Price Formation Education Session – Day 2
Alternative Energy Pricing Frameworks

Anthony Giacomoni
Adam Keech
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Disclaimer

This is not a committee meeting.

- This session is for educational purposes only, to help introduce and clarify different aspects of price formation.
- The material presented is not necessarily representative of any proposal PJM has or will present in the future.

Material and examples in this presentation were used with permission from material initially developed by ISO New England for a discussion on price formation.

- https://www.iso-ne.com/static-assets/documents/support/training/courses/energy_mkt_ancil_serv_top/price_information_technical_session_session4.pdf
- https://www.iso-ne.com/static-assets/documents/support/training/courses/energy_mkt_ancil_serv_top/price_information_technical_session5.pdf

To help stakeholders gain information and understanding of price formation concepts and terminology that may be referenced during the stakeholder process.

- Use simple examples to discuss alternative energy pricing frameworks
- Review the basic concepts of convex-hull pricing
- Understand the difference between convex-hull pricing and extended locational marginal pricing (ELMP)
- Review an approximate extended locational marginal pricing (aELMP) example

Outline

- Convex-Hull Pricing – Overview
- Example – Convex-Hull Pricing with Minimum Generation
- Example – Convex-Hull Pricing with Fixed Costs
- Example – Approximate Extended Locational Marginal Pricing
- Questions

CONVEX-HULL PRICING

Overview

Ideal Market Clearing Price

- In a market, prices can perform a coordinating function.
- Ideal market-clearing prices exist if the amount that profit-maximizing producers want to produce is equal to the amount that benefit-maximizing consumers want to consume at the given prices.
  - Societal surplus is allocated in such a way that no group could do better by trading among themselves outside the market.

- The locational marginal price (LMP) reflects the incremental cost of supplying the next megawatt of load at a particular location while satisfying all operational constraints.

  Note: The commitment cannot change in response to an increment in load.

- LMPs are produced as a result of economic dispatch with the commitment fixed.

LMPs produced by economic dispatch are **not** ideal market clearing prices. In general:

- They do not incorporate start-up costs, no-load costs, costs of resources at minimum output, etc.
- Uplift payments may be needed to ensure that generators follow dispatch instructions.

Unit Commitment

- Incremental energy cost
- Start-up cost
- No-load cost

Economic Dispatch

Incremental energy cost

Uplift = Make-Whole Payments + Lost Opportunity Cost

- Make-whole payments: Occur when a resource's revenue cannot cover its total offer costs, including fixed costs like start-up cost and no-load cost.
- Lost opportunity cost: Occurs when a resource could have made more profit by not following RTO/ISO direction.

What prices would come as close to clearing the market as possible?

One Possible Measure: Uplift needed to ensure participants follow dispatch can be used as a measure of how far the prices are from the ideal market clearing.

Prices that minimize uplift would come as close as possible to clearing the market by this measure.

Incorporating Offer Costs in Prices

- Unit commitment considers all offer costs and parameters:
  - Incremental energy offer
  - Start-up cost
  - No-load cost
- **Idea:** Use the dual of the unit commitment to determine prices, as opposed to the dual of the economic dispatch.
- Using the dual of the unit commitment to set prices would result in prices that incorporate all offer costs.

- The dual of the unit commitment forms the convex hull of the total cost curve:
  - The prices are based on the slope of the convex hull.
- The approach has been called **convex-hull pricing**.

The Many Names of Convex-Hull Pricing

Convex-Hull Pricing

Minimum Uplift Pricing

Extended Locational Marginal Pricing (ELMP)

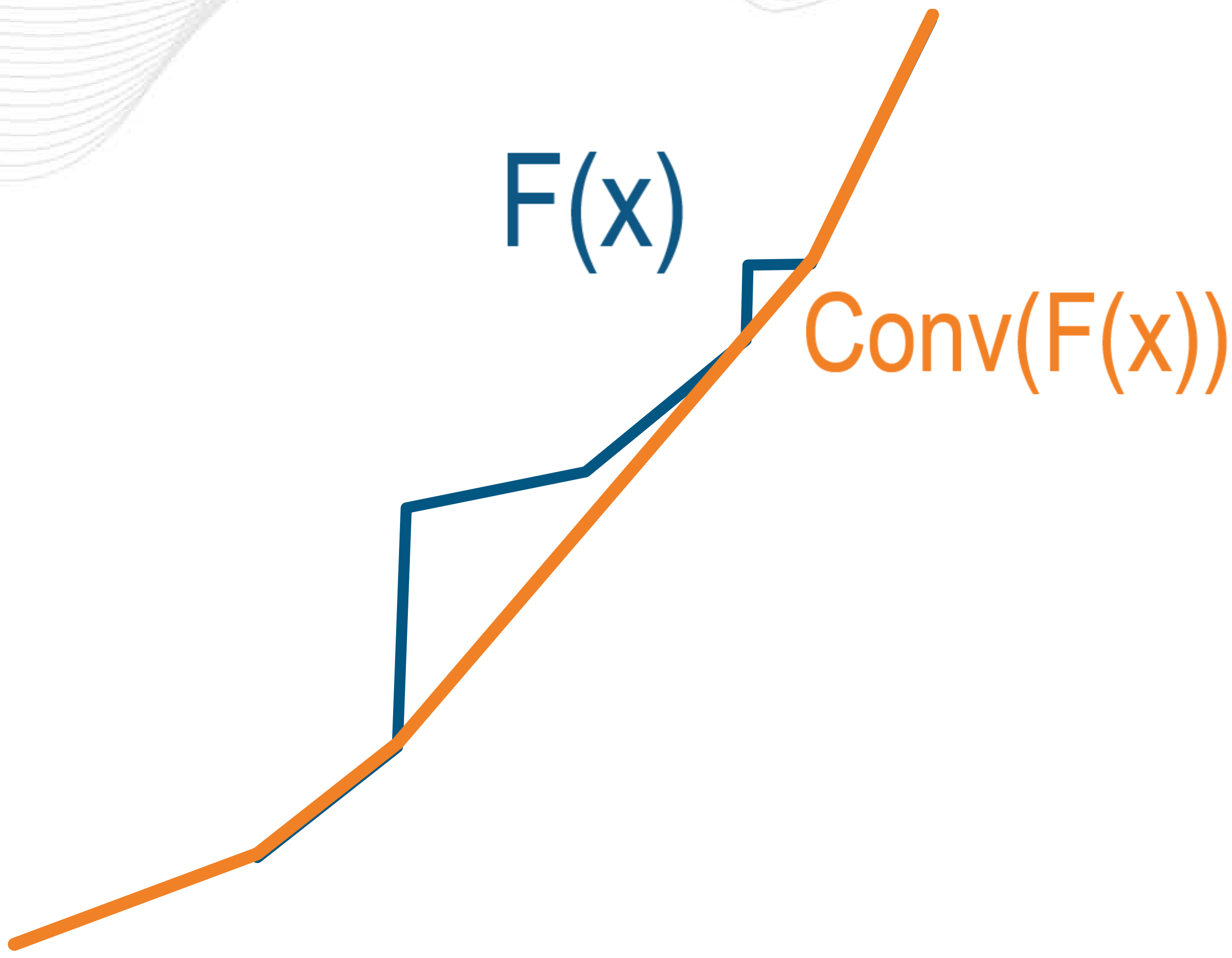
Since the resulting prices minimize uplift, the approach has been called **minimum uplift pricing**.

Since the result is extending LMP to incorporate commitment related costs, the approach has also been called **extended locational marginal pricing (ELMP)**.

What is Convex Hull?

- The convex hull of a non-convex function is the closest convex function that encloses the function.

- **The convex-hull price is the slope of the convex hull of the total cost curve.**

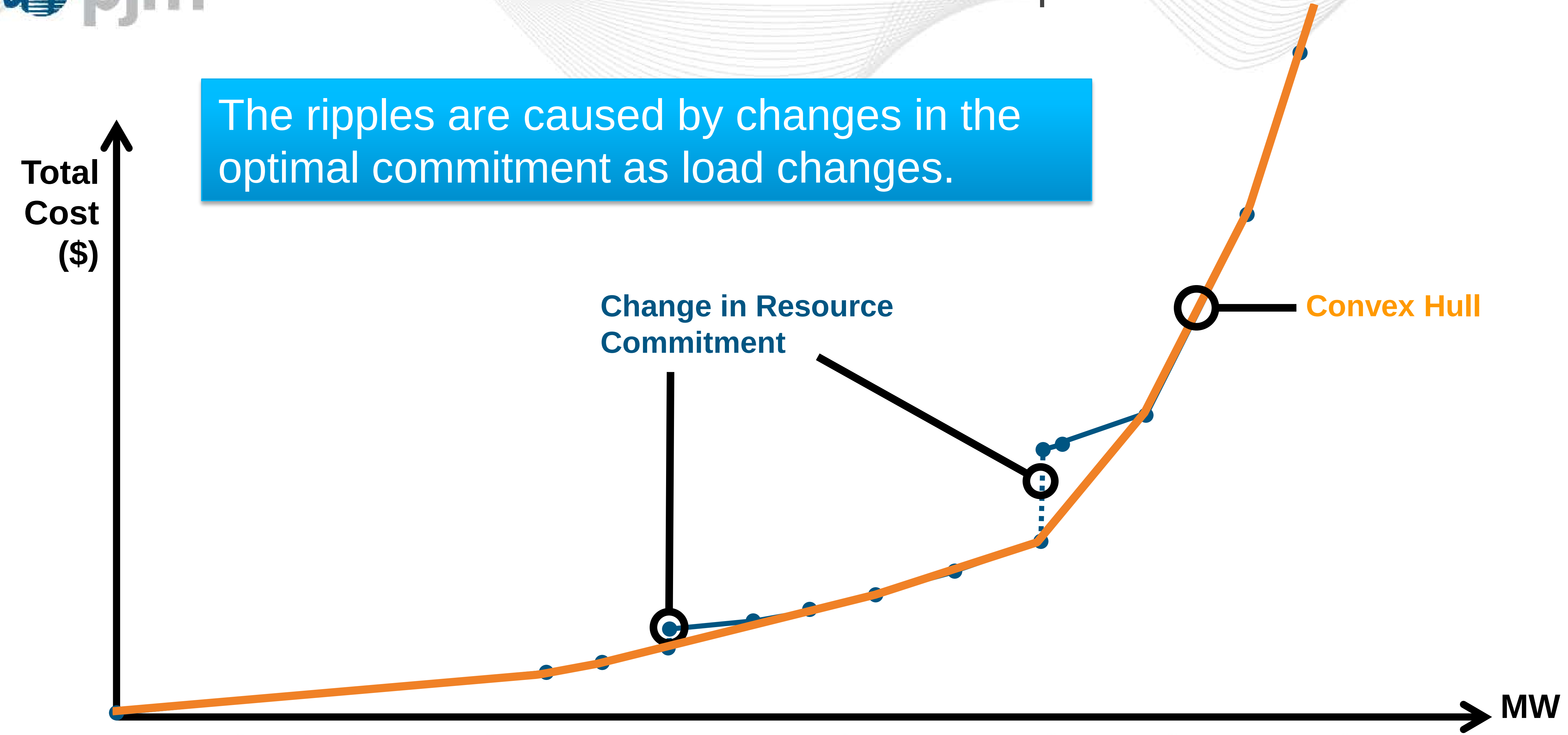


The total cost curve as a function of load has ripples in it that make it non-convex.

- The ripples are caused by changes in the optimal commitment as load changes.
- The ripples are small in terms of the total cost at any point.
- The ripples can have a large impact on the slope (i.e., the incremental cost) at any point, and therefore on the LMP.
- Convex-hull pricing smoothes out these ripples.

Example: Total Cost Curve

The ripples are caused by changes in the optimal commitment as load changes.



Advantages

- Produces more “intuitive” relationships between changes in load and price
  - When load increases, price stays the same or increases.
  - When load decreases, price stays the same or decreases.
- Incorporates start-up and no-load costs into the price
- Minimizes total uplift
- Allows block-loaded resources and those operating at their minimum or maximum limits to affect the price when appropriate

Disadvantages

- Difficult to calculate computationally
- Difficult to interpret – no simple interpretation
- In realistic examples, can have “counterintuitive” properties:
  - Positive prices for nonbinding system constraints (i.e., transmission or reserve constraints)
  - Occur when a “lumpy” resource is needed for the least-cost solution, but its excess supply both (1) backs down other, cheaper resources and (2) unbinds an (otherwise binding) transmission or reserve constraint

Example #1

Convex-hull pricing with minimum generation

Example #2

Convex-hull pricing with fixed costs

Example #3

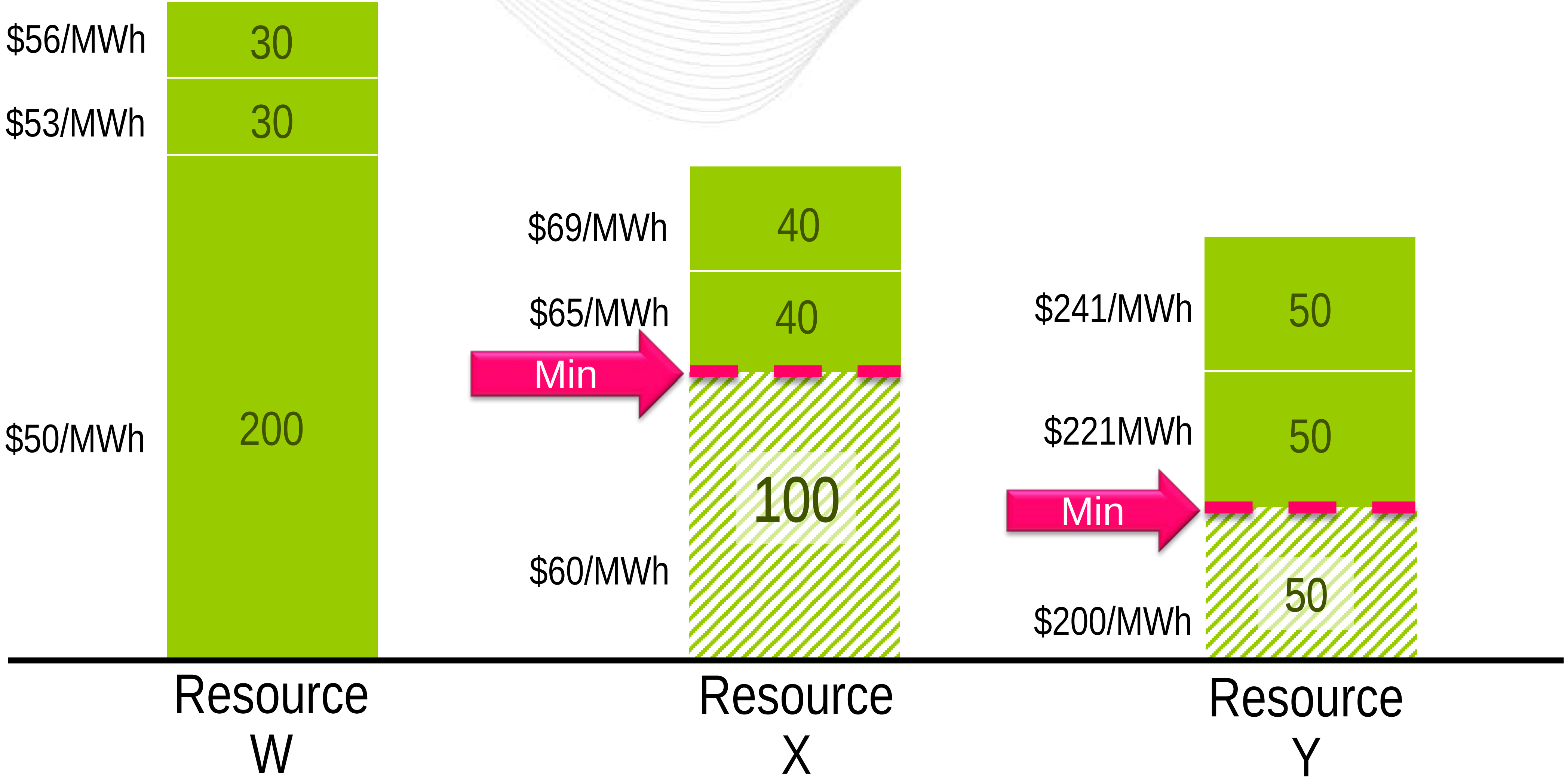
Approximate extended locational marginal pricing

Example #1

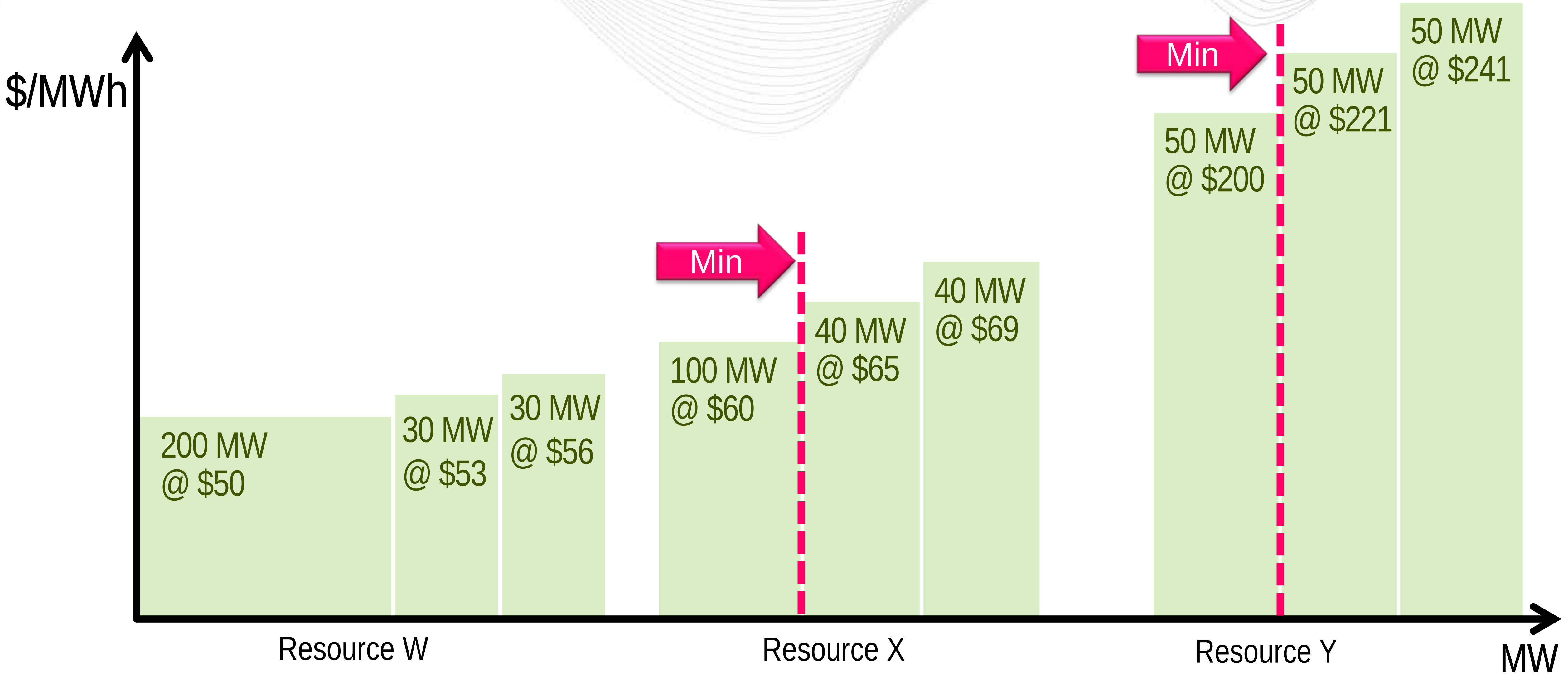
- **Load = 480 MW**
- No imports, exports or price-sensitive demand
- Can be considered in the context of the Day-Ahead or Real-Time Market
- Objective: to determine the **least-cost commitment and dispatch** to meet the load

Example #1: Convex-Hull Pricing with Minimum Generation Offer Blocks (MW) & Minimums

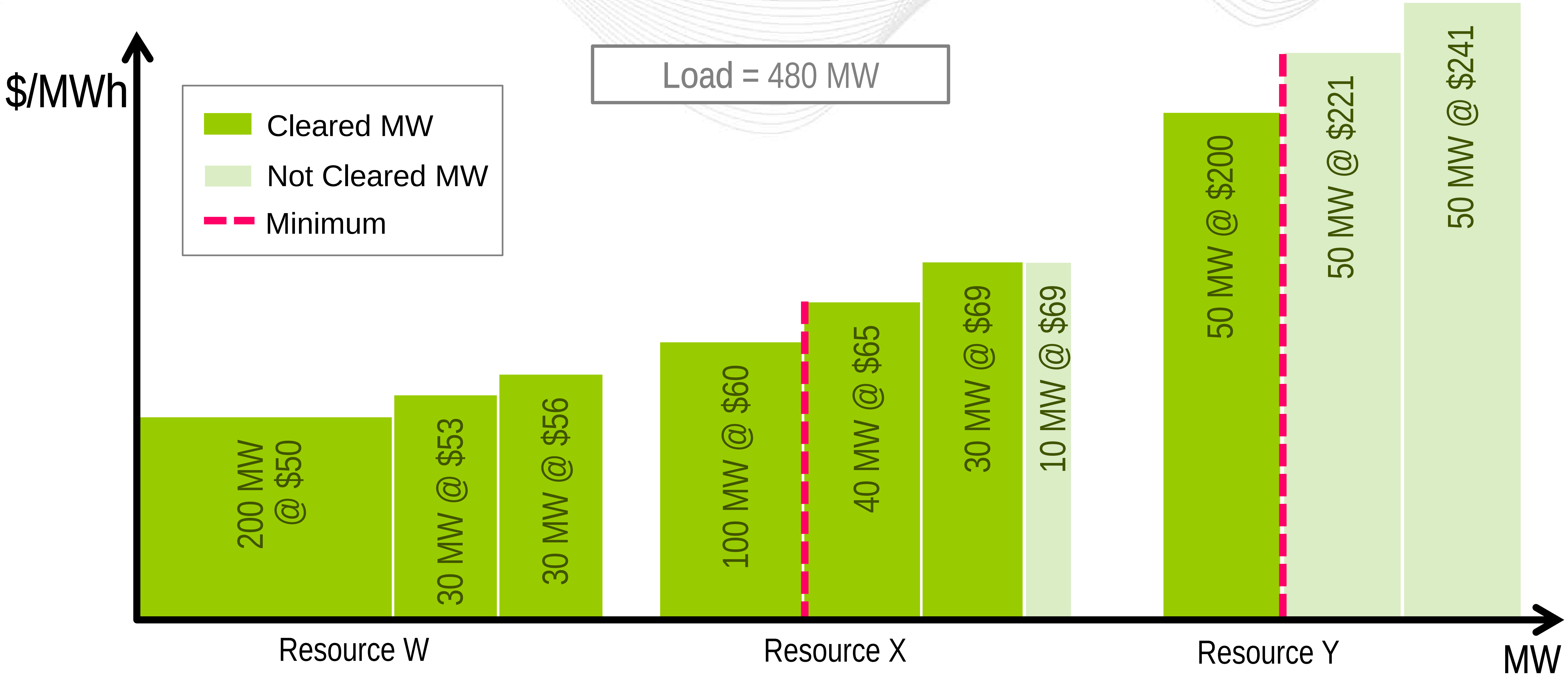
Any resource that is "committed" must run at least at its minimum.



Example #1: Convex-Hull Pricing with Minimum Generation



Example #1: What Is the Commitment and Dispatch?

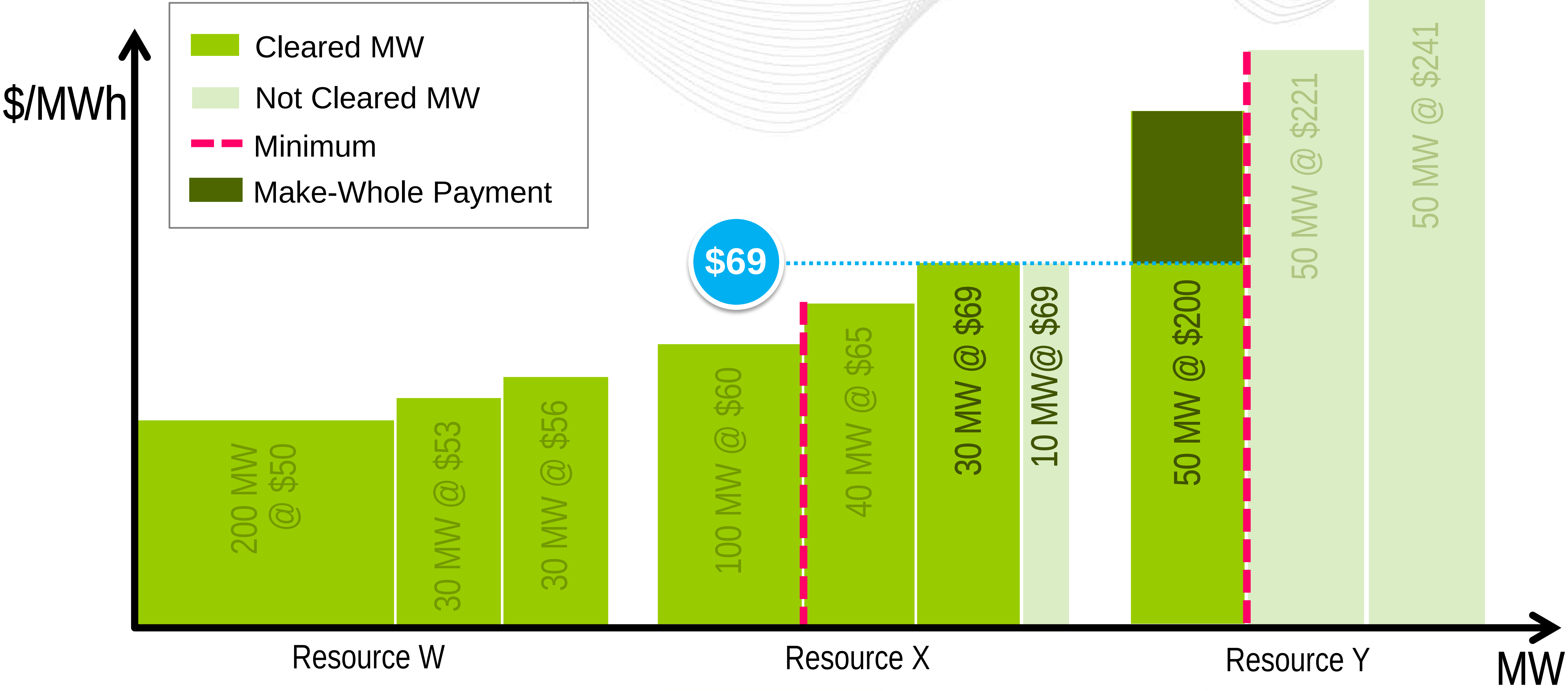


Example #1: Least-Cost Commitment and Dispatch

The commitment and dispatch that minimizes the production cost for meeting **480 MW load**:

Resource	Commitment	Dispatch (MW)	Total Offer Cost ($)
W	On	260	13,270
X	On	170	10,670
Y	On	50	10,000

Example #1: What Is the Commitment and Dispatch?



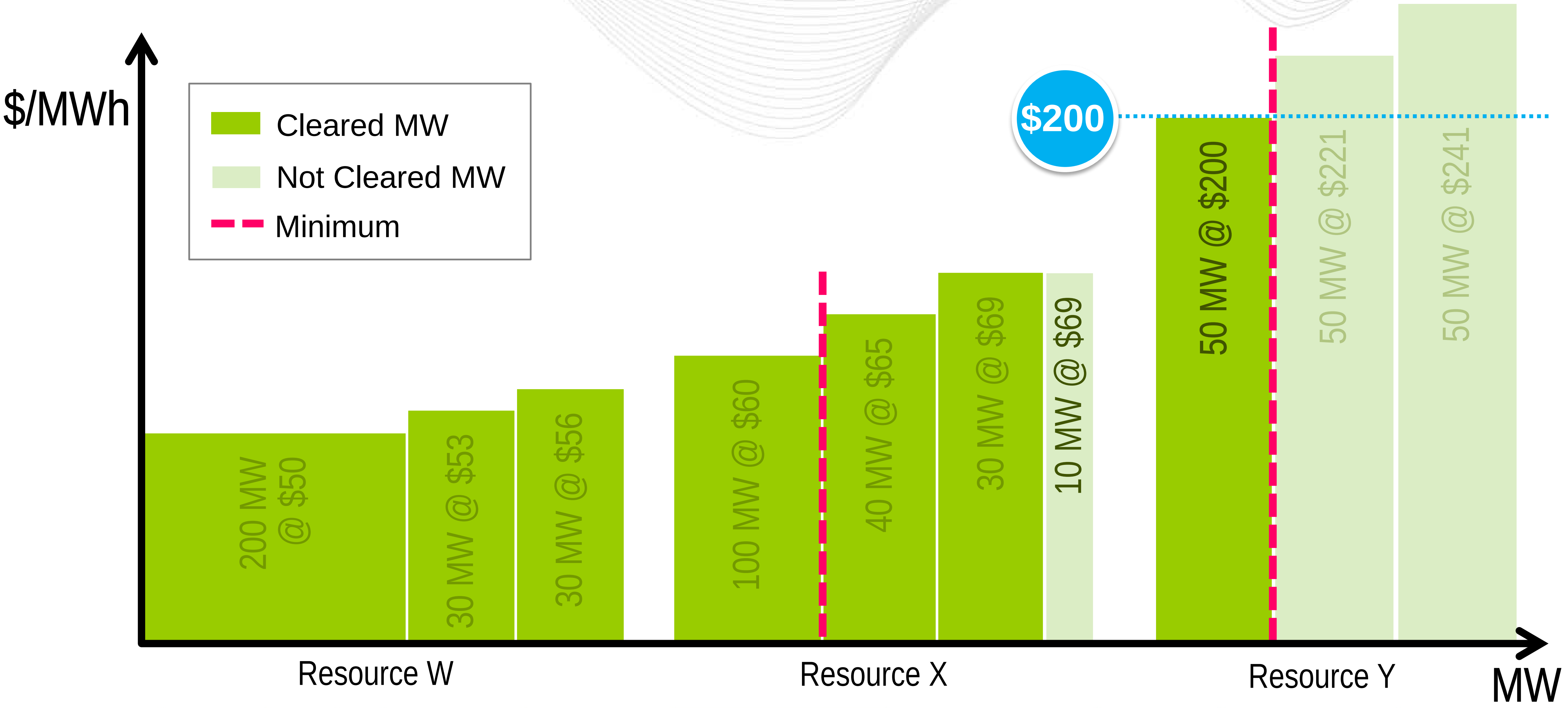
The settlement:

Price = $69/MWh under marginal pricing

Resource	Commitment	Dispatch (MW)	Total Offer Cost ($)	Payment ($)	MWP ($)
W	On	260	13,270	17,940	0
X	On	170	10,670	11,730	0
Y	On	50	10,000	3,450	6,550

Y has an incentive to deviate from the 50 MW dispatch
(it would prefer 0 MW given the $69/MWh price) without the make-whole payment.

Example #1: Alternative Price-Setting Highest Price of Selected Blocks



Example #1: Alternative Price-Setting and Settlement

The settlement:

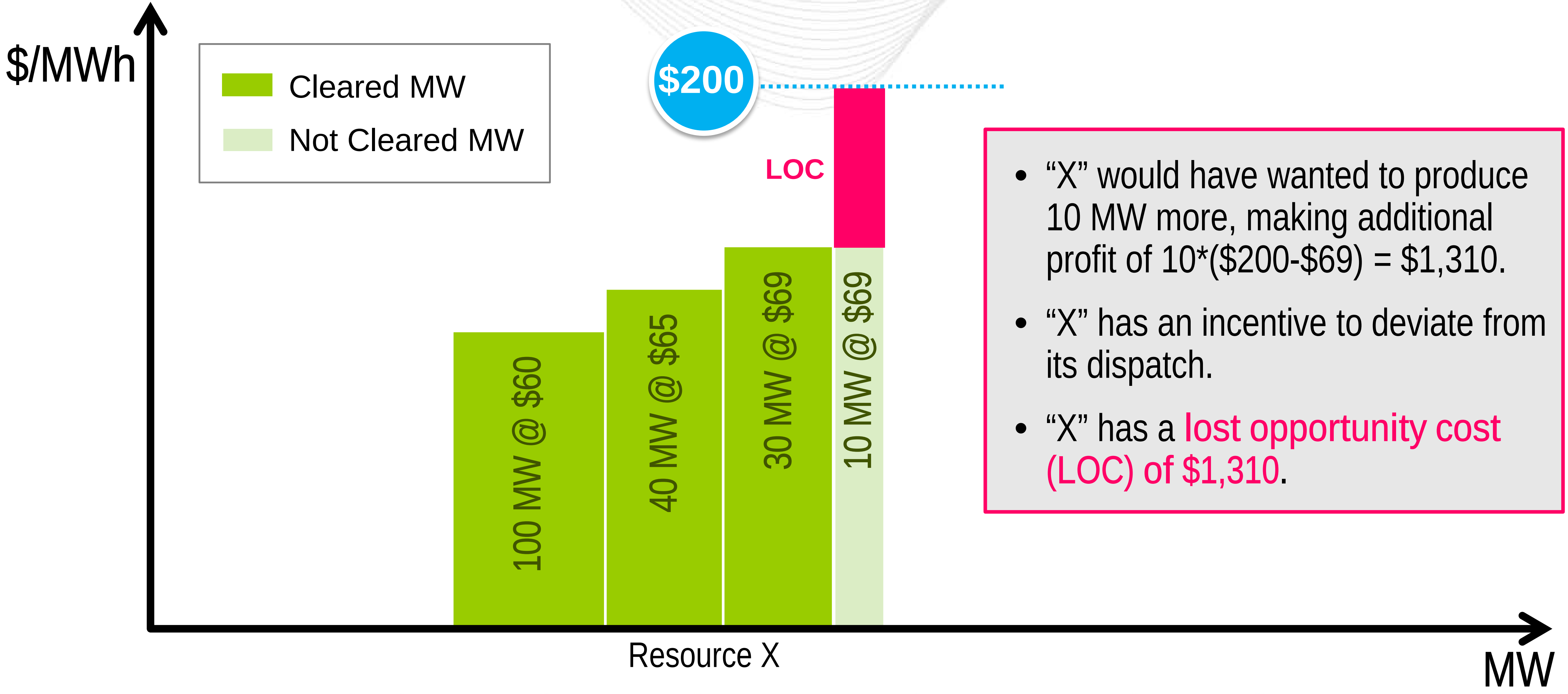
Price = $200/MWh under alternative pricing

Resource	Commitment	Dispatch (MW)	Total Offer Cost ($)	Payment ($)	MWP ($)
W	On	260	13,270	52,000	0
X	On	170	10,670	34,000	0
Y	On	50	10,000	10,000	0

No make-whole payments

Does any resource have incentive to deviate? Yes!

Example #1: Lost Opportunity Cost Under Alternative Price-Setting



- "X" would have wanted to produce 10 MW more, making additional profit of 10*($200-$69) = $1,310.
- "X" has an incentive to deviate from its dispatch.
- "X" has a lost opportunity cost (LOC) of $1,310.

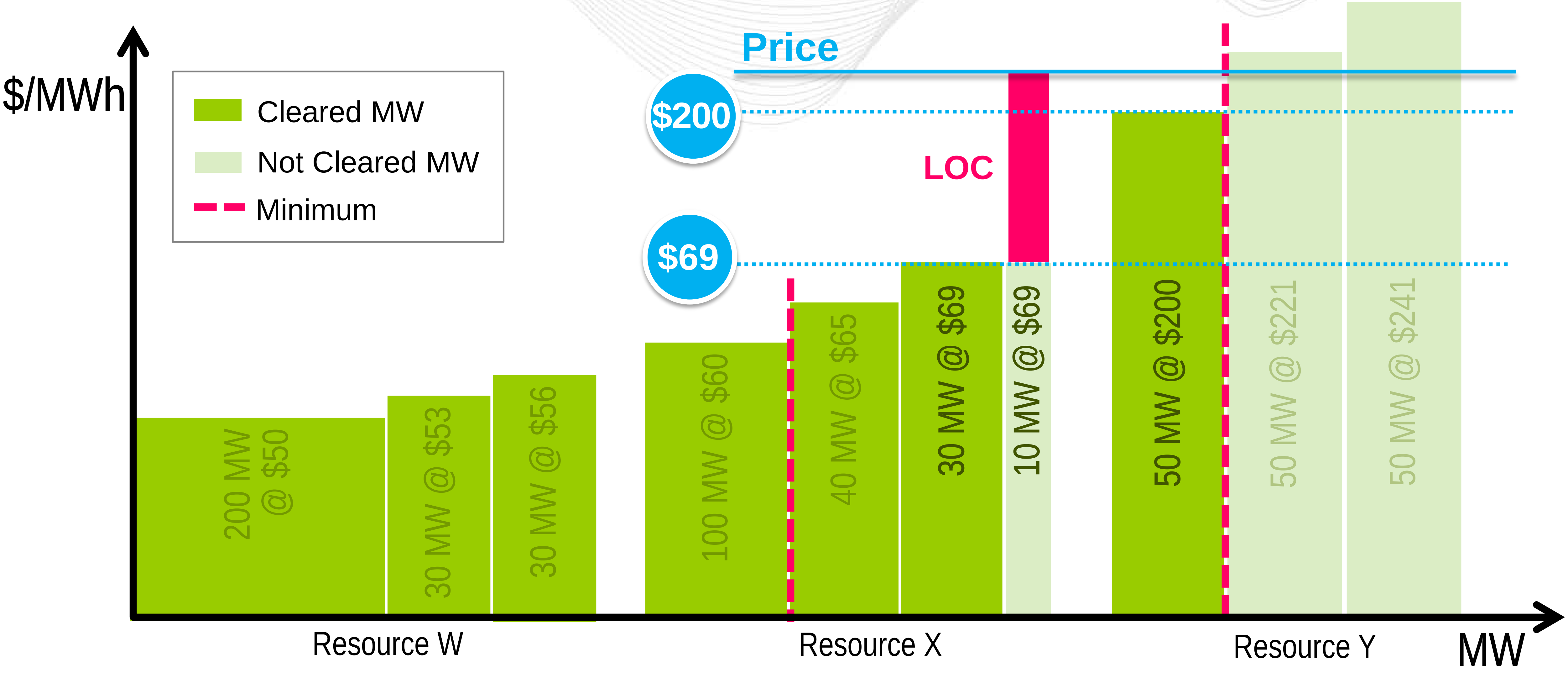
Uplift Under Alternative Price Setting

Uplift under the alternative price **$200/MWh** is $1,310, which is **less** than under marginal pricing ($6,550).

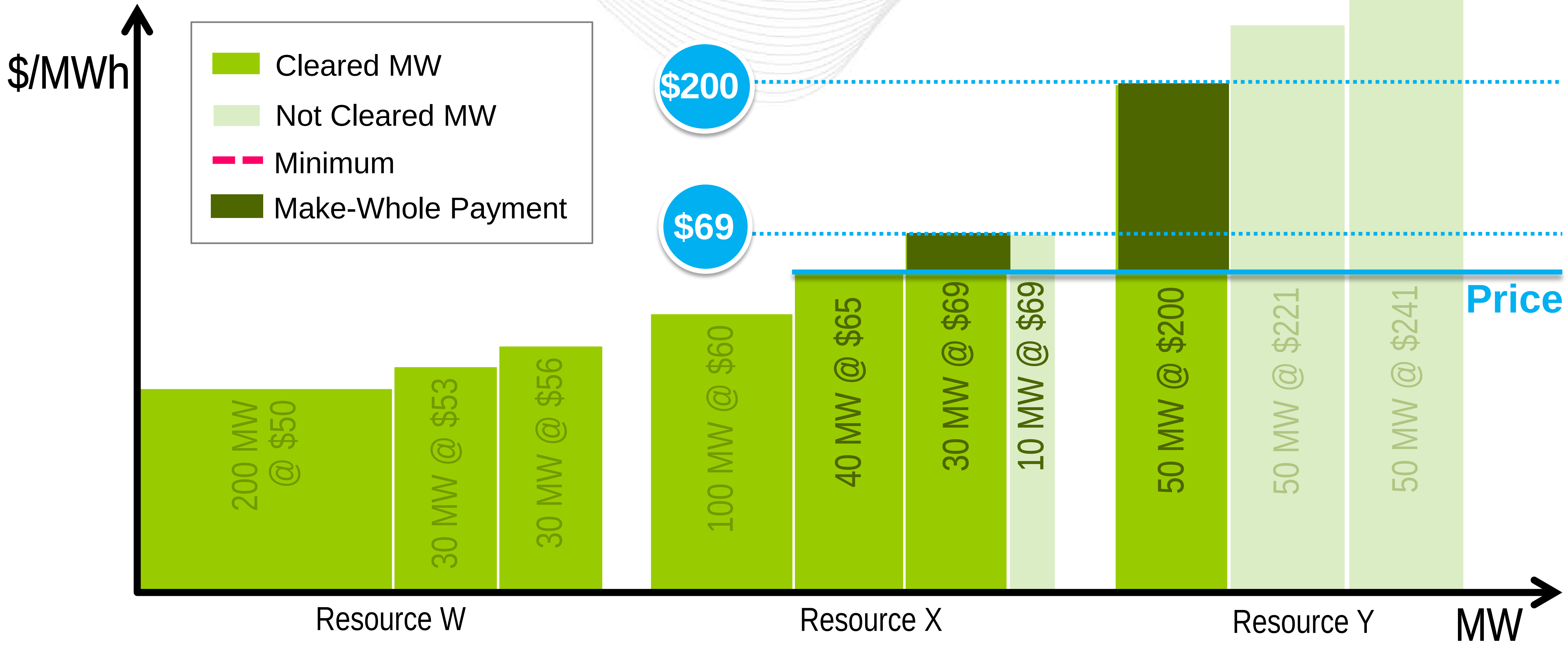
Resource	Commitment	Dispatch (MW)	Total Offer Cost ($)	Payment ($)	MWP ($)	LOC ($)
W	On	260	13,270	52,000	0	0
X	On	170	10,670	34,000	0	1,310
Y	On	50	10,000	10,000	0	0

Generalize the idea: Find the price that **minimizes total uplift**

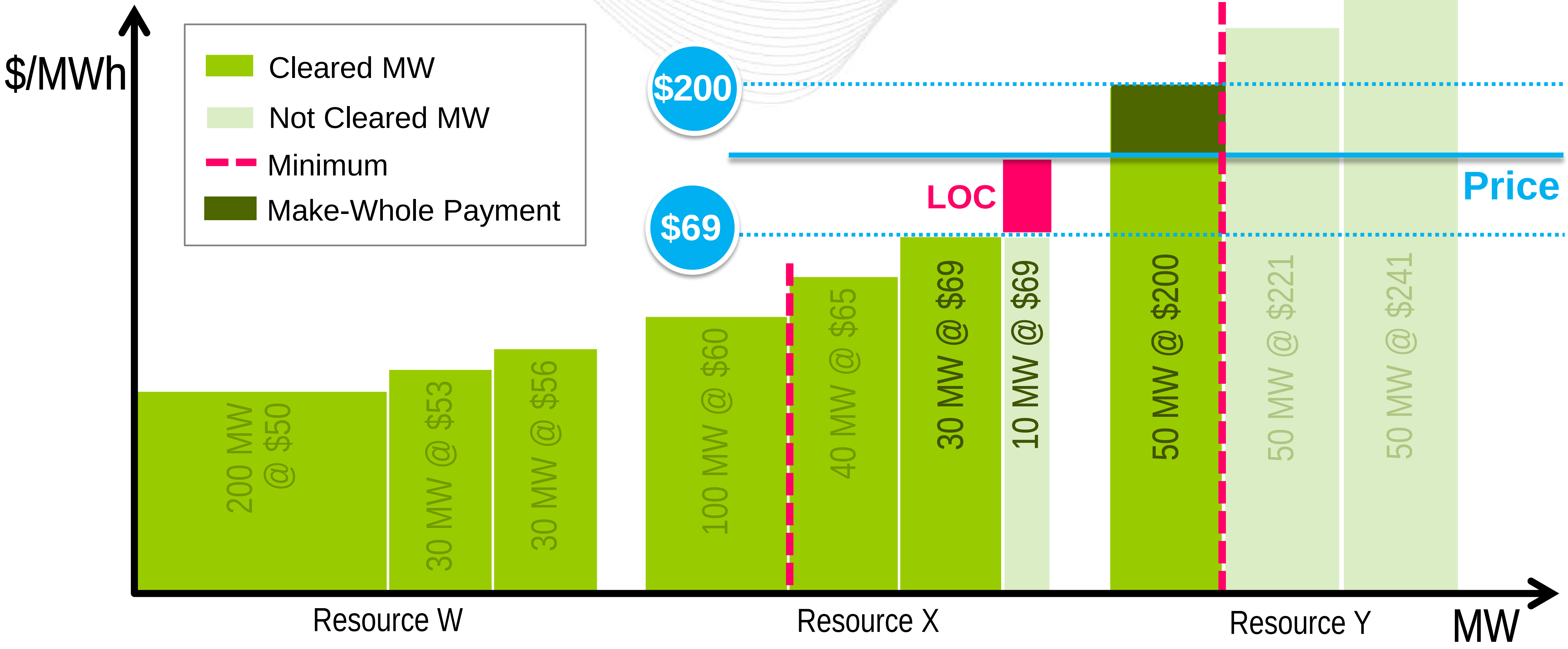
Example #1: Uplift with Price > $200/MWh



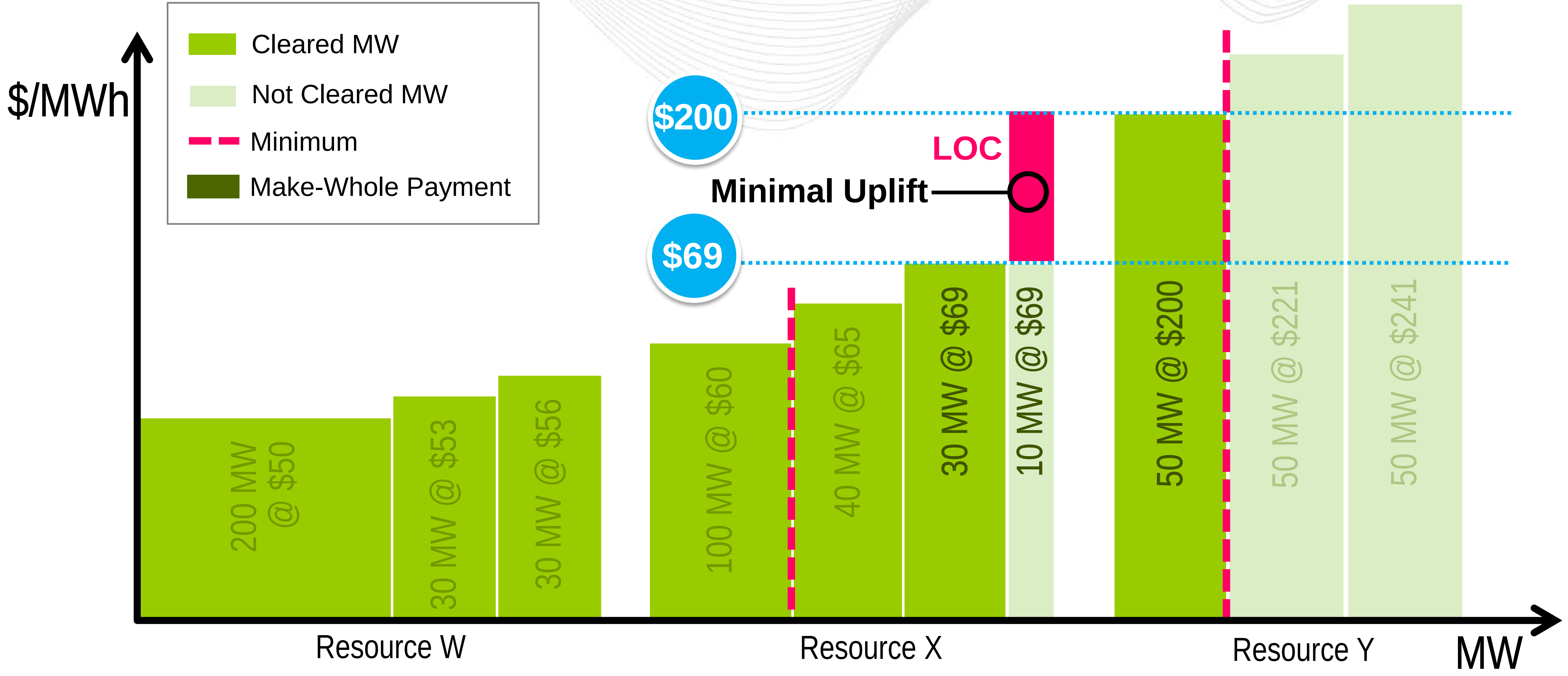
Example #1: Uplift with Price < $69/MWh



Example #1: Uplift with $69 < Price < $200



Example #1: Minimum Uplift Price is $200/MWh



So Does $200/MWh Produce the Least Uplift?

Let’s do an experiment.

- Set the clearing price up to $201/MWh.
- Set the clearing price down to $199/MWh.
- Check the uplift.

Uplift Under Alternative Price Setting

Total uplift under $201/MWh

Resource	Commitment	Dispatch (MW)	Total Offer Cost ($)	Payment ($)	MWP ($)	LOC ($)
W	On	260	13,270	52,260	0	0
X	On	170	10,670	34,170	0	$1,320
Y	On	50	10,000	10,050	0	0

Uplift Under Alternative Price Setting

Total uplift under $199/MWh

Resource	Commitment	Dispatch (MW)	Total Offer Cost ($)	Payment ($)	MWP ($)	LOC ($)
W	On	260	13,270	51,740	0	0
X	On	170	10,670	33,830	0	$1,300
Y	On	50	10,000	9,950	$50	0

So Does $200/MWh Produce the Least Uplift?

Total Uplift

Clearing Price	MWP ($)	LOC ($)	Total Uplift ($)
$200/MWh	0	1,310	1,310
$201/MWh	0	1,320	1,320
$199/MWh	50	1,300	1,350

For this example, a clearing price of $200/MWh **does** produce the least uplift ($1,310).

Observations

- Total uplift includes both make-whole payments and lost opportunity cost.
- Uplift payments are not transparent.
- In the example, no price can eliminate the uplift payments.
- The minimal uplift price could happen to be the highest price of selected blocks.
  - While this is true in this example, this is not always true.

Revisit Example #1

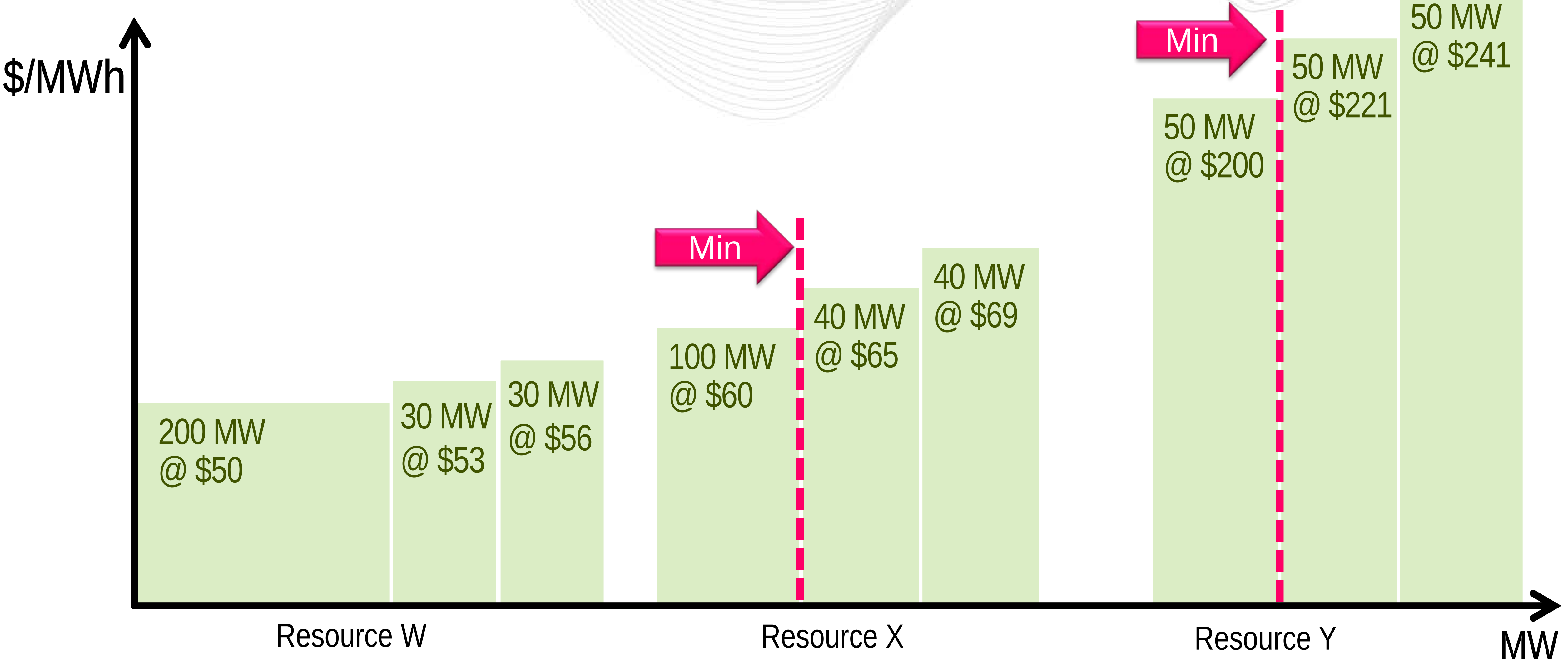


Illustration of Marginal Pricing: Example #1

- **Consider first marginal pricing**
  - Draw the **total cost curve** as demand increases.
  - The **slope** of the total cost curve represents the marginal cost of serving load (i.e., the marginal price).
- **How to construct the total cost curve for Example 1?**
  - **Different sets of resources** may be committed for different load levels.
  - The total cost curve cannot be obtained by a simple rank of bid blocks from low prices to high prices, due to minimum MW (lumpy) outputs of resources.

Illustration of Marginal Price Setting: Example #1

As load increases → Calculate the total cost

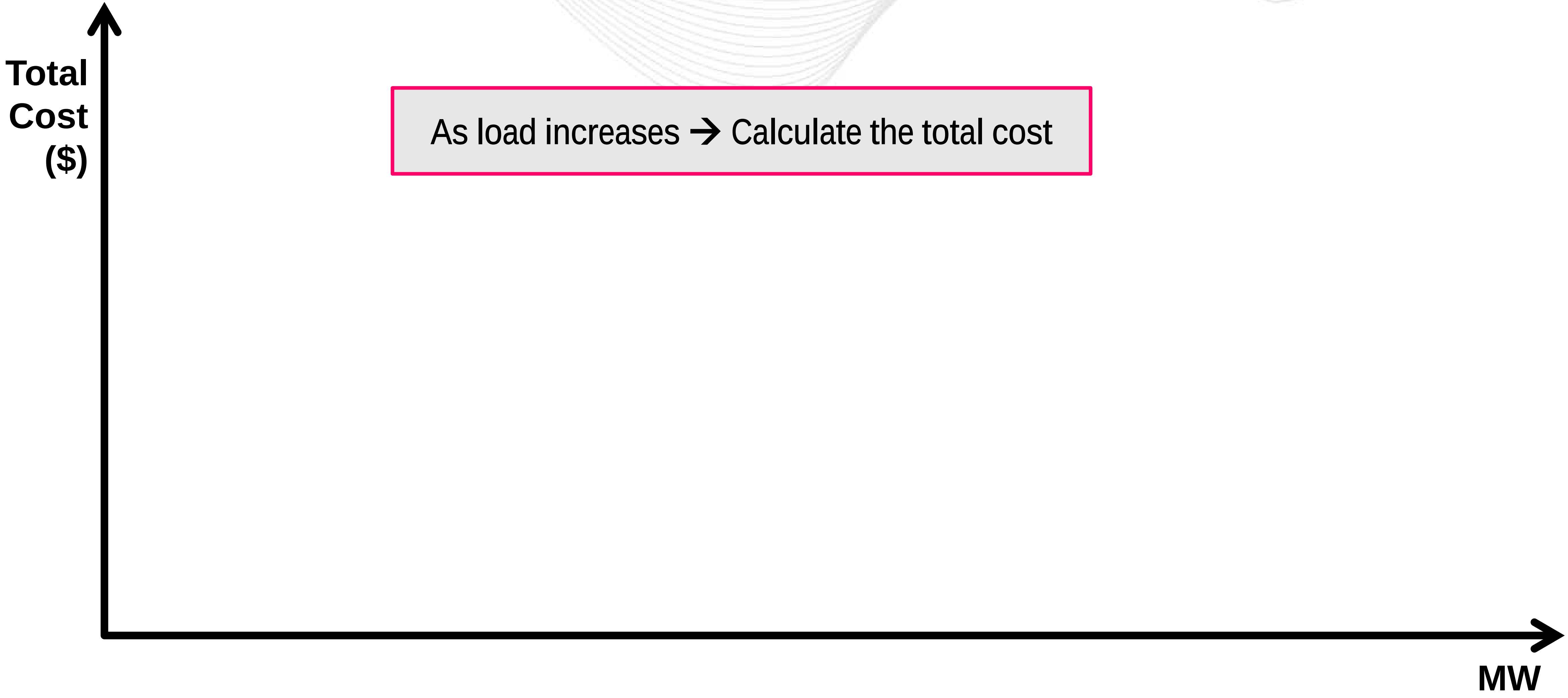
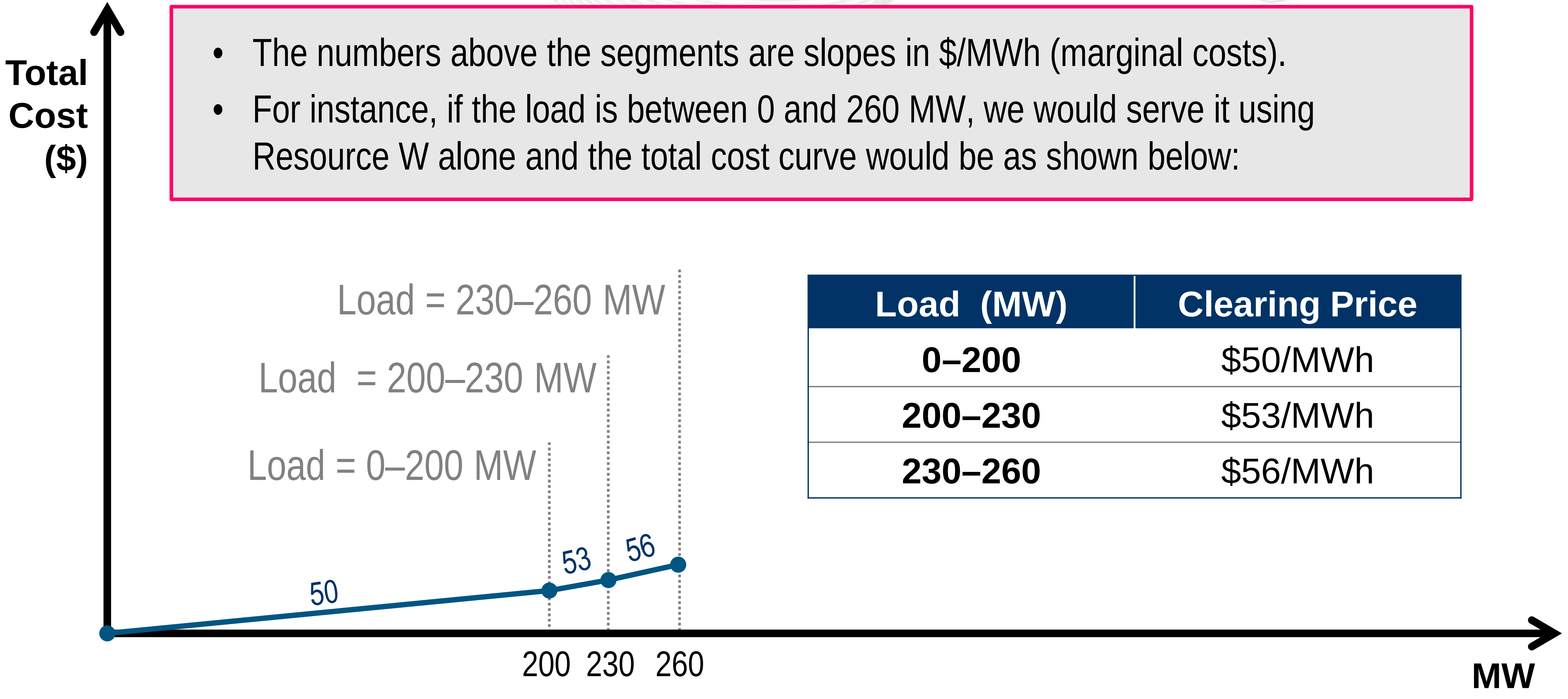


Illustration of Marginal Price Setting: Example #1

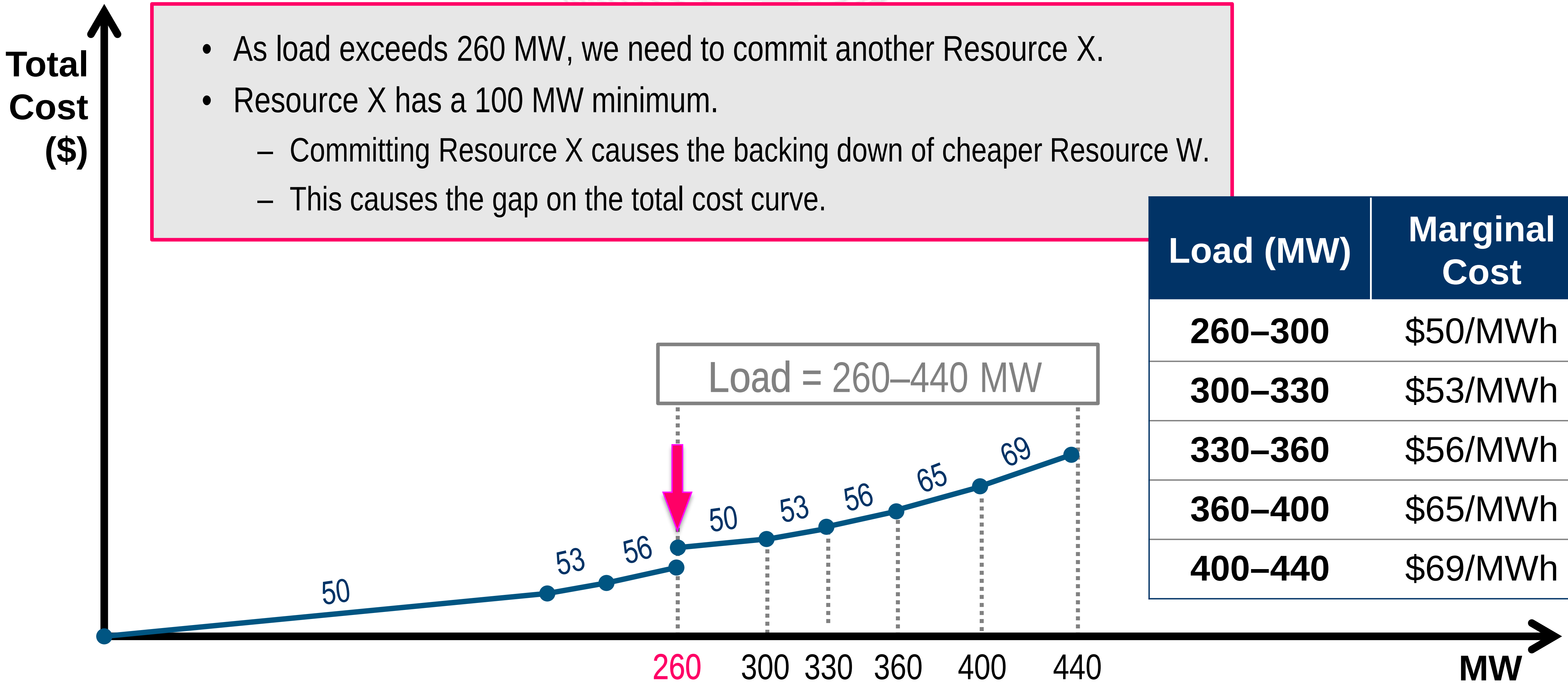
- The numbers above the segments are slopes in $/MWh (marginal costs).
- For instance, if the load is between 0 and 260 MW, we would serve it using Resource W alone and the total cost curve would be as shown below:



Load (MW)	Clearing Price
0–200	$50/MWh
200–230	$53/MWh
230–260	$56/MWh

Illustration of Marginal Price Setting: Example #1

- As load exceeds 260 MW, we need to commit another Resource X.
- Resource X has a 100 MW minimum.
  - Committing Resource X causes the backing down of cheaper Resource W.
  - This causes the gap on the total cost curve.



Load (MW)	Marginal Cost
260–300	$50/MWh
300–330	$53/MWh
330–360	$56/MWh
360–400	$65/MWh
400–440	$69/MWh

Illustration of Marginal Price Setting: Example #1

- As load gets above 440 MW, we need to commit Resource Y.
- The total cost curve for all three resources is as shown.

Note: The price does not always increase as demand increases.

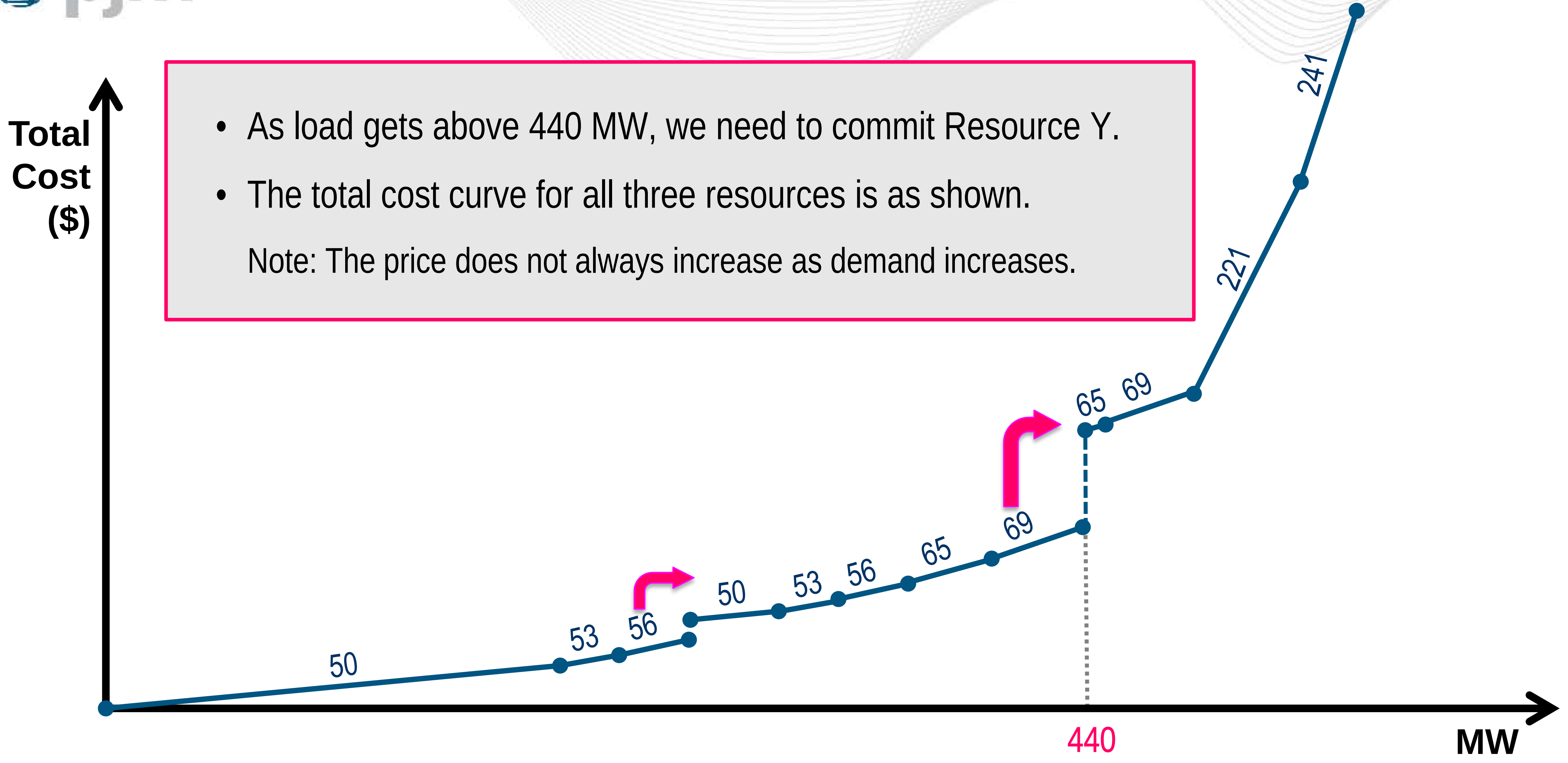


Illustration of Marginal Price Setting: Example #1

At 480 MW of load, the slope of the total cost curve is $69/MWh.

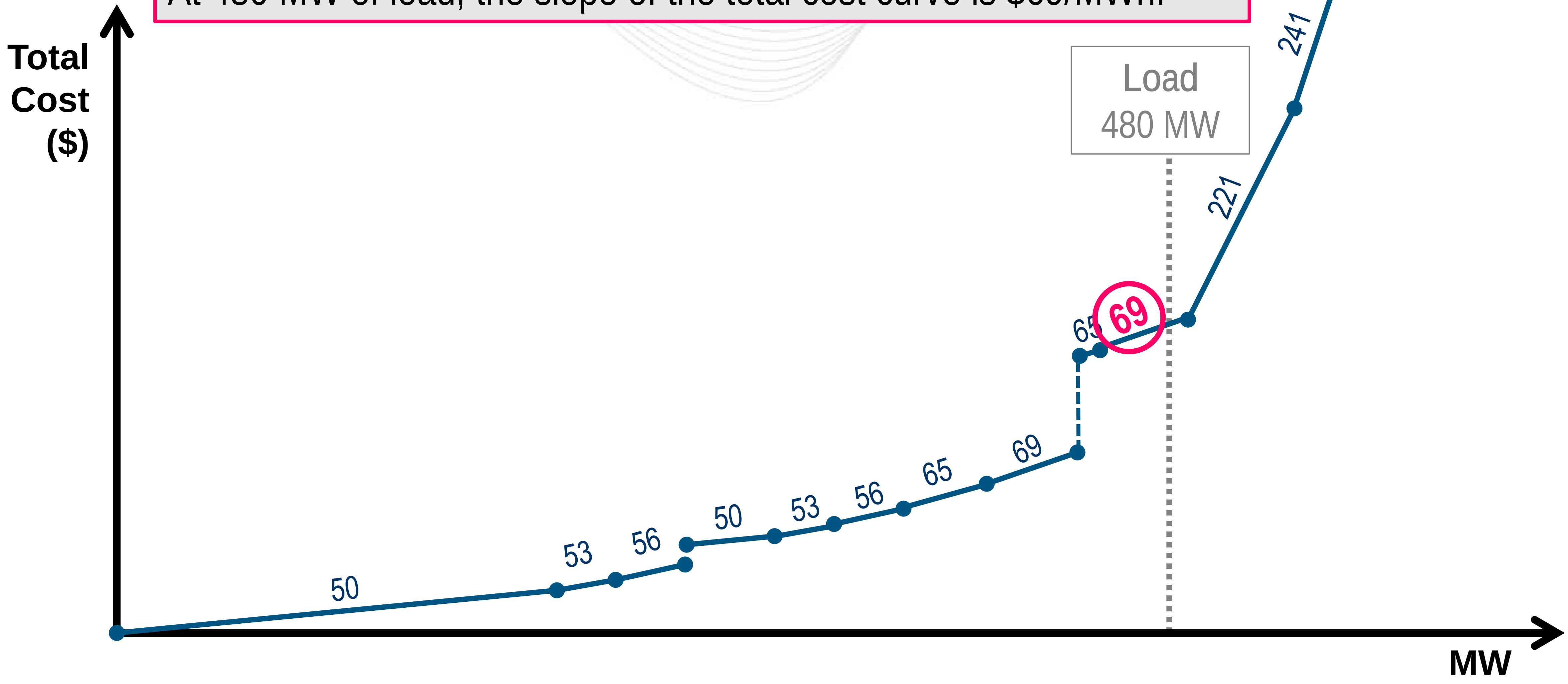


Illustration of Convex-Hull Pricing: Example #1

Convex-hull price is the slope (marginal cost) of the convex-hull function.

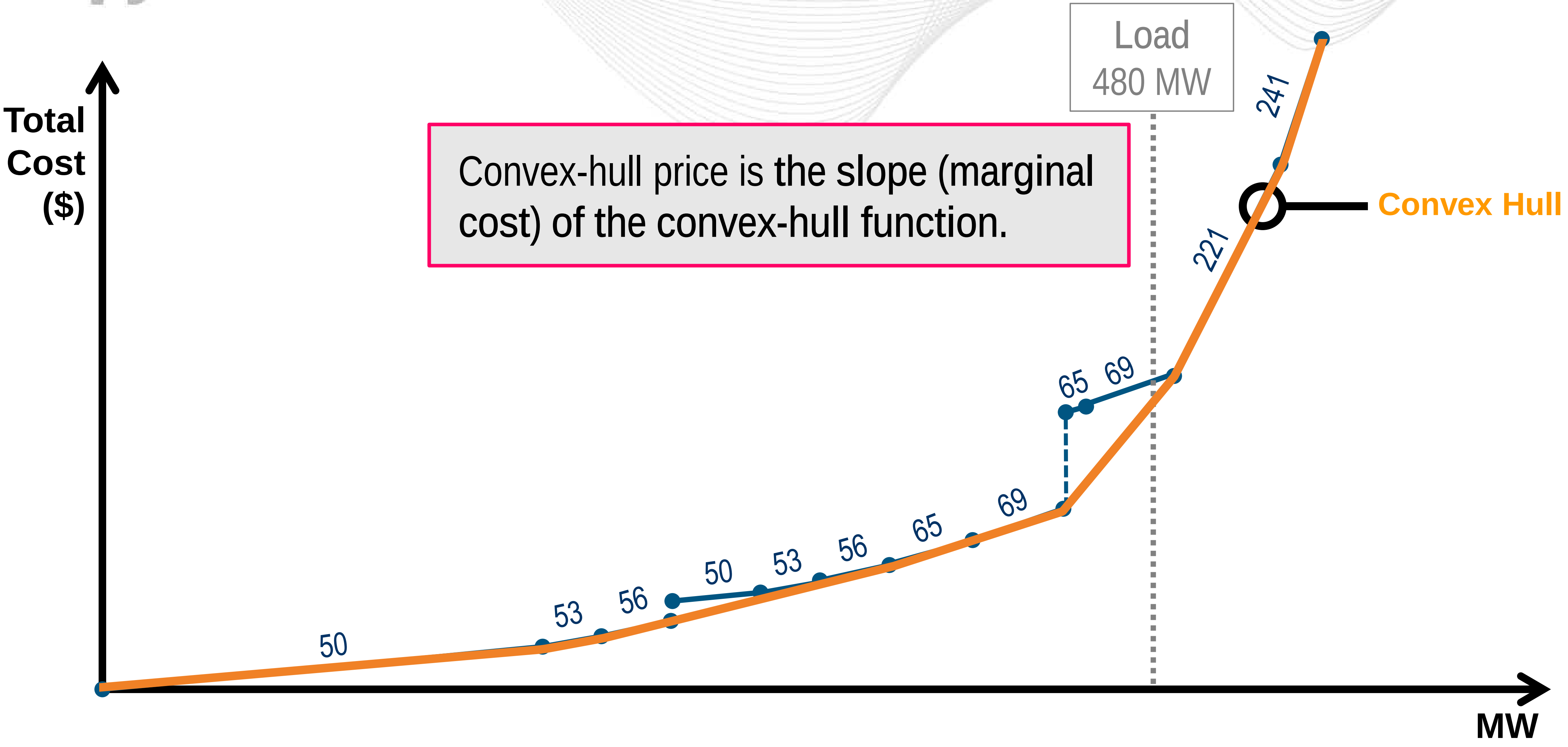
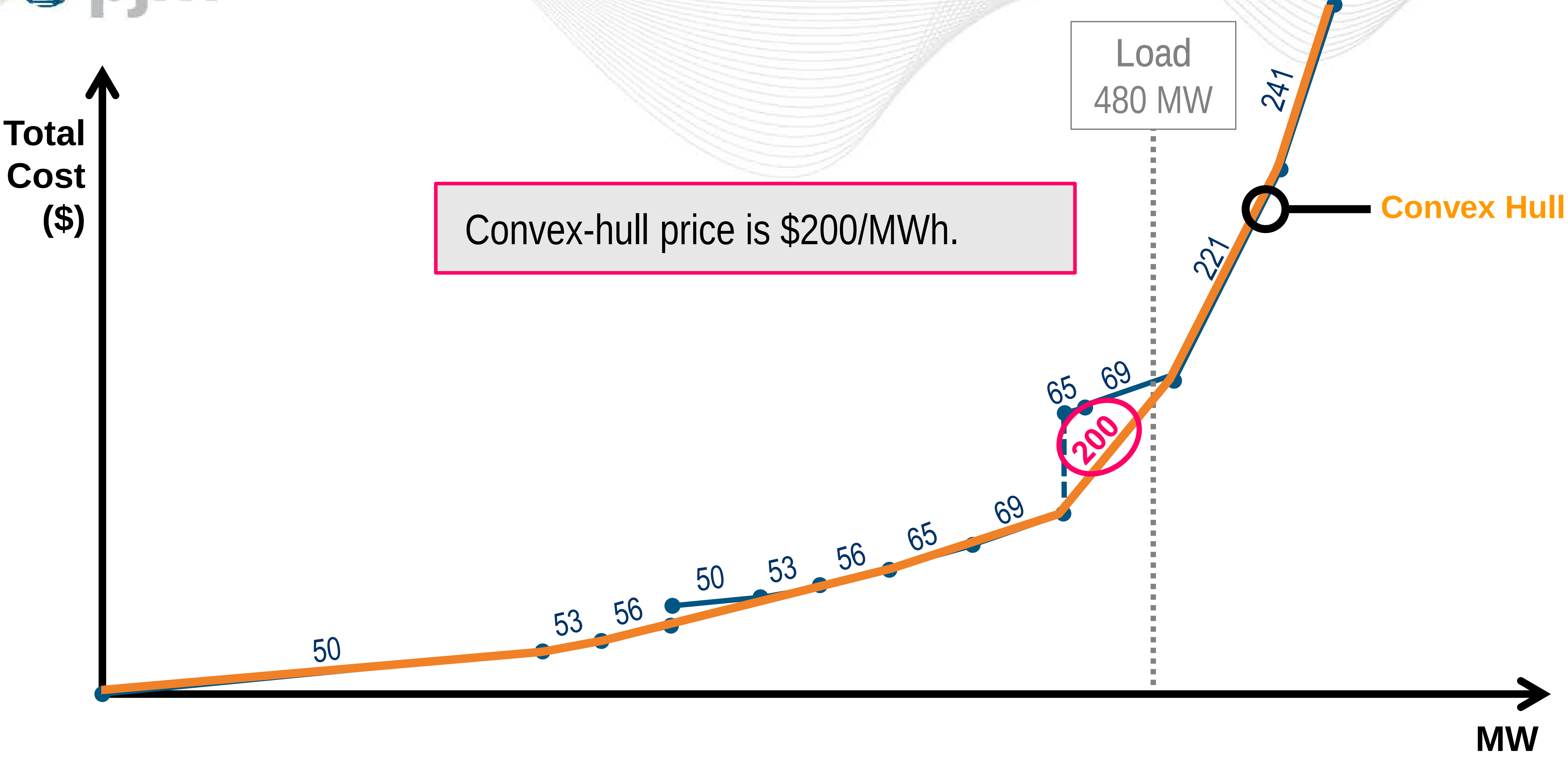


Illustration of Convex-Hull Pricing: Example #1

Convex-hull price is $200/MWh.



Summary of Example #1

- In this example, the convex-hull price minimizes total uplift payments, including both make-whole payments and lost opportunity cost.
- The convex-hull price is the slope of the convex hull of the total cost curve.

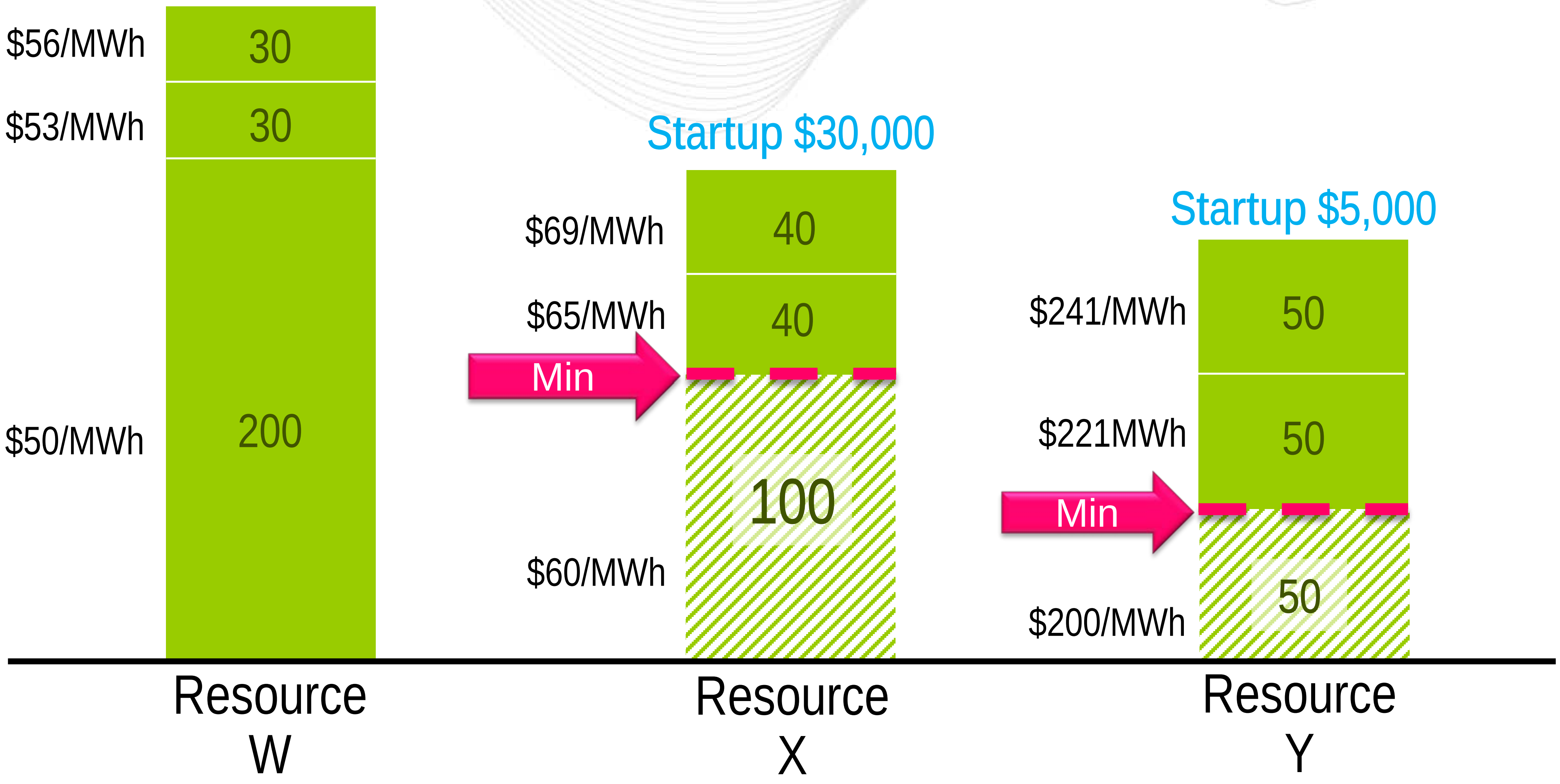
Example #1	Convex-Hull Pricing with Minimum Generation
Example #2	Convex-Hull Pricing with Fixed Costs
Example #3	Approximate Extended Locational Marginal Pricing

Features of Example #2a

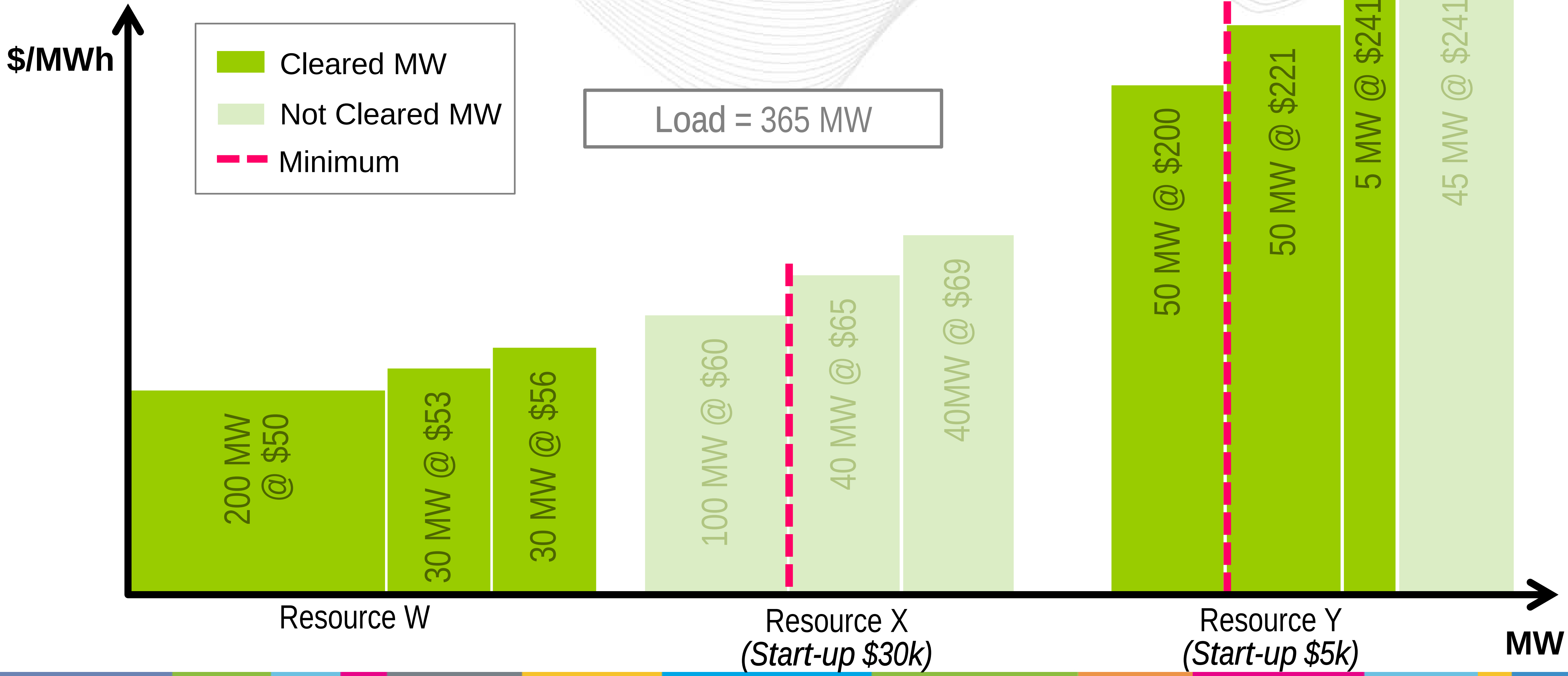
- **Same offer blocks** as Example #1 for each resource
- **Fixed costs (start-up) added** to Resource X and Resource Y
- **Demand = 365 MW**

Example #2: Offer Blocks (MW) & Fixed Costs

Any resource that is "committed" must run at least at its minimum



The Commitment and Dispatch: Example #2a

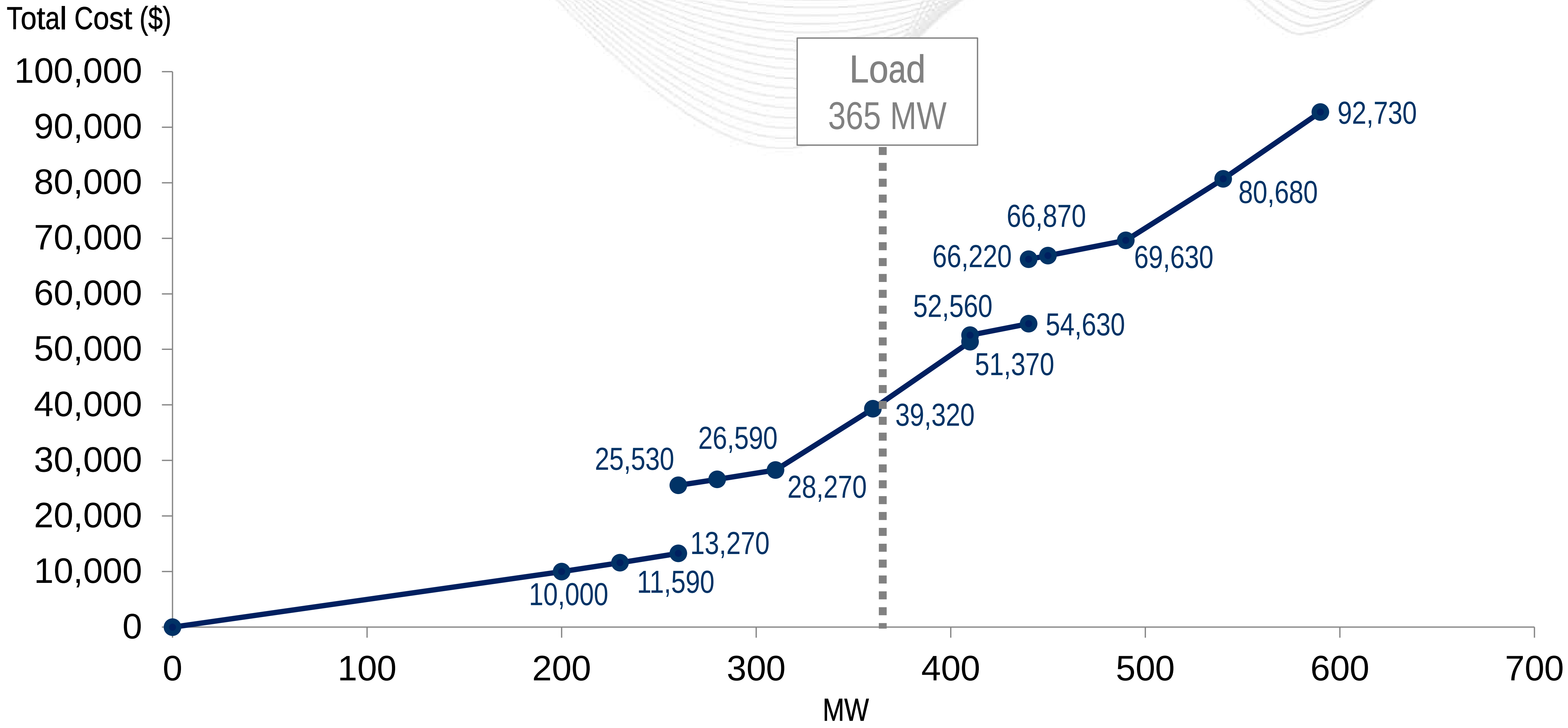


Least-Cost Commitment and Dispatch: Example #2a

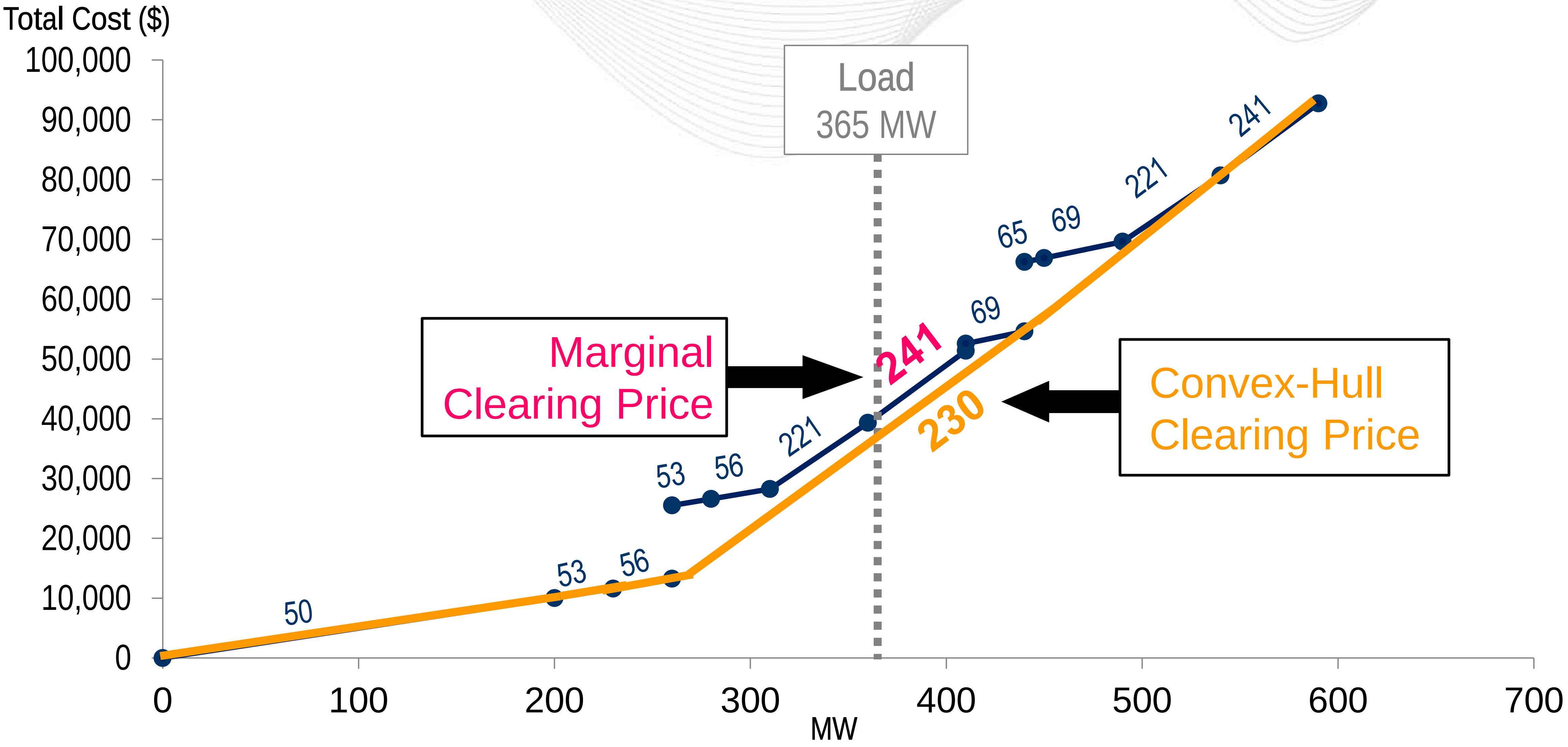
The commitment and dispatch that minimize the total offer cost for meeting **365 MW of load**

Resource	Commitment	Dispatch (MW)	Total Offer Cost ($)
W	On	260	13,270
X	Off	0	0
Y	On	105	27,255

Total Offer Cost Graph: Example #2a



Total Offer Cost Graph: Example #2a



The convex-hull price is achieved at $230/MWh.

Resource	Commitment	Dispatch (MW)	Total Offer Cost ($)	Payment ($)	MWP ($)	LOC ($)
W	On	260	13,270	59,800	0	0
X	Off	0	0	0	0	0
Y	On	105	27,255	24,150	3,105	0

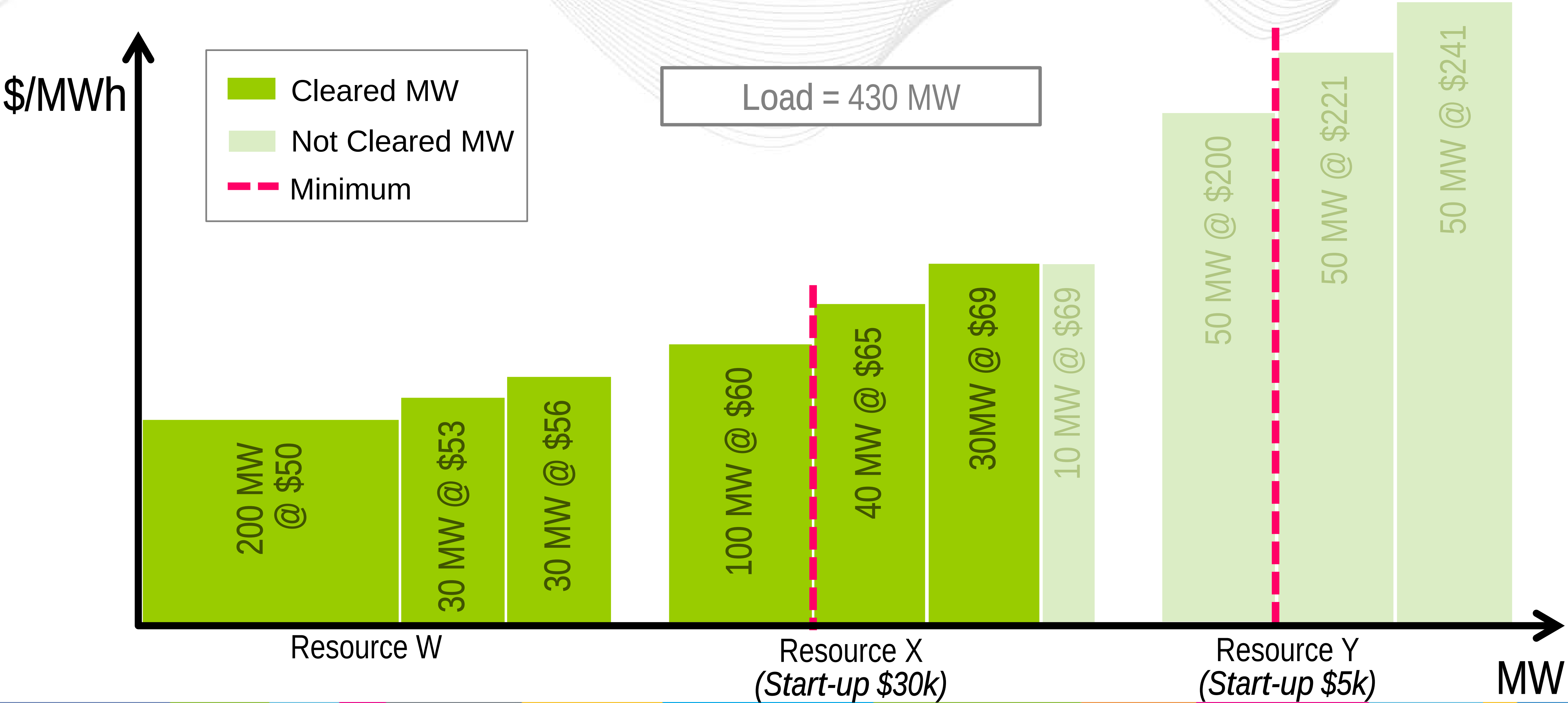
- At a marginal clearing price of $241/MWh:
  - W is paid $241 x 260 MW = $62,660.
  - X is paid LOC of $2,020.
  - Y is paid the same $27,255 ($25,305 + MWP of $1,950).

Reminder: At X's offer prices of $60–$69/MWh, it would want to come online at a $241/MWh clearing pricing since it would make a profit at $241/MWh of $2,020. Today's markets in general do not pay this LOC to offline resources.

What if the Load Went Up for this Example?

- As total load rises, the total offer cost of meeting that demand rises.
- One of the benefits of convex-hull pricing is that as the load goes up, the clearing prices do not go down.
- **This is not true of marginal pricing.**
- Experiment, increase load to:
  - Example 2b – Load = 430 MW
  - Example 2c – Load = 445 MW

The Commitment and Dispatch: Example #2b



Least-Cost Commitment and Dispatch: Example #2b

The commitment and dispatch that minimize the total offer cost for meeting 430 MW of load:

Resource	Commitment	Dispatch (MW)	Total Offer Cost ($)
W	On	260	13,270
X	On	170	40,670
Y	Off	0	0

- Total offer cost includes fixed costs and incremental costs.

Total Offer Cost Graph: Example #2b

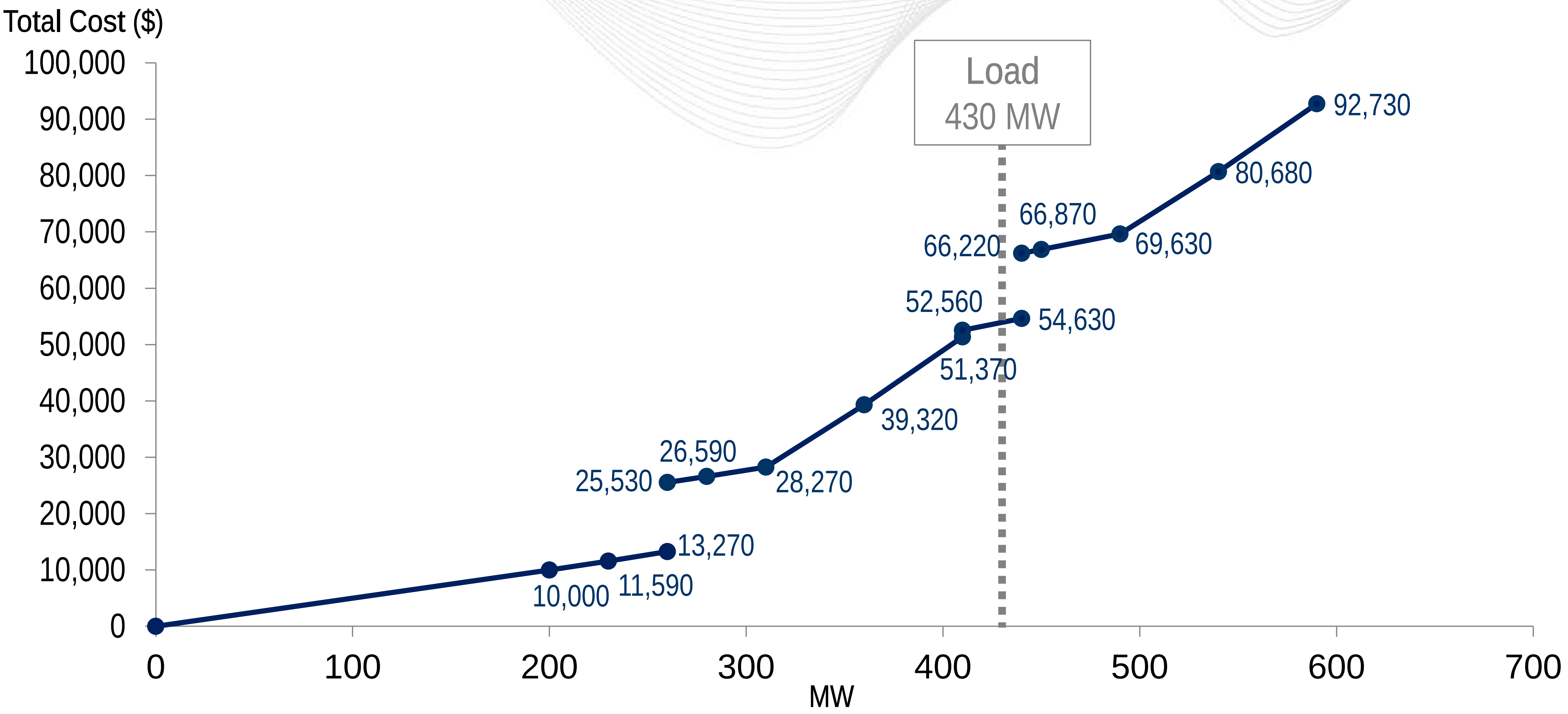
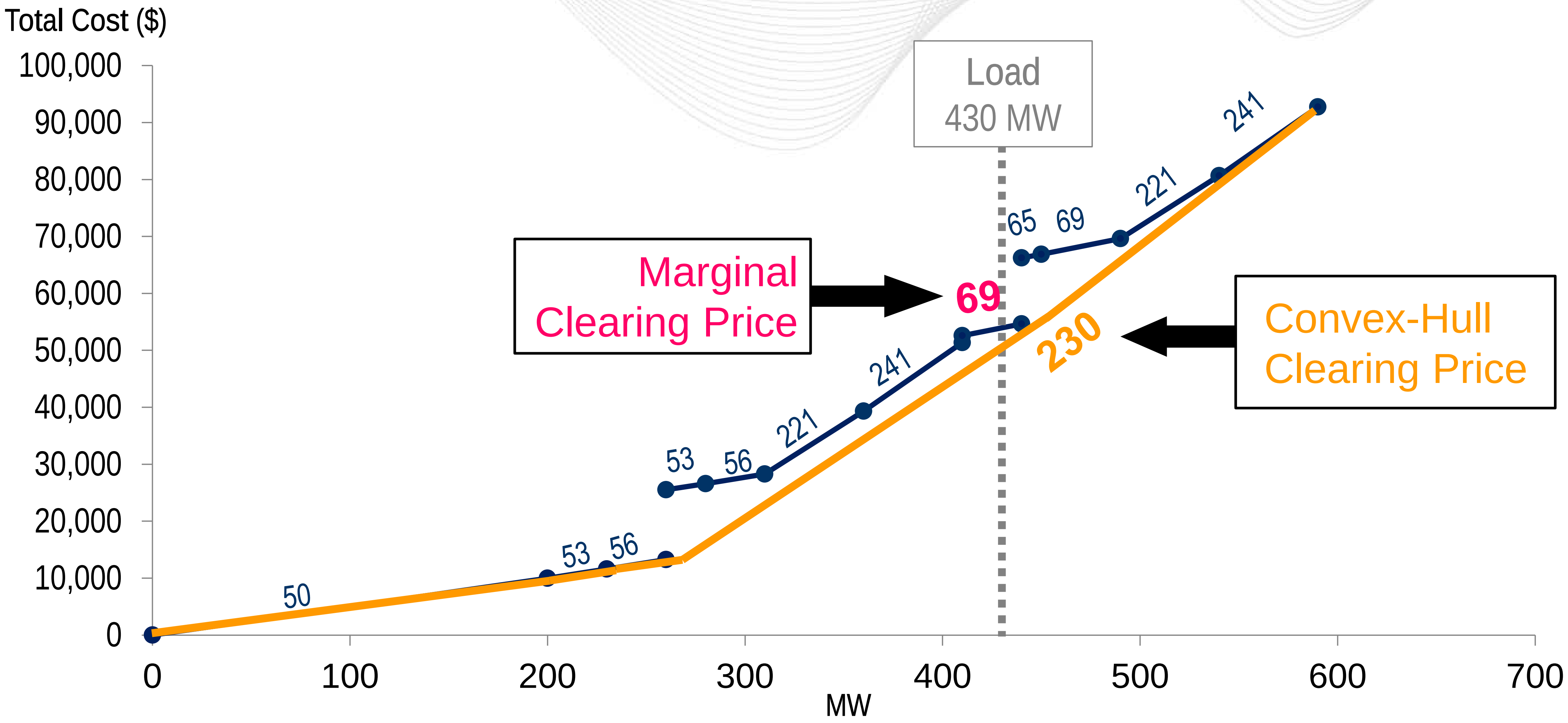


Illustration of Convex-Hull Pricing: Example #2b



Convex-Hull Pricing and Settlement: Example #2b

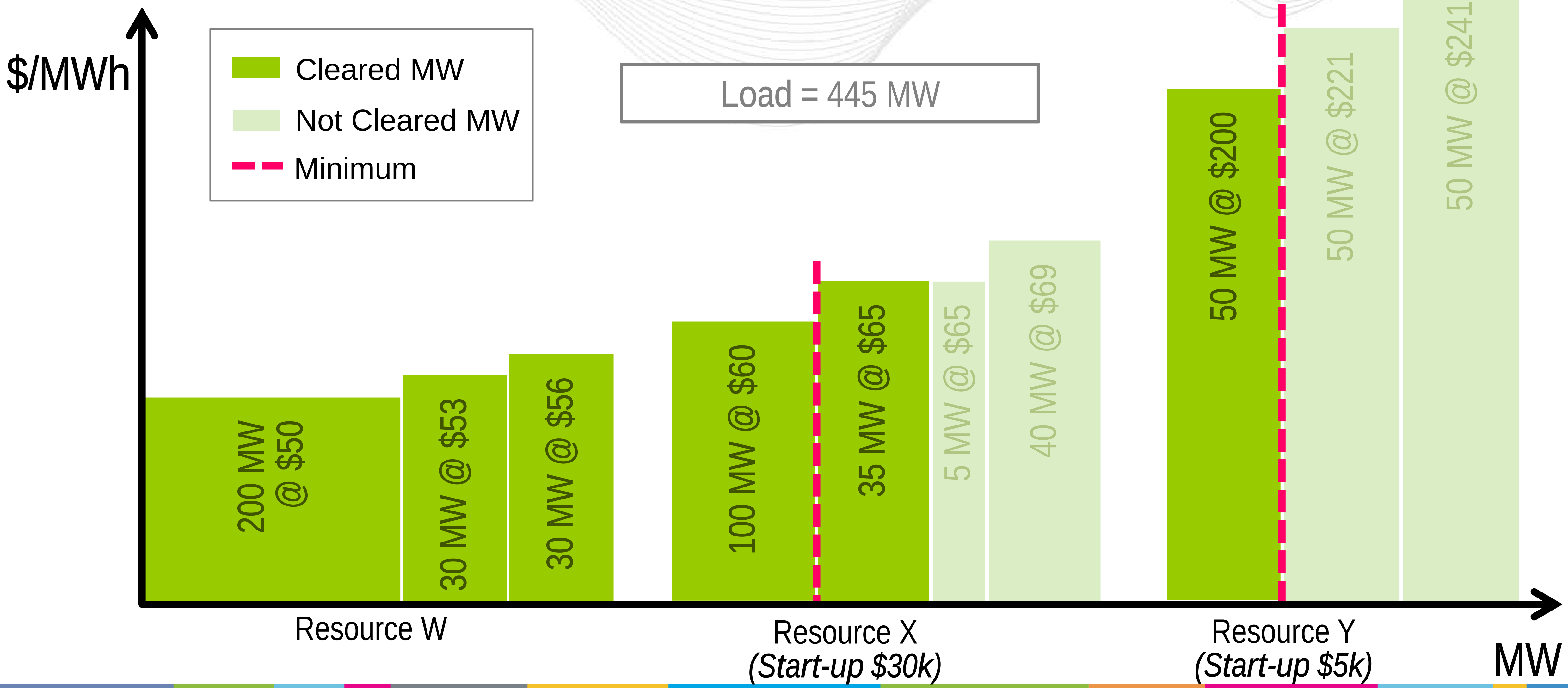
The convex-hull price is still achieved at $230/MWh.

Resource	Commitment	Dispatch (MW)	Total Offer Cost ($)	Payment ($)	MWP ($)	LOC ($)
W	On	260	13,270	59,800	0	0
X	On	170	40,670	39,100	1,570	0
Y	Off	0	0	0	0	0

At the marginal clearing price of $69/MWh:

- W is paid $69 x 260 MW = $17,940.
- X is paid $40,670 ($11,730 + MWP of $28,940).

The Commitment and Dispatch: Example #2c



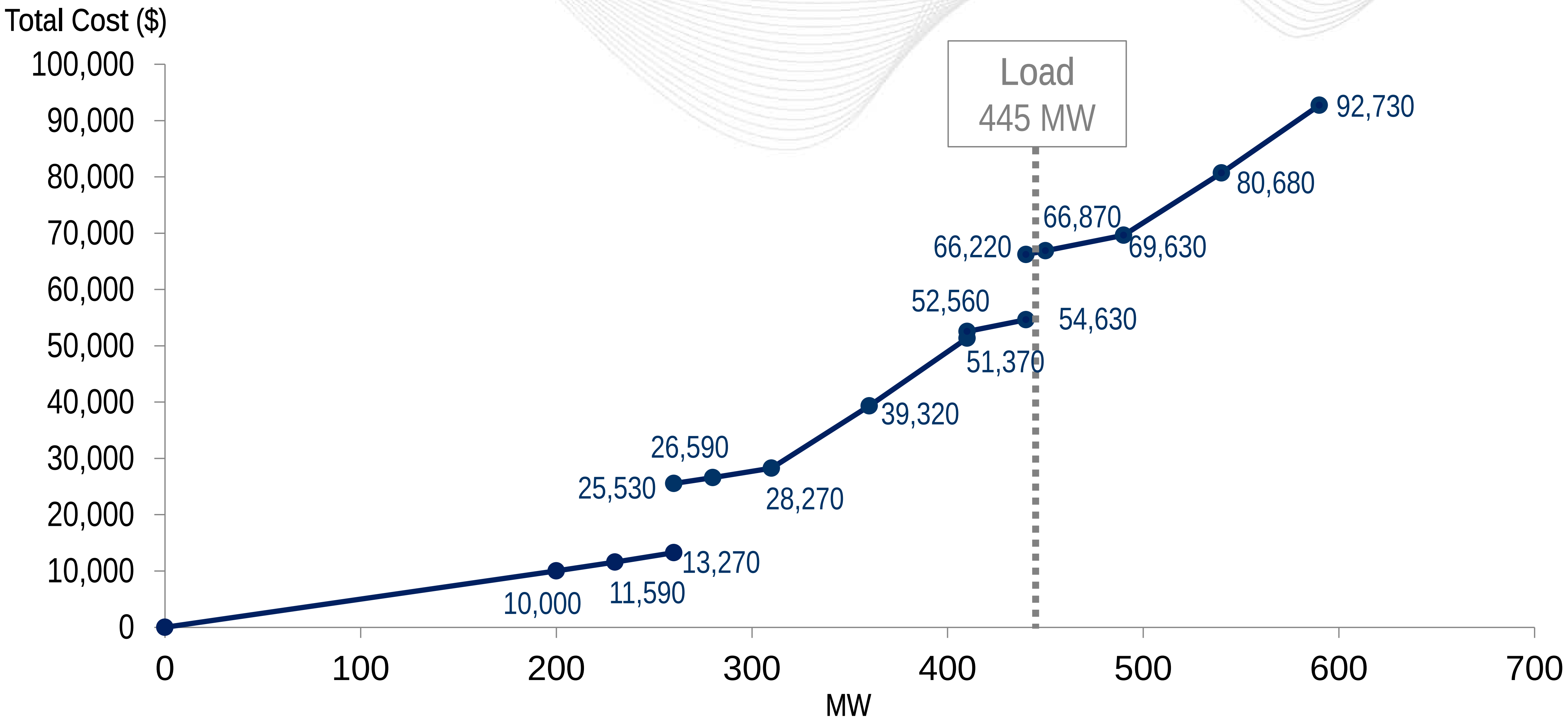
Least-Cost Commitment and Dispatch: Example #2c

The commitment and dispatch that minimizes the total offer cost for meeting 445 MW of load:

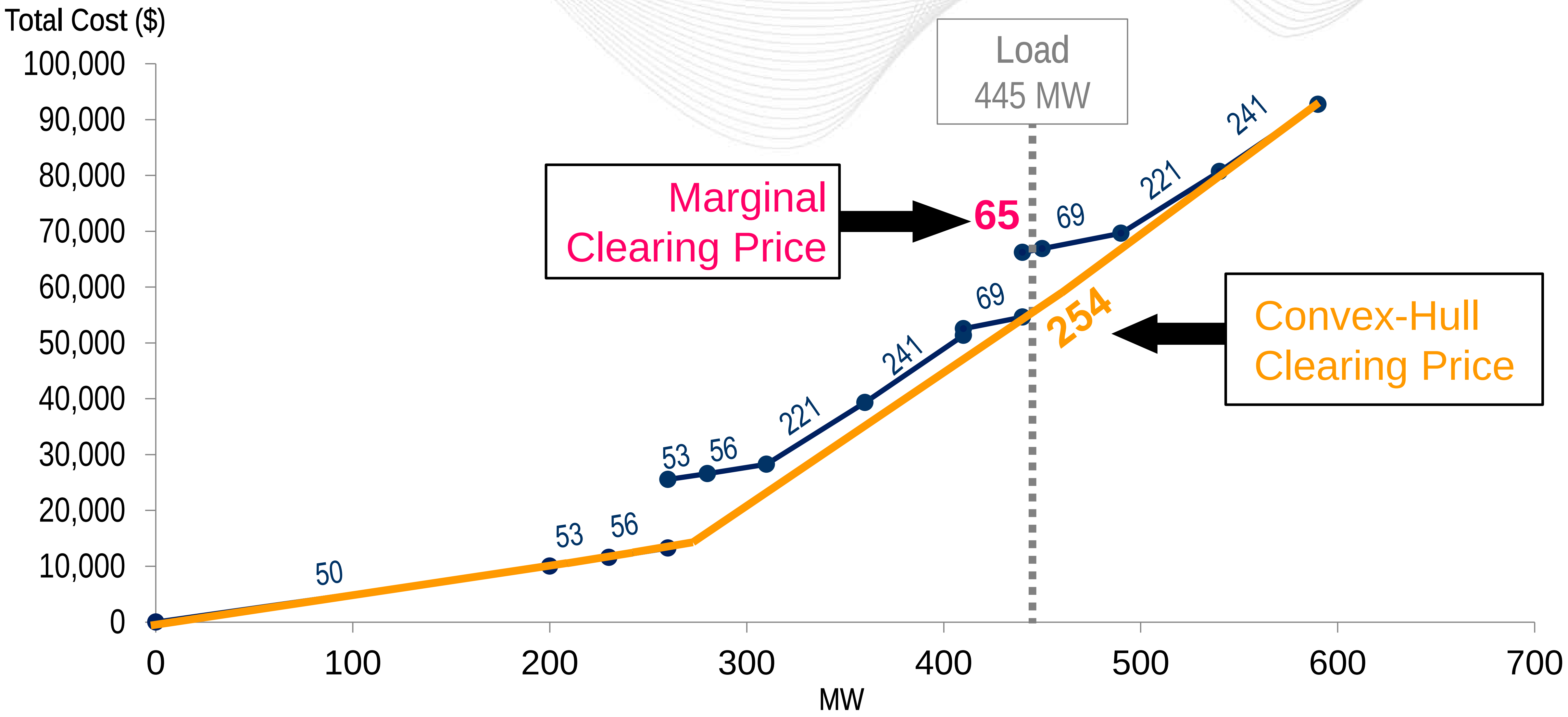
Resource	Commitment	Dispatch (MW)	Total Offer Cost ($)
W	On	260	13,270
X	On	135	38,275
Y	On	50	15,000

- Total offer cost includes fixed costs and incremental costs.

Total Offer Cost Graph: Example #2c



Total Offer Cost Graph: Example #2c



Convex-Hull Pricing and Settlement: Example #2c

The convex-hull price is achieved at $254/MWh:

Resource	Commitment	Dispatch (MW)	Total Offer Cost ($)	Payment ($)	MWP ($)	LOC ($)
W	On	260	13,270	66,040	0	0
X	On	135	38,275	34,290	3,985	4,360
Y	On	50	15,000	12,700	2,300	0

- At the marginal clearing price of $65/MWh:
  - W is paid $65 x 260 MW = $16,900.
  - X is paid $38,275 ($8,775 + MWP of $29,500).
  - Y is paid $15,000 ($3,250 + MWP of $11,750).

Summary of Examples #2a–2c

Load (MW)	Marginal Clearing Price ($/MWh)	Total Marginal Price Uplift Payment ($)	Convex-Hull Clearing Price ($/MWh)	Total Convex-Hull Price Uplift Payment ($)
365	241	3,970	230	3,105
430	69	28,940	230	1,570
445	65	41,250	254	10,645

The following are true about convex-hull pricing:

- Under convex-hull pricing, the prices will:
  - **Rise**, or stay the same, with an **increase** in load
  - **Fall**, or stay the same, with a **decrease** in load
- Under marginal pricing, the price could go **up** or **down** with an increase in load (due to lumpiness).

Example #3

Example #1

Convex-Hull Pricing with Minimum Generation

Example #2

Convex-Hull Pricing with Fixed Costs

Example #3

Approximate Extended Locational Marginal Pricing

- Implementing convex-hull pricing is not computationally feasible.
- In order to calculate an approximate convex-hull solution, one can run separate dispatch and pricing runs.
- Using separate dispatch and pricing runs is currently used by many other ISOs/RTOs in their approximate ELMP designs.

Separate Dispatch and Pricing Runs

Dispatch Run

- Make no modifications to resource parameters
- Determine desired dispatch points
- Do not calculate prices

Pricing Run

- Modify resource parameters
- Calculate prices

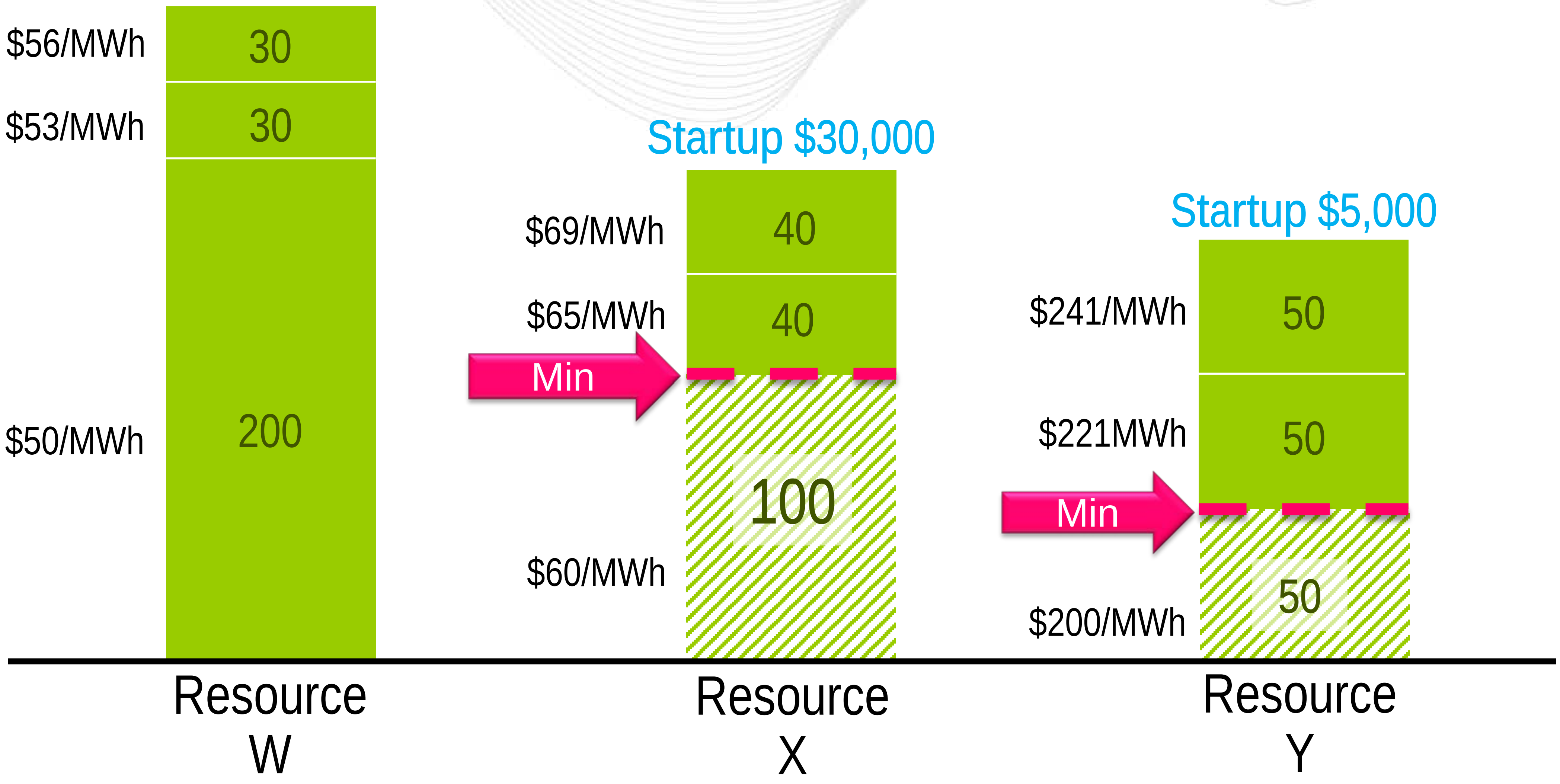
Example #3a – Approximate ELMP

- Same offers and load (365 MW) as Example #2a
- **Policy:** Offline resources **do not** participate in pricing.
- **Policy:** Fixed costs (start-up and no-load) are considered in setting the price.

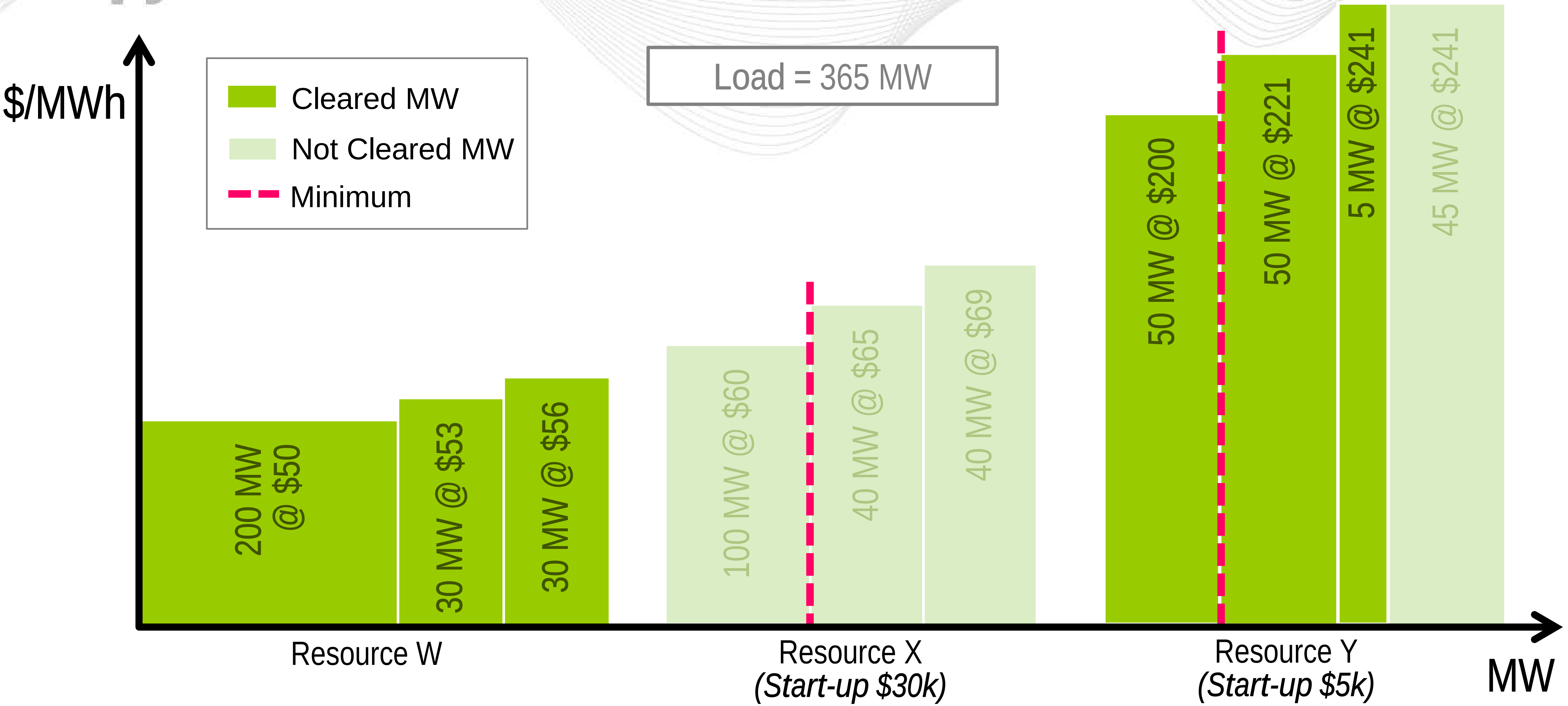
Note: this is just one example of how approximate ELMP can be implemented. Others are possible.

Example #3a: Offer Blocks (MW) & Fixed Costs

Any resource that is "committed" must run at least at its minimum



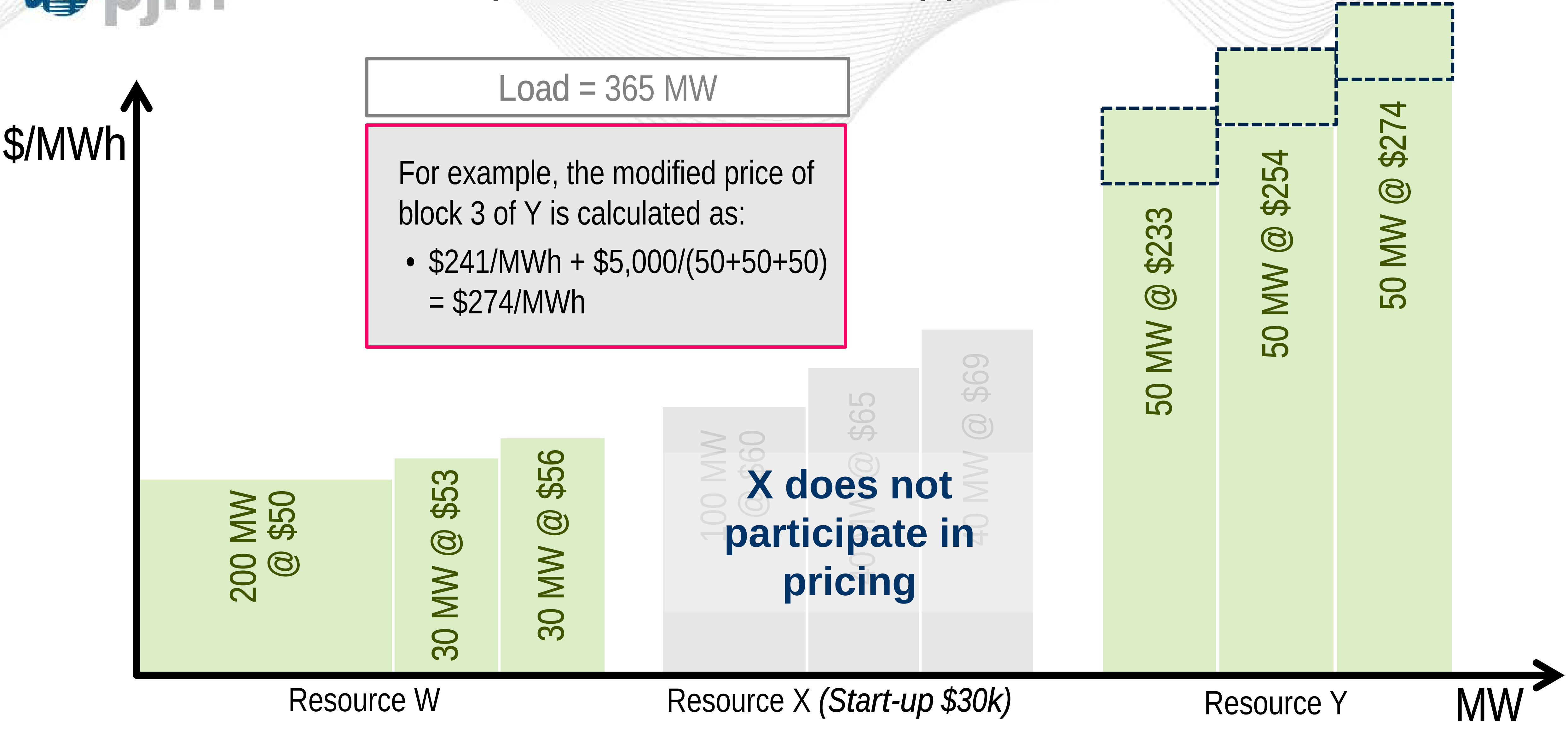
The Commitment and Dispatch Run: Example #3a



Pricing Run Offer Modifications for Example #3a

- Offline resource X **does not** participate in pricing.
- Approximate ELMP relaxes the 0/1 commitment variable to be continuous for pricing calculations:
  - Minimum generation level of Y is relaxed to 0 for pricing calculations.
- Start-up cost of Y is proportionally distributed to its MW.
  - The bid blocks of Resource Y can be equivalently modified to incorporate the proportional start-up costs.

Equivalent Offers for Approximate ELMP: Ex. #3a



Approximate ELMP: Example #3a

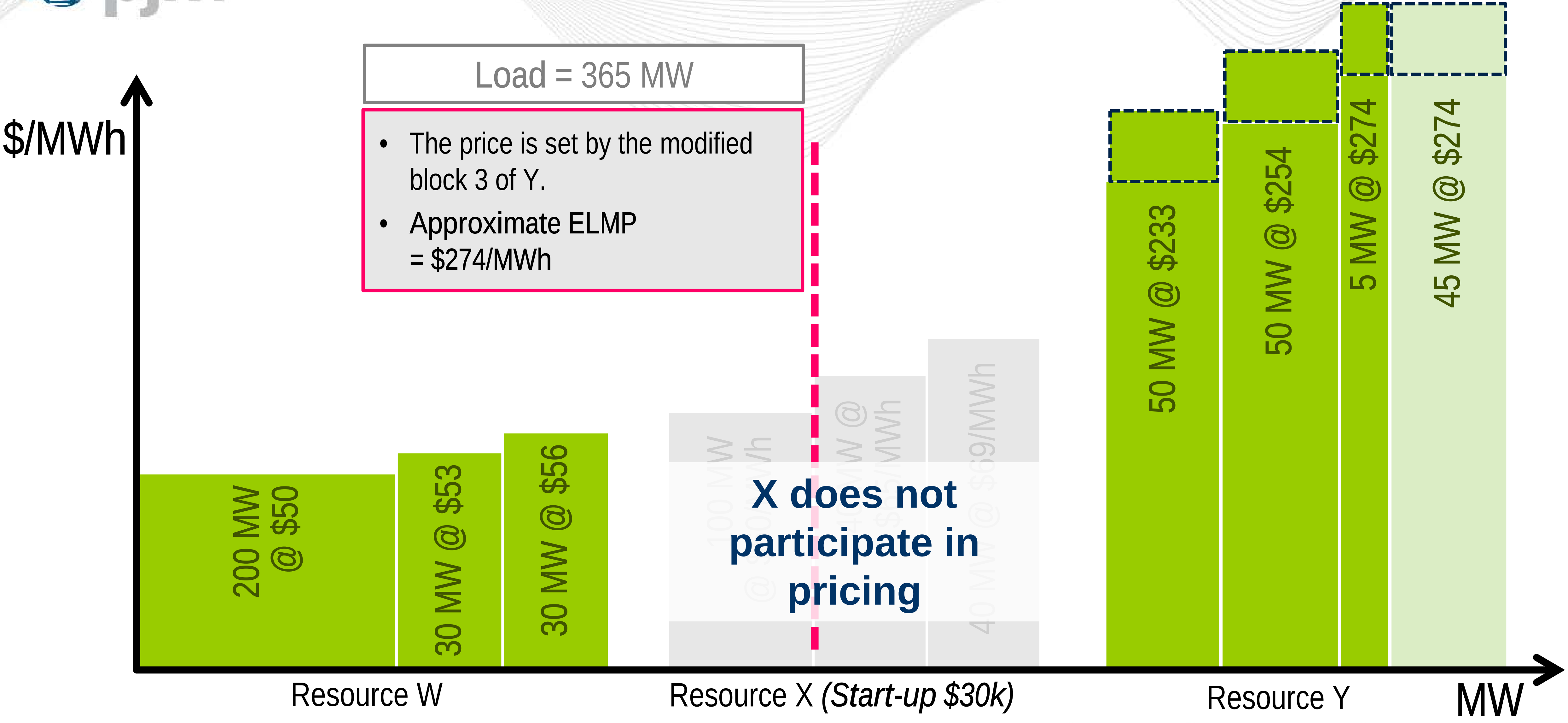
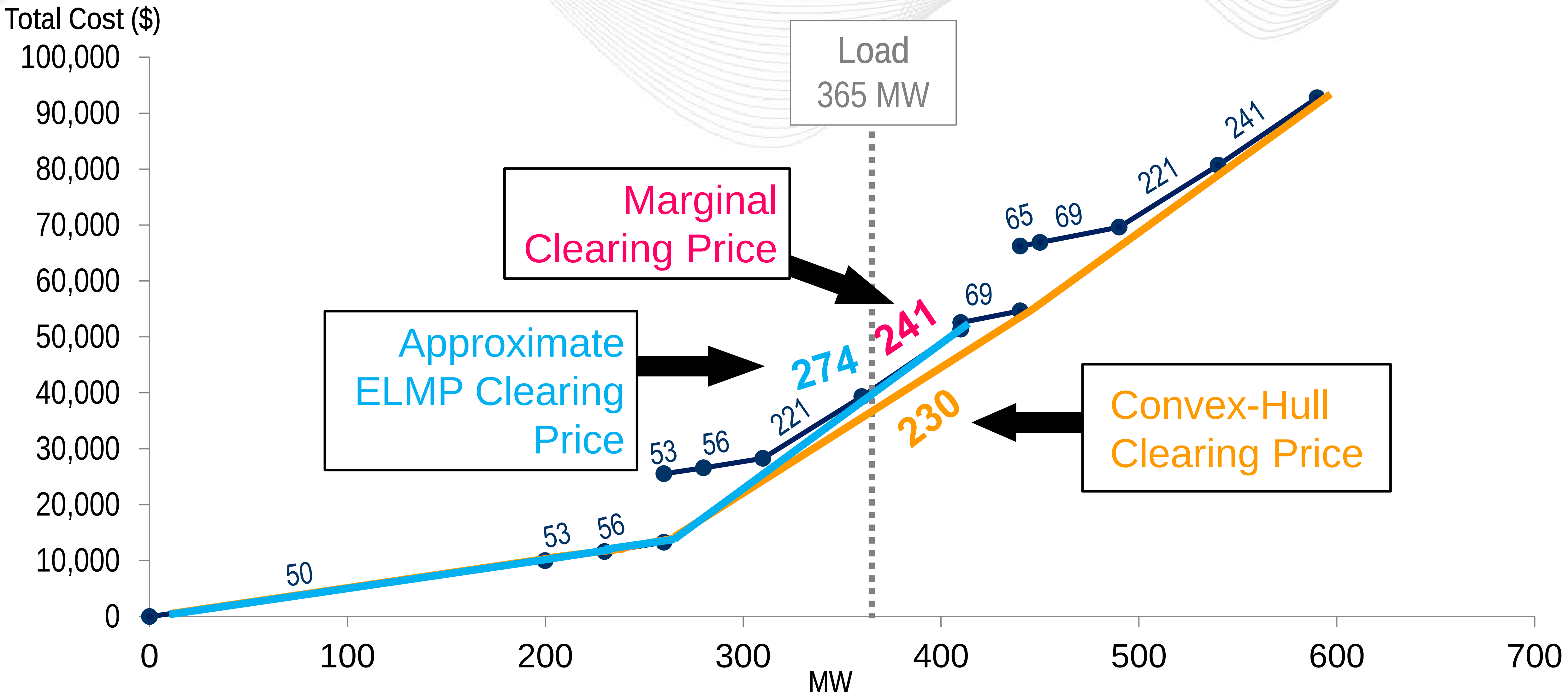


Illustration of Approximate ELMP Pricing: Example #3a



Approximate ELMP Pricing and Settlement: Example #3a

The **Approximate ELMP** is calculated at **$274/MWh.**

Asset	Commit.	Dispatch (MW)	Total Offer Cost ($)	Payment ($)	MWP ($)	LOC ($)
W	On	260	13,270	71,240	0	0
X	Off	0	0	0	0	7,960*
Y	On	105	27,255	28,770	0	1,485

Uplift = $9,445 in this example

**Note: LOC is not paid to offline resources in most markets.*

Example #3b – Approximate ELMP

- **New Policy:** Offline resources **do** participate in pricing.
- **Policy:** Fixed costs (start-up and no-load) are considered in setting the price.

- The **Approximate ELMP = $232/MWh** and uplift = $3,295.

Summary of Examples #2a & 2c

Load = 365 MW	Price ($/MWh)	Total Uplift Payment ($)
Marginal	241	3,970
Convex-Hull	230	3,105
Approximate ELMP (offline units cannot set price)	274	9,445
Approximate ELMP (offline units can set price)	232	3,295

Summary of Example #3

- **Approximate ELMP** is different from convex-hull pricing in both theory and implementation.

- Different approximation “policies” lead to different results.
  - For example, letting offline resources participate in pricing vs. not letting offline resources participate in pricing

APPENDIX

History of Convex-Hull Pricing

History of Convex-Hull Pricing

- Duality theory in mathematical optimization was developed decades ago.
- Hogan and Ring 2003 proposed a pricing scheme intended to minimize the total side payments including lost opportunity cost.
  - "On Minimum-Uplift Pricing For Electricity Markets"
    William W. Hogan and Brendan J. Ring
- Gribik, Hogan and Pope in 2007 established the equivalence of minimum side-payment price and the solution of the unit commitment dual problem, and the price is termed "convex-hull price."
  - "Market-Clearing Electricity Prices and Energy Uplift"
    Paul R. Gribik, William W. Hogan, and Susan L. Pope

APPENDIX

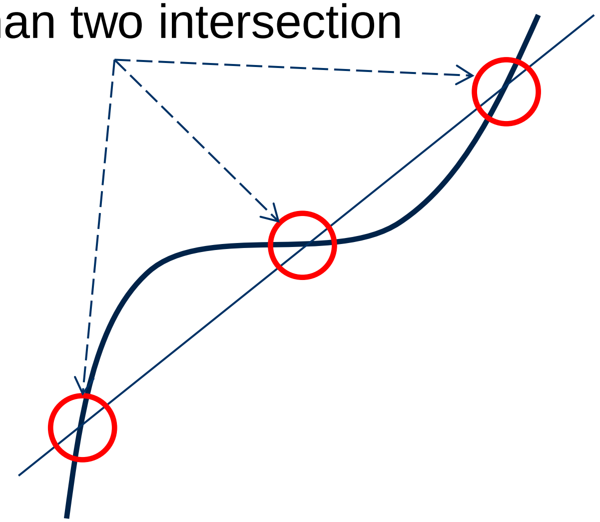
Convexity

What is Convexity?

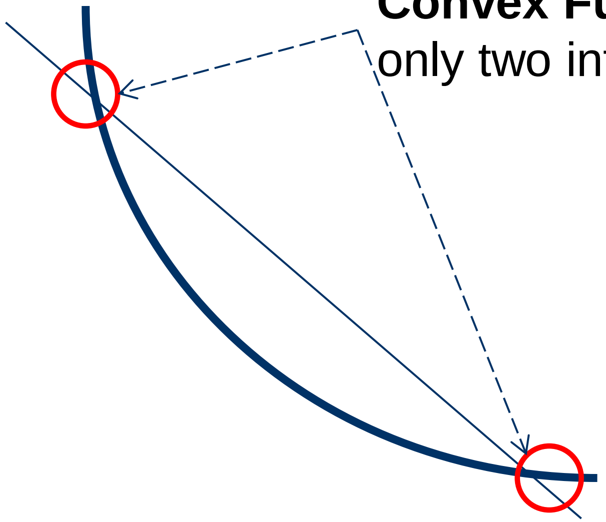
Convexity refers to the curvature of a function.

A function is convex if any straight line you draw across the function does not intersect the function in more than two places.

Non-Convex Function – more than two intersection points



Convex Function – only two intersection points



If you have detailed questions or would like to discuss this presentation further, email:

priceformation@pjm.com