PJM Study of Carbon Pricing & Potential Leakage Mitigation Mechanisms Example Problem Formulations

Carbon Pricing Senior Task Force

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Disclaimer

- All the example problem formulations are provided for illustrative purposes only and are not in any way representative of any market design proposal on behalf of PJM or any of its members.

- The formulation for the one-way border adjustment is adapted from CAISO's Energy Imbalance Market (EIM) Draft Final Proposal (published Sept. 23, 2013).

- The formulation for the two-way border adjustment is a possible extension of CAISO's EIM Draft Final Proposal.

- None of the formulations provided are unique and other formulations are possible.

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  - Carbon Pricing with One-Way Border Adjustment
  - Carbon Pricing with Two-Way Border Adjustment
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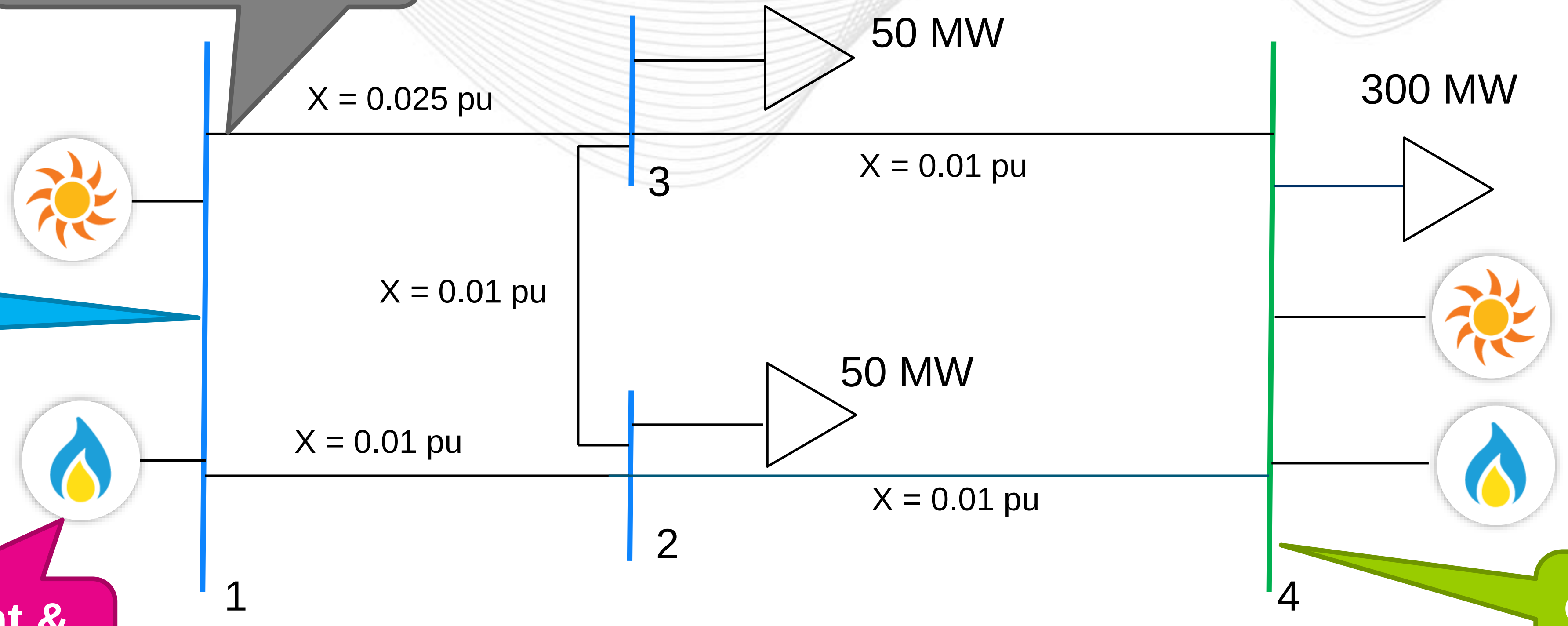
4 Bus System Example

All Line Limits are 225 MW



No-Carbon-Price Region

Carbon-Price Region

Less efficient & higher emissions

Cost Adder (carbon price is $1/short ton)

	No-Carbon-Price Region: Solar	No-Carbon-Price Region: Natural Gas	Carbon-Price Region: Solar	Carbon-Price Region: Natural Gas
EcoMax (MW)	100	400	100	400
Offer ($/MWh)	0	30	0	20
GHG Cost ($/MWh)	0	90	0	80

Notation

Unit Offers	C_{Solar}^{NC}	Solar unit offer (without GHG adder) in the no−carbon−price region
	C_{Gas}^{NC}	Gas unit offer (without GHG adder) in the no−carbon−price region
	C_{Solar}^{C}	Solar unit offer (without GHG adder) in the carbon−price region
	C_{Gas}^{C}	Gas unit offer (without GHG adder) in the carbon−price region
Unit Physical Dispatches	P_{Solar}^{NC}	Dispatch of the solar unit in the no−carbon−price region
	P_{Gas}^{NC}	Dispatch of the gas unit in the no−carbon−price region
	P_{Solar}^{C}	Dispatch of the solar unit in the carbon−price region
	P_{Gas}^{C}	Dispatch of the gas unit in the carbon−price region
Unit GHG Cost Adders	$C_{Solar\ GHG}^{NC}$	Solar unit GHG cost adder in the no−carbon−price region
	$C_{Gas\ GHG}^{NC}$	Gas unit GHG cost adder in the no−carbon−price region
	$C_{Solar\ GHG}^{C}$	Solar unit GHG cost adder in the carbon−price region
	$C_{Gas\ GHG}^{C}$	Gas unit GHG cost adder in the carbon−price region
Unit GHG Dispatches (MW amount being transferred to the other region)	$P_{Solar\ GHG}^{NC}$	Solar unit GHG dispatch in the no−carbon−price region
	$P_{Gas\ GHG}^{NC}$	Gas unit GHG dispatch in the no−carbon−price region
	$P_{Solar\ GHG}^{C}$	Solar unit GHG dispatch in the carbon−price region
	$P_{Gas\ GHG}^{C}$	Gas unit GHG dispatch in the carbon−price region
	θ_i	Bus voltage angle for bus i.
	$Flow_{i,j}$	MW flow on line from bus i to bus j.

Problem Formulation – No Carbon Pricing

Minimize Production Cost

$$Minimize: \{ \ C^{NC}_{Solar} \cdot P^{NC}_{Solar} + C^{NC}_{Gas} \cdot P^{NC}_{Gas} + C^{C}_{Solar} \cdot P^{C}_{Solar} + C^{C}_{Gas} \cdot P^{C}_{Gas} \ \}$$

$$Minimize: \{ \ 0 \cdot P^{NC}_{Solar} + 30 \cdot P^{NC}_{Gas} + 0 \cdot P^{C}_{Solar} + 20 \cdot P^{C}_{Gas} \ \}$$

Subject to:

Generator Constraints

$$0 \le P^{NC}_{Solar} \le 100$$
$$0 \le P^{NC}_{Gas} \le 400$$
$$0 \le P^{C}_{Solar} \le 100$$
$$0 \le P^{C}_{Gas} \le 400$$

Line Constraints

$$-225 \le Flow_{12} \le 225$$
$$-225 \le Flow_{13} \le 225$$
$$-225 \le Flow_{23} \le 225$$
$$-225 \le Flow_{24} \le 225$$
$$-225 \le Flow_{34} \le 225$$

DC Power Flow Equations

$$100 \cdot \theta_1 \ -100 \cdot \theta_2 \ -Flow_{12} = 0$$
$$40 \cdot \theta_1 \ -40 \cdot \theta_3 \ -Flow_{13} = 0$$
$$100 \cdot \theta_2 \ -100 \cdot \theta_3 \ -Flow_{23} = 0$$
$$100 \cdot \theta_2 \ -100 \cdot \theta_4 \ -Flow_{24} = 0$$
$$100 \cdot \theta_3 \ -100 \cdot \theta_4 \ -Flow_{34} = 0$$

Nodal Balance Equations

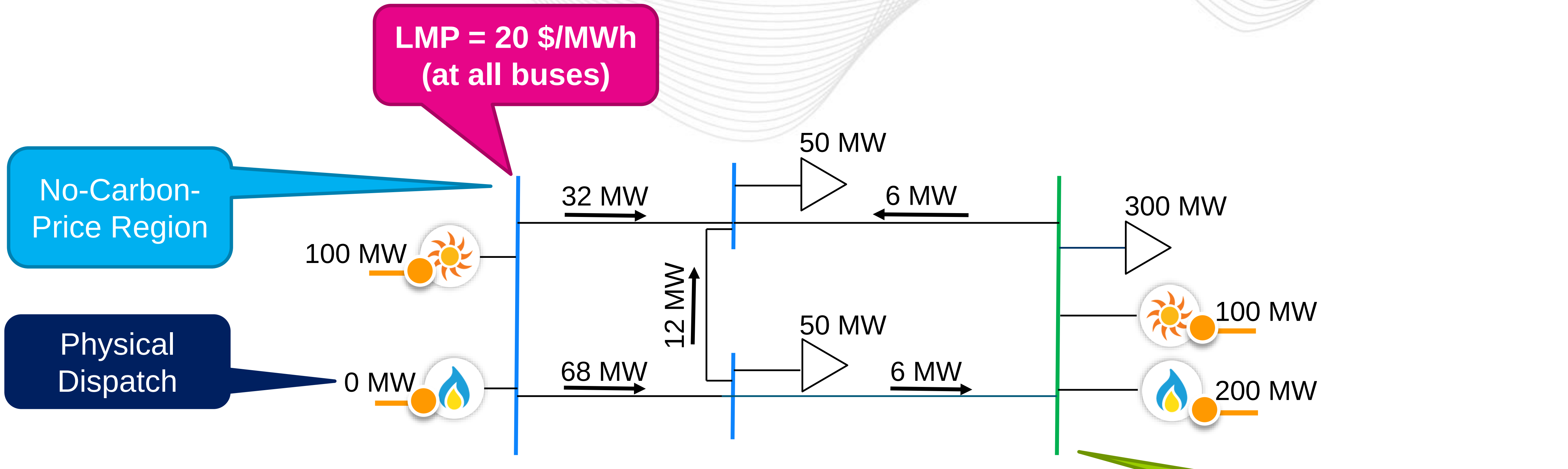
$$P^{NC}_{Solar} + P^{NC}_{Gas} - Flow_{12} - Flow_{13} = 0$$
$$Flow_{12} - Flow_{23} - Flow_{24} - 50 = 0$$
$$Flow_{13} + Flow_{23} - Flow_{34} - 50 = 0$$
$$P^{C}_{Solar} + P^{C}_{Gas} + Flow_{24} + Flow_{34} - 300 = 0$$

$LMP_i = \lambda_i$ for all i buses

$where$:

$\lambda_i =$ shadow price of the nodal balance constraint for bus i

Results – No Carbon Pricing



Carbon-Price Region

	Solar	Gas	Solar	Gas
Offer ($/MWh)	0	30	0	20
~~GHG Cost ($/MWh)~~	~~0~~	~~90~~	~~0~~	~~80~~

Problem Formulation – Carbon Pricing No Border Adjustment

Same Equations With Additional GHG Cost Adders

$$Minimize: \{ \; C^{NC}_{Solar} \cdot P^{NC}_{Solar} + C^{NC}_{Gas} \cdot P^{NC}_{Gas} + (C^{C}_{Solar} + C^{C}_{Solar\ GHG}) \cdot P^{C}_{Solar} + (C^{C}_{Gas} + C^{C}_{Gas\ GHG}) \cdot P^{C}_{Gas} \; \}$$

$$Minimize: \{ \; 0 \cdot P^{NC}_{Solar} + 30 \cdot P^{NC}_{Gas} + (0 + 0) \cdot P^{C}_{Solar} + (20 + 80) \cdot P^{C}_{Gas} \; \}$$

GHG Cost Added to Generator Offer

Subject to:

$$0 \le P^{NC}_{Solar} \le 100$$
$$0 \le P^{NC}_{Gas} \le 400$$
$$0 \le P^{C}_{Solar} \le 100$$
$$0 \le P^{C}_{Gas} \le 400$$

$$-225 \le Flow_{12} \le 225$$
$$-225 \le Flow_{13} \le 225$$
$$-225 \le Flow_{23} \le 225$$
$$-225 \le Flow_{24} \le 225$$
$$-225 \le Flow_{34} \le 225$$

$$100 \cdot \theta_1 \; -100 \cdot \theta_2 \; -Flow_{12} = 0$$
$$40 \cdot \theta_1 \; -40 \cdot \theta_3 \; -Flow_{13} = 0$$
$$100 \cdot \theta_2 \; -100 \cdot \theta_3 \; -Flow_{23} = 0$$
$$100 \cdot \theta_2 \; -100 \cdot \theta_4 \; -Flow_{24} = 0$$
$$100 \cdot \theta_3 \; -100 \cdot \theta_4 \; -Flow_{34} = 0$$

$$P^{NC}_{Solar} + P^{NC}_{Gas} - Flow_{12} - Flow_{13} = 0$$
$$Flow_{12} - Flow_{23} - Flow_{24} - 50 = 0$$
$$Flow_{13} + Flow_{23} - Flow_{34} - 50 = 0$$
$$P^{C}_{Solar} + P^{C}_{Gas} + Flow_{24} + Flow_{34} - 300 = 0$$

$LMP_i = \lambda_i$ for all i buses

$where$:

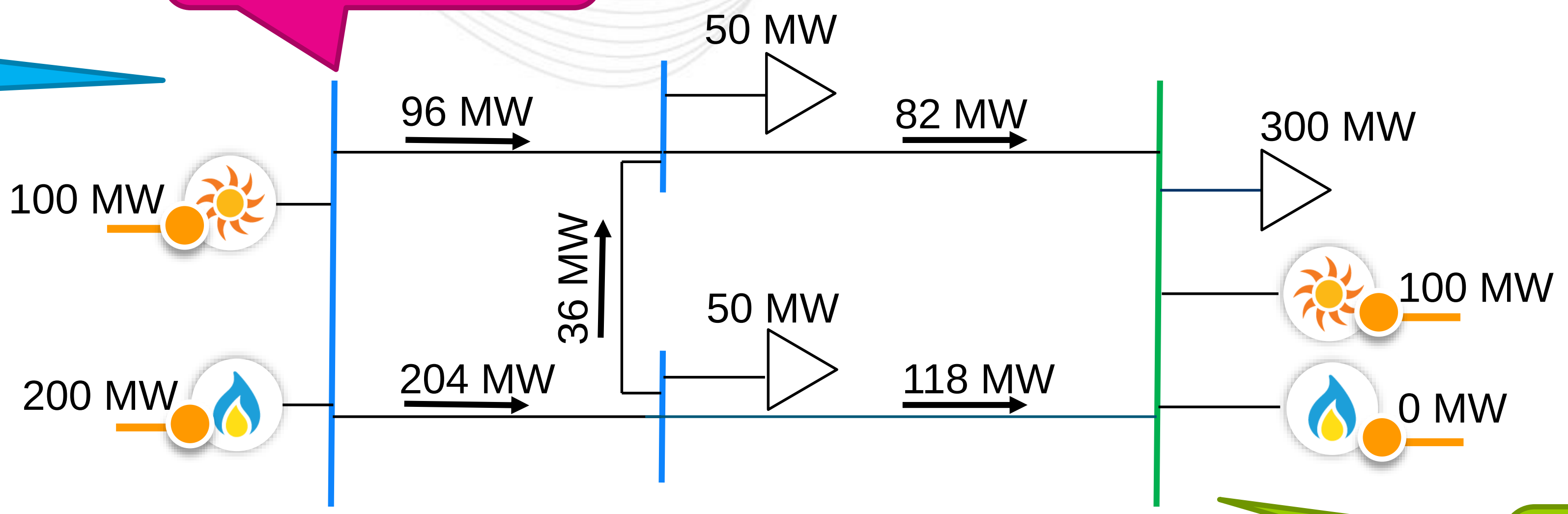
$\lambda_i =$ shadow price of the nodal balance constraint for bus i

Results – Carbon Pricing No Border Adjustment

LMP = 30 $/MWh (at all buses)

No-Carbon-Price Region

Physical Dispatch



Carbon-Price Region

	No-Carbon-Price Region: Solar	No-Carbon-Price Region: Gas	Carbon-Price Region: Solar	Carbon-Price Region: Gas
Offer ($/MWh)	0	30	0	20
GHG Cost ($/MWh)	~~0~~	~~90~~	0	80

Net Offer = 20 $/MWh + 80 $/MWh

Problem Formulation – Carbon Pricing with One-Way Border Adjustment*

*Adapted from CAISO's Energy Imbalance Market (EIM) Draft Final Proposal (published Sept. 23, 2013)

$$Minimize: \{ C^{NC}_{Solar} \cdot P^{NC}_{Solar} + C^{NC}_{Gas} \cdot P^{NC}_{Gas} + C^{NC}_{Solar\ GHG} \cdot P^{NC}_{Solar\ GHG} + C^{NC}_{Gas\ GHG} \cdot P^{NC}_{Gas\ GHG} + \left(C^{C}_{Solar} + C^{C}_{Solar\ GHG}\right) \cdot P^{C}_{Solar} + \left(C^{C}_{Gas} + C^{C}_{Gas\ GHG}\right) \cdot P^{C}_{Gas} \}$$

Additional Terms

$$Minimize: \{ 0 \cdot P^{NC}_{Solar} + 30 \cdot P^{NC}_{Gas} + 0 \cdot P^{NC}_{Solar\ GHG} + 90 \cdot P^{NC}_{Gas\ GHG} + (0+0) \cdot P^{C}_{Solar} + (20+80) \cdot P^{C}_{Gas} \}$$

Physical Dispatch P^{NC}_{Gas}

GHG Dispatch $P^{NC}_{Gas\ GHG}$

Subject to:

$$0 \le P^{NC}_{Solar} \le 100$$
$$0 \le P^{NC}_{Gas} \le 400$$
$$0 \le P^{C}_{Solar} \le 100$$
$$0 \le P^{C}_{Gas} \le 400$$

$$-225 \le Flow_{12} \le 225$$
$$-225 \le Flow_{13} \le 225$$
$$-225 \le Flow_{23} \le 225$$
$$-225 \le Flow_{24} \le 225$$
$$-225 \le Flow_{34} \le 225$$

$$100 \cdot \theta_1 - 100 \cdot \theta_2 - Flow_{12} = 0$$
$$40 \cdot \theta_1 - 40 \cdot \theta_3 - Flow_{13} = 0$$
$$100 \cdot \theta_2 - 100 \cdot \theta_3 - Flow_{23} = 0$$
$$100 \cdot \theta_2 - 100 \cdot \theta_4 - Flow_{24} = 0$$
$$100 \cdot \theta_3 - 100 \cdot \theta_4 - Flow_{34} = 0$$

$$P^{NC}_{Solar} + P^{NC}_{Gas} - Flow_{12} - Flow_{13} = 0$$
$$Flow_{12} - Flow_{23} - Flow_{24} - 50 = 0$$
$$Flow_{13} + Flow_{23} - Flow_{34} - 50 = 0$$
$$P^{C}_{Solar} + P^{C}_{Gas} + Flow_{24} + Flow_{34} - 300 = 0$$

Subject to additional constraints:

$$0 \le P^{NC}_{Solar\ GHG} \le P^{NC}_{Solar}$$
$$0 \le P^{NC}_{Gas\ GHG} \le P^{NC}_{Gas}$$

GHG Limit Constraints: Cannot allocate more than what is physically dispatched

Allocation Constraint: Total allocation plus load must be greater than or equal to total generation in the no-carbon-price region

$$P^{NC}_{Solar} + P^{NC}_{Gas} \le P^{NC}_{Solar\ GHG} + P^{NC}_{Gas\ GHG} + 100$$

Settlement – Carbon Pricing with One-Way Border Adjustment

$LMP_i = \lambda_i$ for all i buses in the carbon-price region

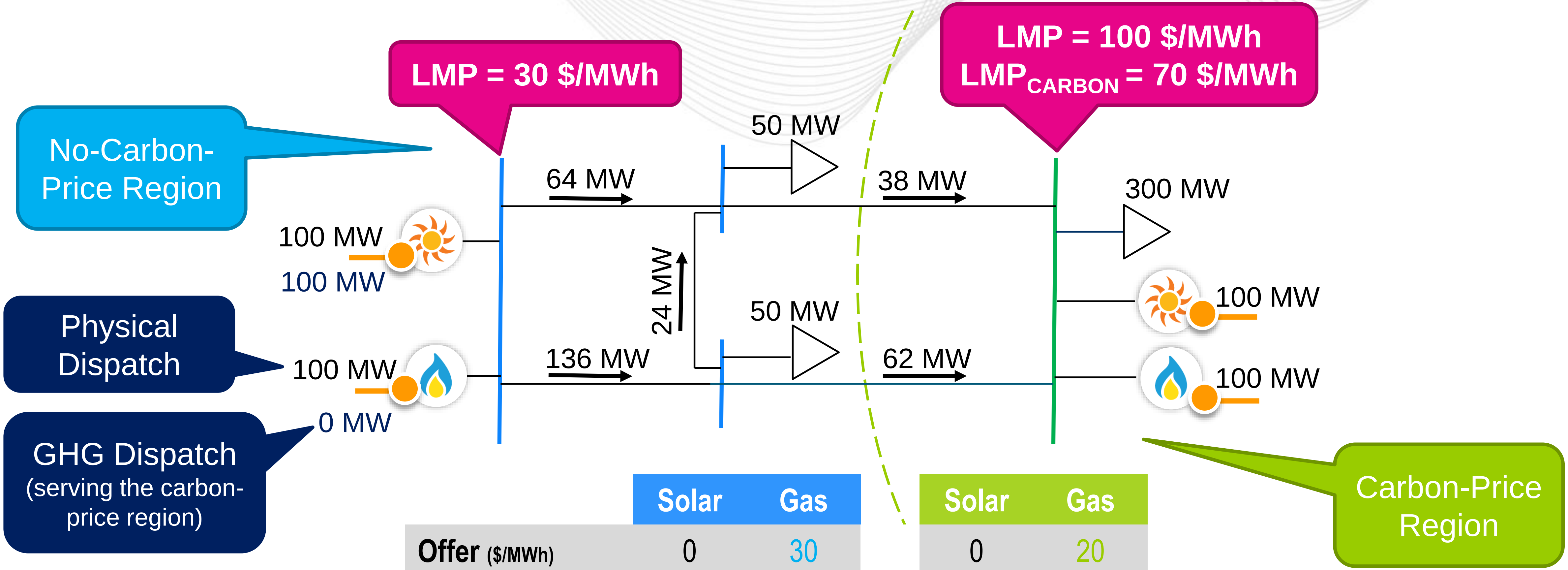
$LMP_j = \lambda_j + \eta$ for all j buses in the no-carbon-price region

$LMP_{Carbon} = -\eta$

$where$:

$\lambda_i =$ shadow price of the nodal balance constraint for bus i
$\eta =$ shadow price of the allocation constraint

Results – Carbon Pricing With One-Way Border Adjustment



	Solar	Gas	Solar	Gas
Offer ($/MWh)	0	30	0	20
GHG Cost ($/MWh)	0	90	0	80

Problem Formulation – Carbon Pricing with Two-Way Border Adjustment

$$Minimize: \{ C^{NC}_{Solar} \cdot P^{NC}_{Solar} + C^{NC}_{Gas} \cdot P^{NC}_{Gas} + C^{NC}_{Solar\ GHG} \cdot P^{NC}_{Solar\ GHG} + C^{NC}_{Gas\ GHG} \cdot P^{NC}_{Gas\ GHG} + \left(C^{C}_{Solar} + C^{C}_{Solar\ GHG}\right) \cdot P^{C}_{Solar} + \left(C^{C}_{Gas} + C^{C}_{Gas\ GHG}\right) \cdot P^{C}_{Gas} - C^{C}_{Solar\ GHG} \cdot P^{C}_{Solar\ GHG} - C^{C}_{Gas\ GHG} \cdot P^{C}_{Gas\ GHG} \}$$

Additional Terms

$$Minimize: \{ 0 \cdot P^{NC}_{Solar} + 30 \cdot P^{NC}_{Gas} + 0 \cdot P^{NC}_{Solar\ GHG} + 90 \cdot P^{NC}_{Gas\ GHG} + (0 + 0) \cdot P^{C}_{Solar} + (20 + 80) \cdot P^{C}_{Gas} - 0 \cdot P^{C}_{Solar\ GHG} - 80 \cdot P^{C}_{Gas\ GHG} \}$$

Subject to:

$$0 \le P^{NC}_{Solar} \le 100$$
$$0 \le P^{NC}_{Gas} \le 400$$
$$0 \le P^{C}_{Solar} \le 100$$
$$0 \le P^{C}_{Gas} \le 400$$

$$-225 \le Flow_{12} \le 225$$
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$$100 \cdot \theta_1 - 100 \cdot \theta_2 - Flow_{12} = 0$$
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$$100 \cdot \theta_2 - 100 \cdot \theta_4 - Flow_{24} = 0$$
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$$P^{NC}_{Solar} + P^{NC}_{Gas} - Flow_{12} - Flow_{13} = 0$$
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$$P^{C}_{Solar} + P^{C}_{Gas} + Flow_{24} + Flow_{34} - 300 = 0$$

Subject to additional constraints:

$$0 \le P^{NC}_{Solar\ GHG} \le P^{NC}_{Solar}$$
$$0 \le P^{NC}_{Gas\ GHG} \le P^{NC}_{Gas}$$
$$0 \le P^{C}_{Solar\ GHG} \le P^{C}_{Solar}$$
$$0 \le P^{C}_{Gas\ GHG} \le P^{C}_{Gas}$$

GHG Limit Constraints:
Cannot allocate more than what is physically dispatched

$$P^{C}_{Solar\ GHG} + P^{C}_{Gas\ GHG} \le P^{NC}_{Solar\ GHG} + P^{NC}_{Gas\ GHG} + P^{C}_{Solar} + P^{C}_{Gas} - 300$$

Allocation Constraint

Settlement – Carbon Pricing with Two-Way Border Adjustment

$LMP_i = \lambda_i - \eta$ for all i buses in the carbon-price region

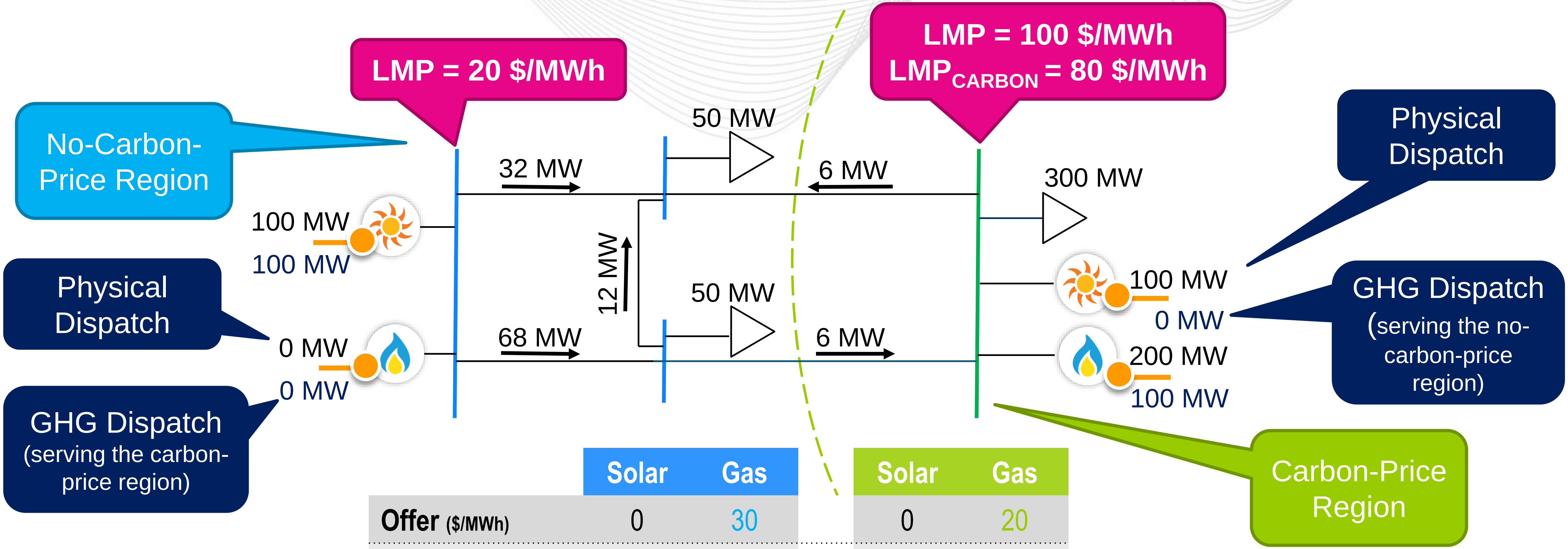
$LMP_j = \lambda_j$ for all j buses in the no-carbon-price region

$$LMP_{Carbon} = -\eta$$

$where$:

λ_i = shadow price of the nodal balance constraint for bus i
η = shadow price of the allocation constraint

Results – Carbon Pricing With Two-Way Border Adjustment



	Solar	Gas	Solar	Gas
Offer ($/MWh)	0	30	0	20
GHG Cost ($/MWh)	0	90	0	80

Border Adjustment Modeling in PLEXOS

- In order to model the border adjustment cases in PLEXOS, the following methodology was used.
- Note: PLEXOS is a production cost model, and is not meant to represent any actual implementation.

Methodology:

- In PLEXOS, each fossil fuel burning generator was modeled as having two fuels available to it:
  - One fuel had a cost that included the cost of carbon emissions.
  - One fuel had a cost that did not include the cost of carbon emissions.

No Border Adjustment Case in PLEXOS

- Carbon-Price Sub-Region:
  - Each fossil fuel generator was restricted to use only the fuel that included the cost of carbon emissions.

- Rest of RTO Sub-Region:
  - Each fossil fuel generator was restricted to use only the fuel that did not include the cost of carbon emissions.

One-Way Border Adjustment Case in PLEXOS

- Carbon-Price Sub-Region:
  - Each fossil fuel generator was restricted to use only the fuel that included the cost of carbon emissions.
- Rest of RTO Sub-Region:
  - Each fossil fuel generator was allowed to use either fuel available to it.
- Border Adjustment Constraint:
  - A custom constraint was added to the model that restricted the amount of generation from fossil fuel generators using fuels that did not include the cost of carbon emissions to the amount of load in the Rest of RTO sub-region.

Two-Way Border Adjustment Case in PLEXOS

- Carbon-Price Sub-Region:
  - Each fossil fuel generator was allowed to use either fuel available to it.

- Rest of RTO Sub-Region:
  - Each fossil fuel generator was allowed to use either fuel available to it.

- Border Adjustment Constraint:
  - A custom constraint was added to the model that restricted the amount of generation from fossil fuel generators using fuels that did not include the cost of carbon emissions to the amount of load in the Rest of RTO sub-region.