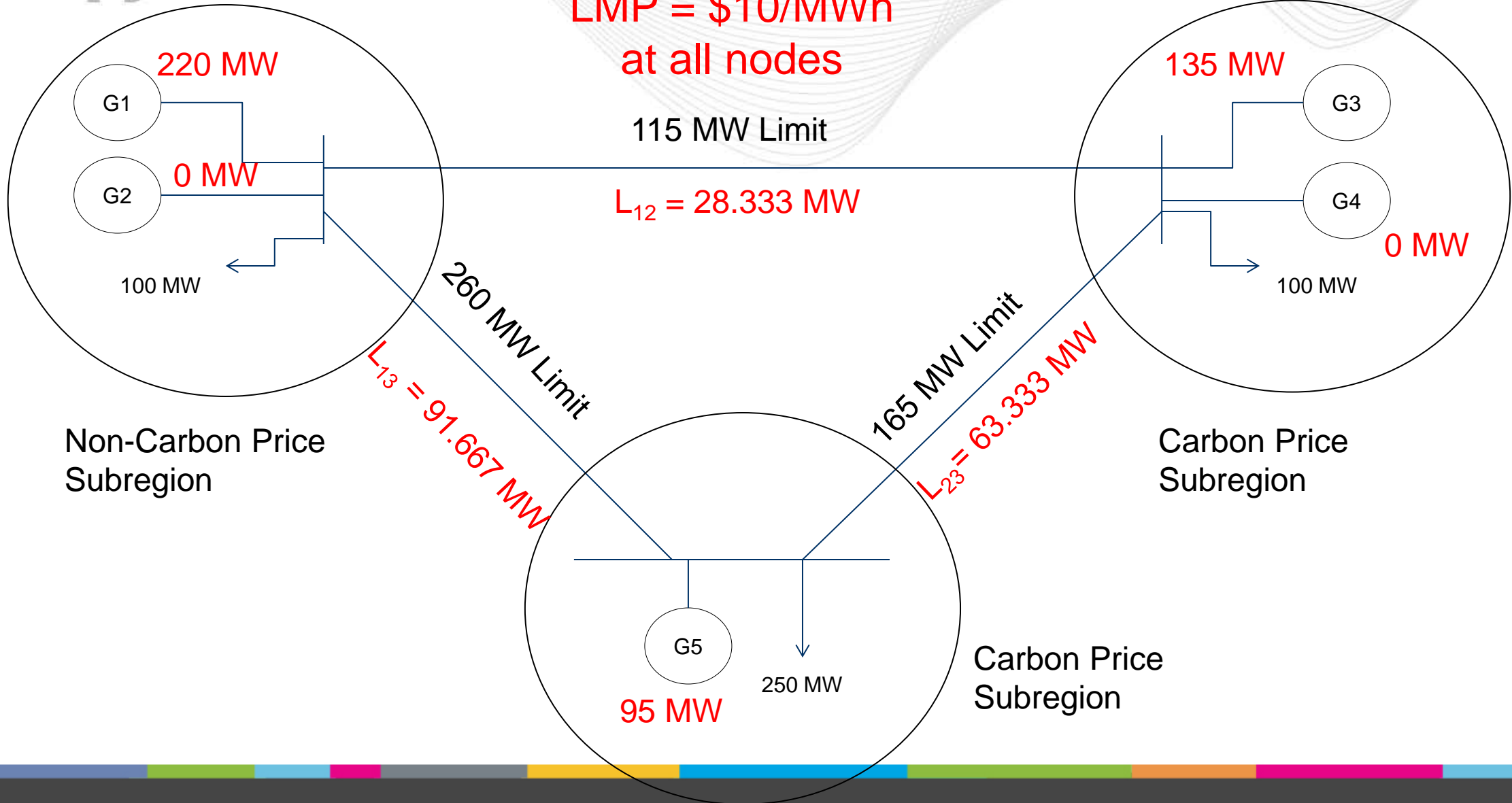


Base Case



Unit	EcoMax (MW)	Offer (\$/MWh)	Emissions (tons/MWh)
Gen. 1	300	10	5
Gen. 2	305	11	15
Gen. 3	135	9	8
Gen. 4	135	13	5
Gen. 5	95	8	12

**LMP = \$10/MWh
at all nodes**



Non-Carbon Price Subregion

Carbon Price Subregion

Carbon Price Subregion

Unit	EcoMax (MW)	Offer (\$/MWh)	Dispatch — Base (MW)
Gen. 1	300	10	220
Gen. 2	305	11	0
Gen. 3	135	9	135
Gen. 4	135	13	0
Gen. 5	95	8	95

Unit	Production Cost — Base (\$)
Gen. 1	2,200
Gen. 2	0
Gen. 3	1,215
Gen. 4	0
Gen. 5	760
Total	4,175

Unit	Emissions – Base (tons)
Gen. 1	1,100
Gen. 2	0
Gen. 3	1,080
Gen. 4	0
Gen. 5	1,140
Total	3,320

Base Case with Carbon Price Subregion Adjusted Offers





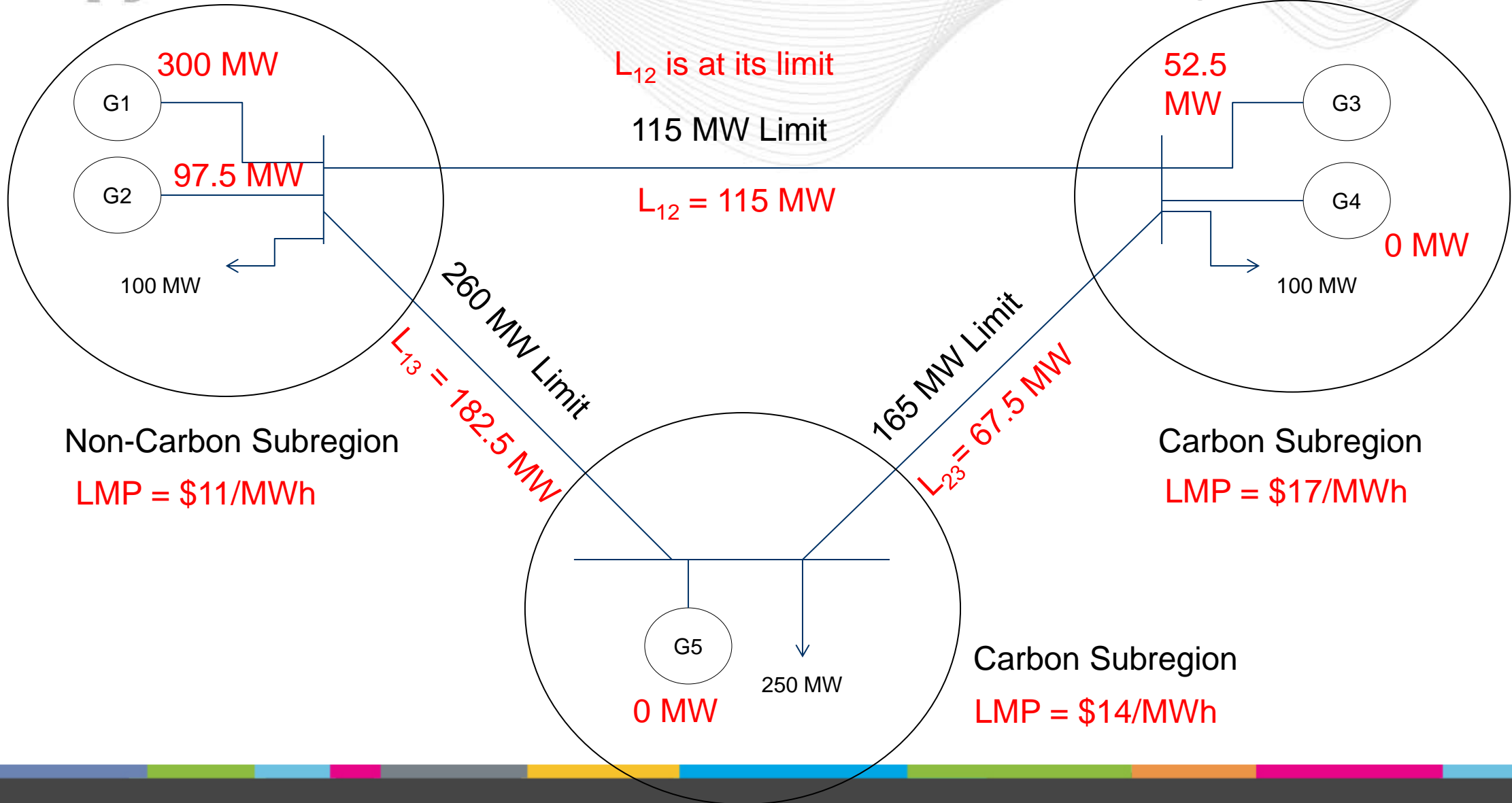
Base Case With Carbon Price Subregion Adjusted Offers

Unit	EcoMax (MW)	Offer (\$/MWh)	Offer (w/Carbon Costs) (\$/MWh)
Gen. 1	300	10	10
Gen. 2	305	11	11
Gen. 3	135	9	17
Gen. 4	135	13	18
Gen. 5	95	8	20

Note: Carbon Price is \$1/ton



Base Case With Carbon Price Subregion Adjusted Offers Solution





Base Case With Carbon Price Subregion Adjusted Offers Solution — Dispatch

Unit	EcoMax (MW)	Offer (\$/MWh)	Dispatch – Base (MW)	Offer (w/Carbon Costs) (\$/MWh)	Dispatch – (w/Carbon Costs) (MW)
Gen. 1	300	10	220	10	300
Gen. 2	305	11	0	11	97.5
Gen. 3	135	9	135	17	52.5
Gen. 4	135	13	0	18	0
Gen. 5	95	8	95	20	0



Base Case With Carbon Price Subregion Adjusted Offers Solution — Production Cost

Unit	Production Cost – Base (\$)	Production Cost – (w/Carbon Costs) (\$)
Gen. 1	2,200	3,000
Gen. 2	0	1,072.50
Gen. 3	1,215	892.50
Gen. 4	0	0
Gen. 5	760	0
Total	4,175	4,965



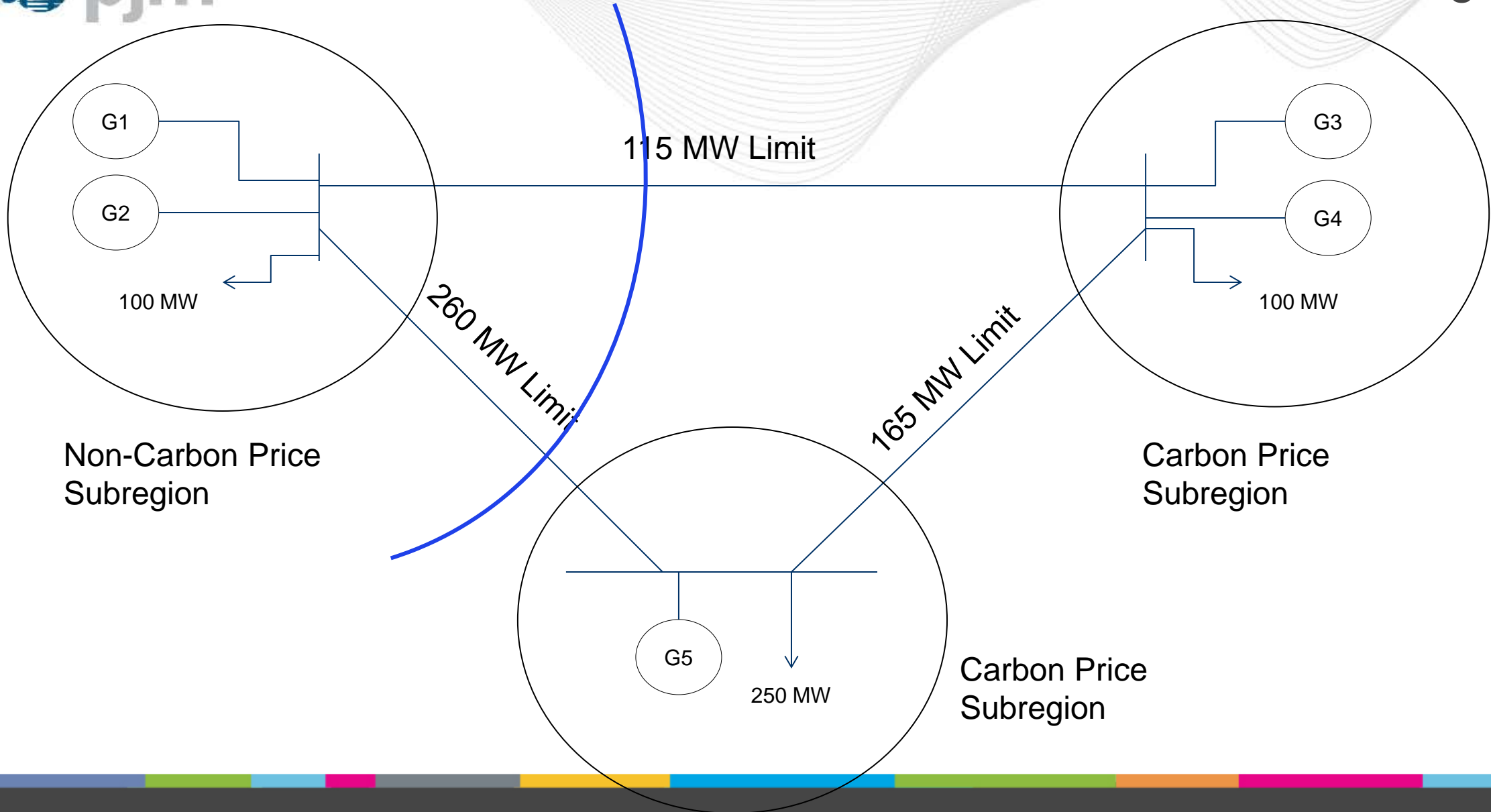
Base Case With Carbon Price Subregion Adjusted Offers Solution — Emissions

Unit	Emissions - Base (tons)	Emissions - (w/Carbon Costs) (tons)
Gen. 1	1,100	1,500
Gen. 2	0	1,462.5
Gen. 3	1,080	420
Gen. 4	0	0
Gen. 5	1,140	0
Total	3,320	3,382.5

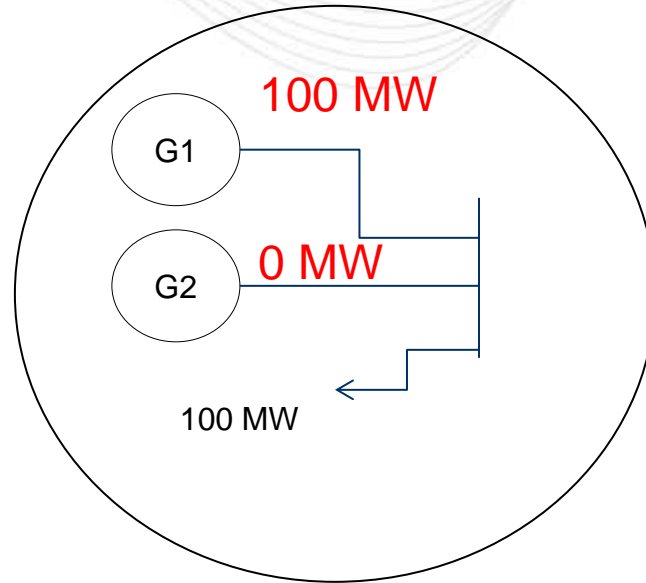
Two-Pass Method



- **1st Optimization Pass:** Calculate a “base” economic dispatch not allowing net imports from the non-carbon price subregion into the carbon-price subregion.
- **2nd Optimization Pass:** Calculate the economic dispatch allowing net imports from the non-carbon price subregion into the carbon price subregion, but limit the imports into the carbon-price subregion to the incremental dispatch above each unit’s base schedule (determined in the 1st optimization pass).



1st Optimization Pass Solution for Non-Carbon Price Subregion



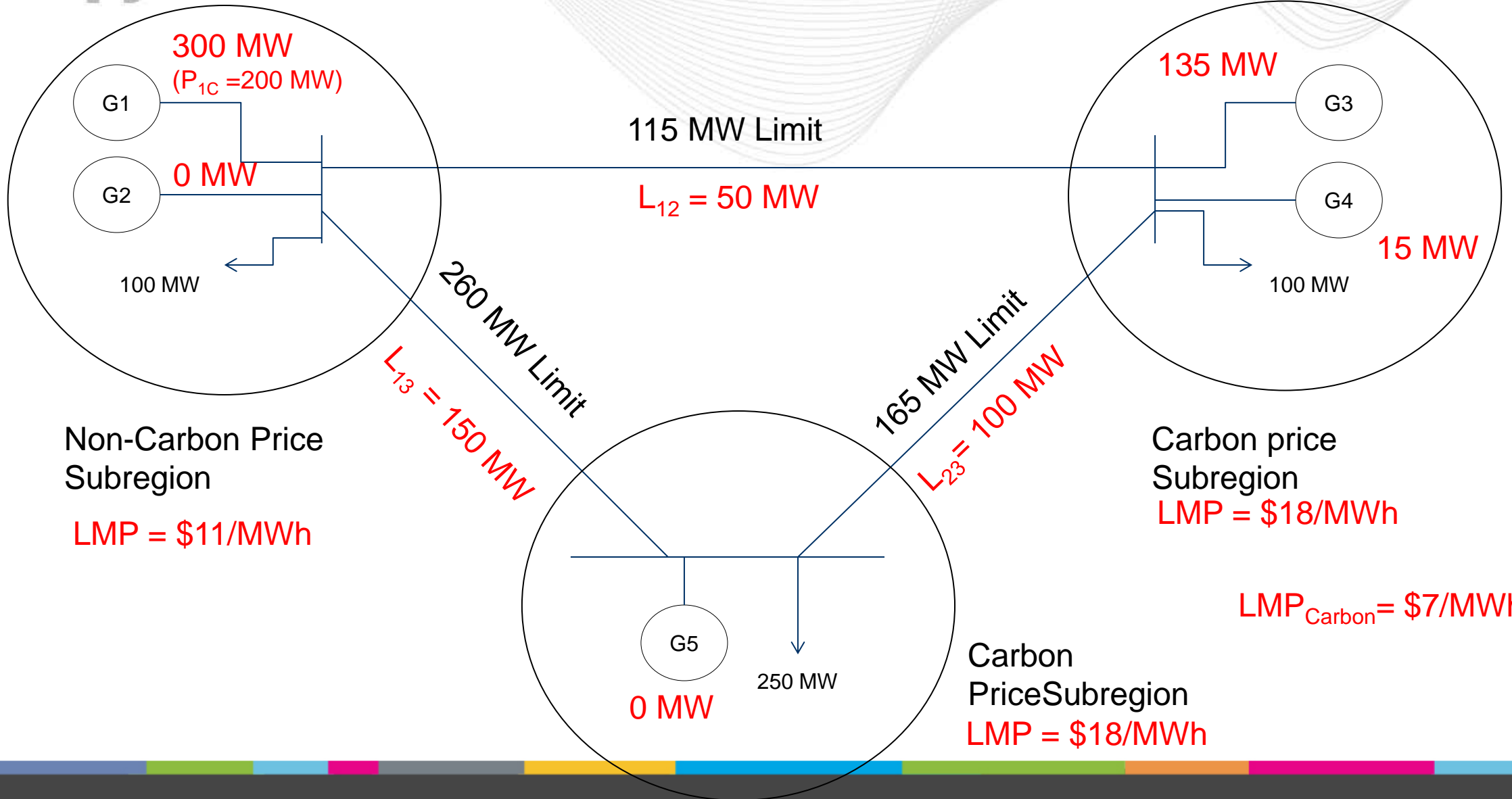
Non-Carbon Price Subregion

Carbon Cost Adders for Non-Carbon Price Subregion

	Offer (\$/MWh)	Carbon Cost Adder (\$/MWh)
CG ₁	10	5
CG ₂	11	15

Note: Carbon Price is \$1/ton

Two-Pass Method: Example 1 Solution



- Generator 1 supports imports into the carbon price subregion and will receive carbon award revenue:
 - Gen 1: $200 \text{ MW} \times \$7/\text{MWh} (LMP_{Carbon}) = \$1,400$



Two-Pass Method: Example 1 Solution — Dispatch

Unit	EcoMax (MW)	Offer (\$/MWh)	Dispatch – Base (MW)	Offer (w/Carbon Costs) (\$/MWh)	Dispatch – (w/Carbon Costs) (MW)	Dispatch – 2 Pass – Ex. 1 (MW)
Gen. 1	300	10	220	10	300	300
Gen. 2	305	11	0	11	97.5	0
Gen. 3	135	9	135	17	52.5	135
Gen. 4	135	13	0	18	0	15
Gen. 5	95	8	95	20	0	0

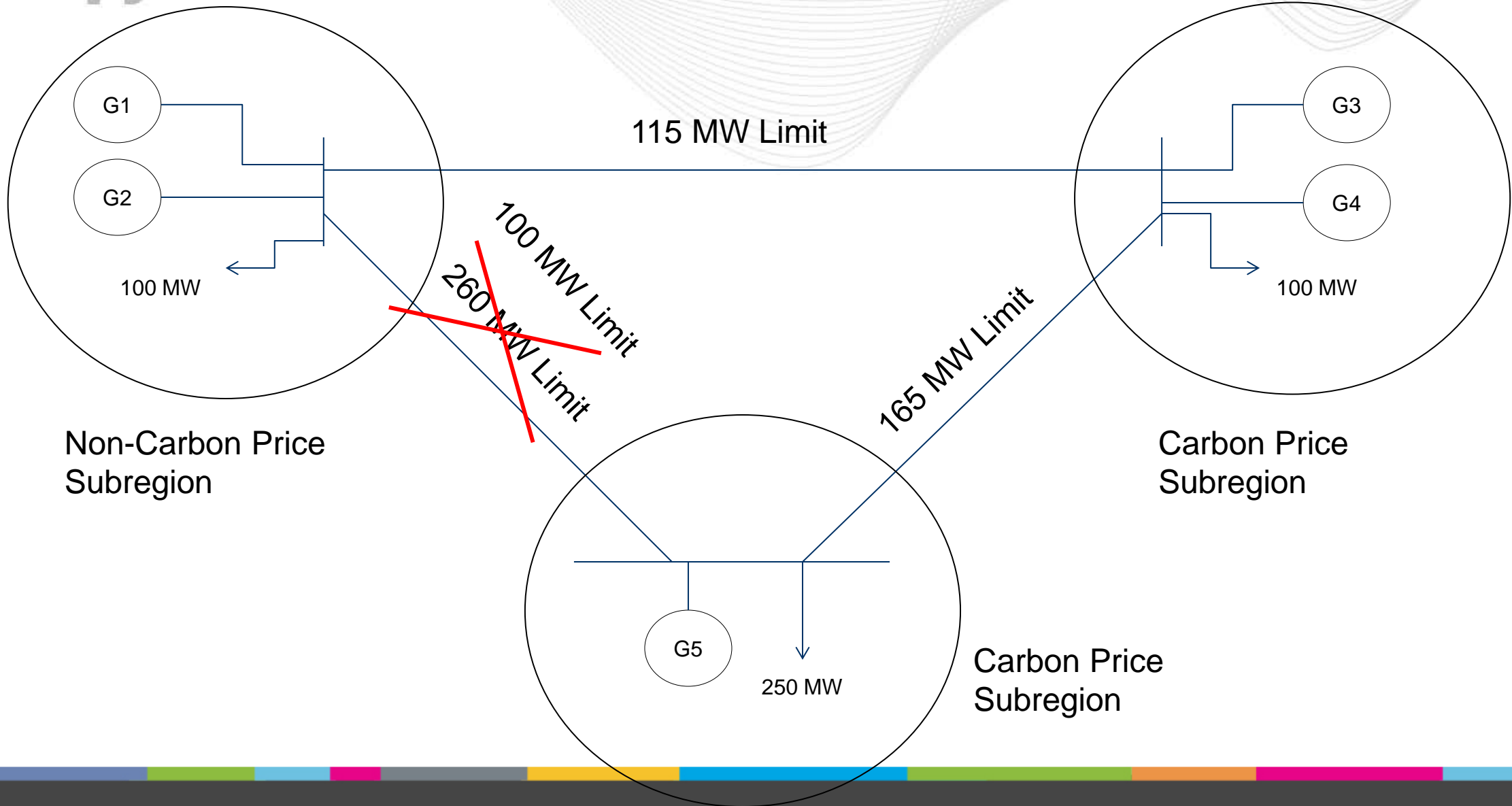


Two-Pass Method: Example 1 Solution — Production Cost

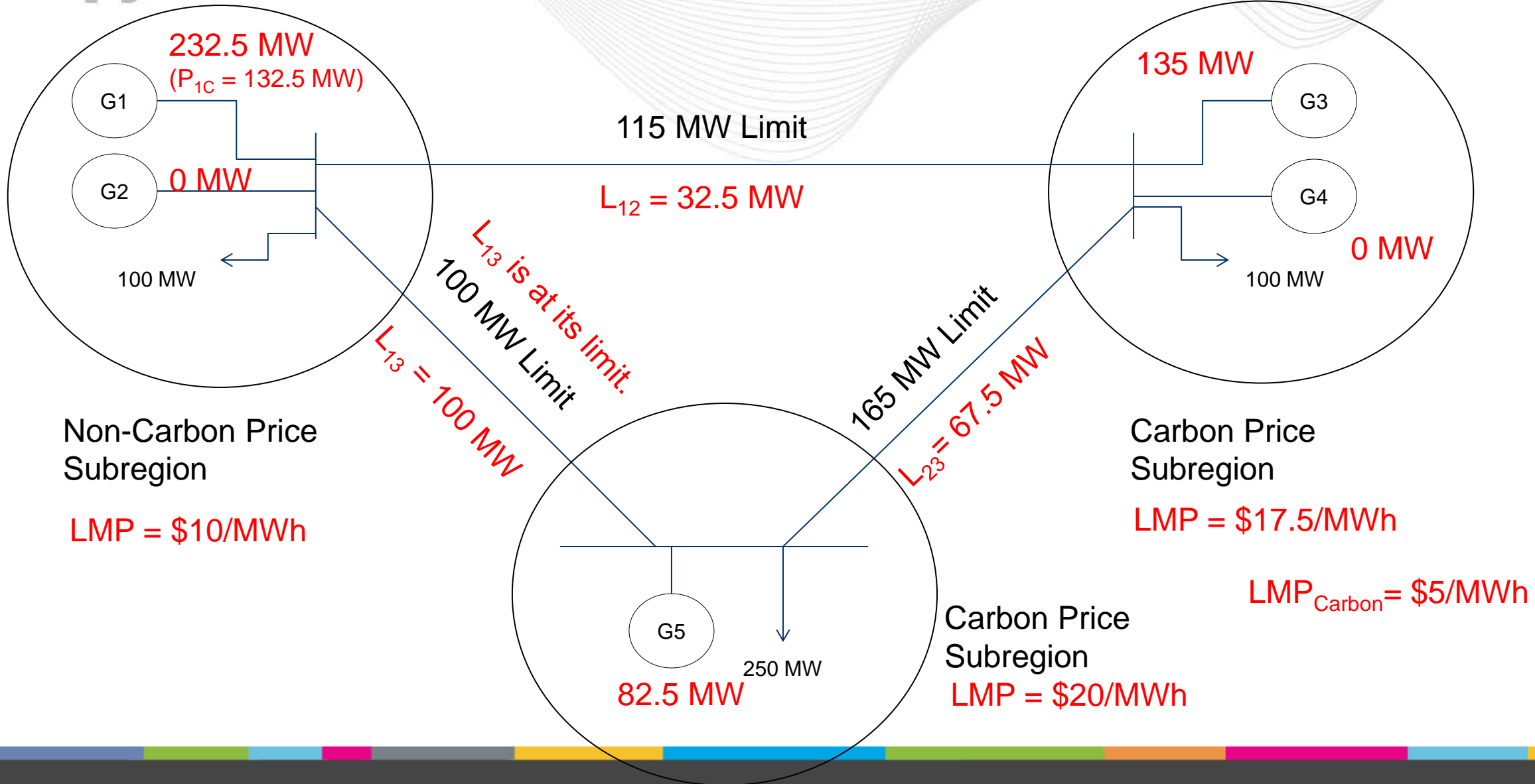
Unit	Production Cost – Base (\$)	Production Cost – (w/Carbon Costs) (\$)	Production Cost – 2 Pass – Ex. 1 (\$)
Gen. 1	2,200	3,000	4,000
Gen. 2	0	1,072.50	0
Gen. 3	1,215	892.50	2,295
Gen. 4	0	0	270
Gen. 5	760	0	0
Total	4,175	4,965	6,565

Unit	Emissions – Base (tons)	Emissions – (w/Carbon Costs) (tons)	Emissions – 2 Pass – Ex. 1 (tons)
Gen. 1	1,100	1,500	1,500
Gen. 2	0	1,462.5	0
Gen. 3	1,080	420	1,080
Gen. 4	0	0	75
Gen. 5	1,140	0	0
Total	3,320	3,382.5	2,655

Two-Pass Method: Example 2 — Congestion



Two-Pass Method: Example 2 — Congestion Solution



- Generator 1 supports imports into the carbon price subregion and will receive carbon award revenue:
 - Gen 1: $132.5 \text{ MW} \times \$5/\text{MWh} (LMP_{Carbon}) = \662.50



Two-Pass Method: Example 2 — Congestion Solution — Dispatch

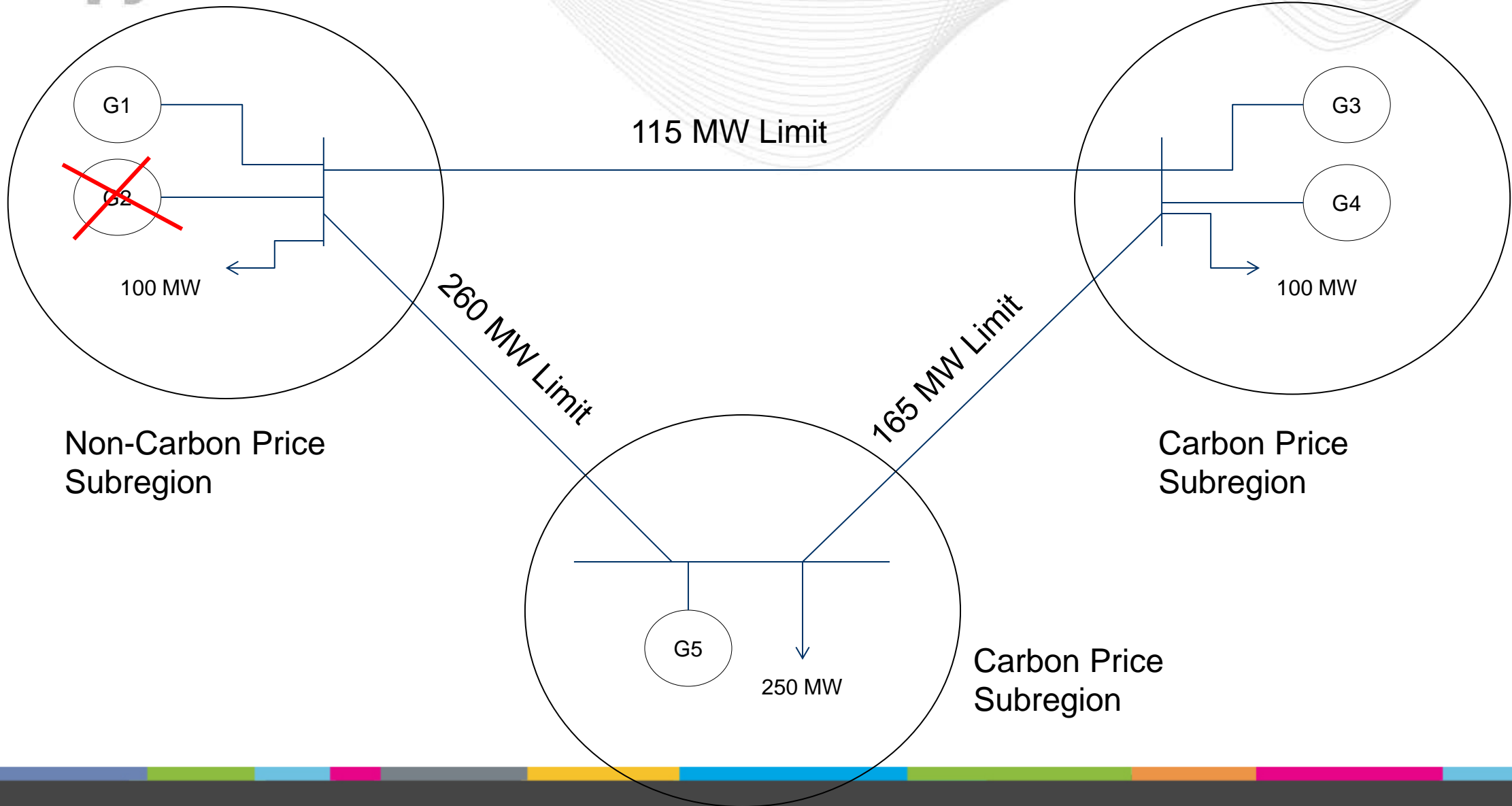
Unit	EcoMax (MW)	Offer (\$/MWh)	Dispatch – Base (MW)	Offer (w/Carbon Costs) (\$/MWh)	Dispatch – (w/Carbon Costs) (MW)	Dispatch – 2 Pass – Ex. 1 (MW)	Dispatch – 2 Pass – Ex. 2 (MW)
Gen. 1	300	10	220	10	300	300	232.5
Gen. 2	305	11	0	11	97.5	0	0
Gen. 3	135	9	135	17	52.5	135	135
Gen. 4	135	13	0	18	0	15	0
Gen. 5	95	8	95	20	0	0	82.5

Two-Pass Method: Example 2 — Congestion Solution — Production Cost

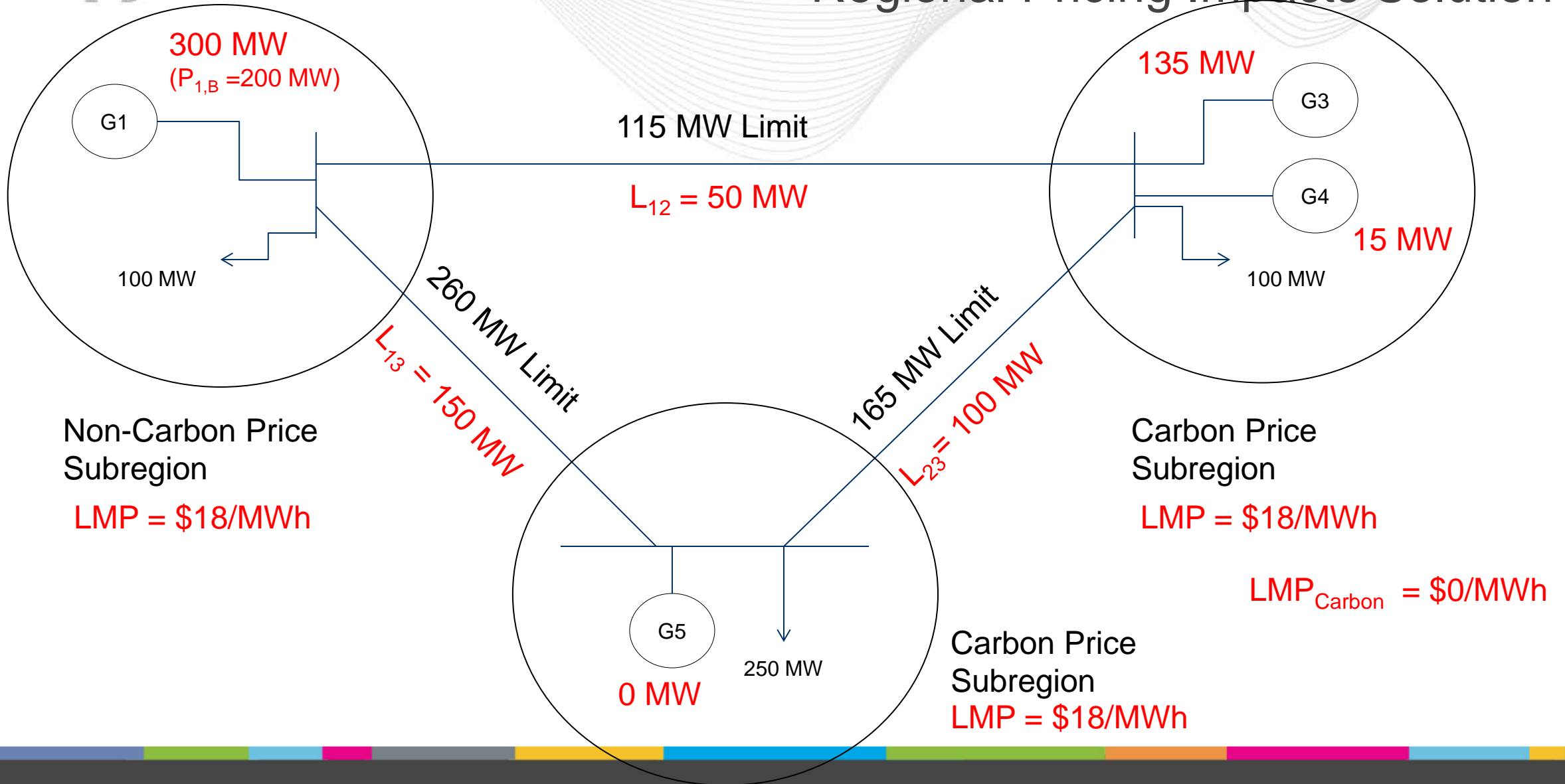
Unit	Production Cost – Base (\$)	Production Cost – (w/Carbon Costs) (\$)	Production Cost – 2 Pass – Ex. 1 (\$)	Production Cost – 2 Pass – Ex. 2 (\$)
Gen. 1	2,200	3,000	4,000	2,987.50
Gen. 2	0	1,072.50	0	0
Gen. 3	1,215	892.50	2,295	2,295
Gen. 4	0	0	270	0
Gen. 5	760	0	0	1,650
Total	4,175	4,965	6,565	6,932.50

Unit	Emissions – Base (tons)	Emissions – (w/Carbon Costs) (tons)	Emissions – 2 Pass – Ex. 1 (tons)	Emissions – 2 Pass – Ex. 2 (tons)
Gen. 1	1,100	1,500	1,500	1,162.5
Gen. 2	0	1,462.5	0	0
Gen. 3	1,080	420	1,080	1,080
Gen. 4	0	0	75	0
Gen. 5	1,140	0	0	990
Total	3,320	3,382.5	2,655	3,232.5

Two-Pass Method: Example 3 — Regional Pricing Impacts



Two-Pass Method: Example 3 — Regional Pricing Impacts Solution



Unit	Production Cost – Base (\$)	Production Cost – (w/Carbon Costs) (\$)	Production Cost – 2 Pass Ex. 1 (\$)	Production Cost – 2 Pass Ex. 2 (\$)	Production Cost – 2 Pass Ex. 3 (\$)
Gen. 1	2,200	3,000	4,000	2,987.50	4,000
Gen. 2	0	1,072.50	0	0	0
Gen. 3	1,215	892.50	2,295	2,295	2,295
Gen. 4	0	0	270	0	270
Gen. 5	760	0	0	1,650	0
Total	4,175	4,965	6,565	6,932.5	6,565

Unit	Emissions – Base (tons)	Emissions – (w/Carbon Costs) (tons)	Emissions – 2 Pass – Ex. 1 (tons)	Emissions – 2 Pass – Ex. 2 (tons)	Emissions – 2 Pass – Ex. 3 (tons)
Gen. 1	1,100	1,500	1,500	1,162.5	1,500
Gen. 2	0	1,462.5	0	0	0
Gen. 3	1,080	420	1,080	1,080	1,080
Gen. 4	0	0	75	0	75
Gen. 5	1,140	0	0	990	0
Total	3,320	3,382.5	2,655	3,232.5	2,655