

Use prices to encourage efficient operation and investment of critical infrastructure as we transition to net zero

### Finance

Flow trading

### Electricity

A forward energy market to improve reliability and resiliency

### Communications

An open access market for global communications

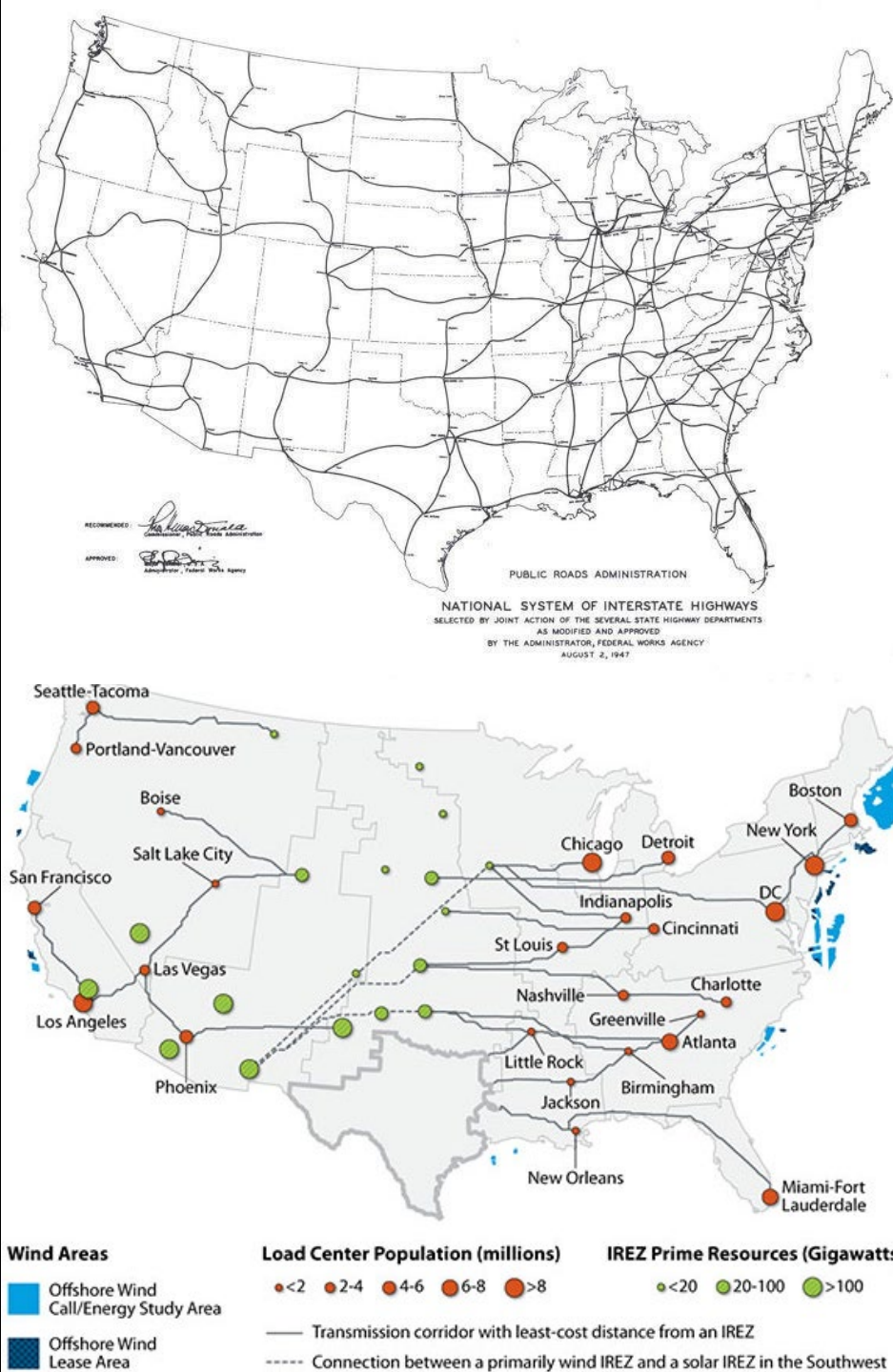
### Transportation

A market for airport slots

Peter Cramton, University of Maryland\*

21 November 2024

\*In collaboration with Erik Bohlin, Ivey Business School; Eric Budish, University of Chicago; Simon Brandkamp and Axel Ockenfels, University of Cologne; Hung-po Chao, Energy Trading Analytics; Albert S. Kyle and David Malec, University of Maryland; Jason Dark, Darrell Hoy, and Chris Wilkens, Cramton Associates; Jeongmin Lee, Board of Governors of the Federal Reserve System; Marleen Marra, Sciences Po; Robert Wilson, Stanford University.



# Market design



**Goal: maximize social welfare  
subject to physical constraints**



**What potential market failures  
arise, and how to mitigate?**

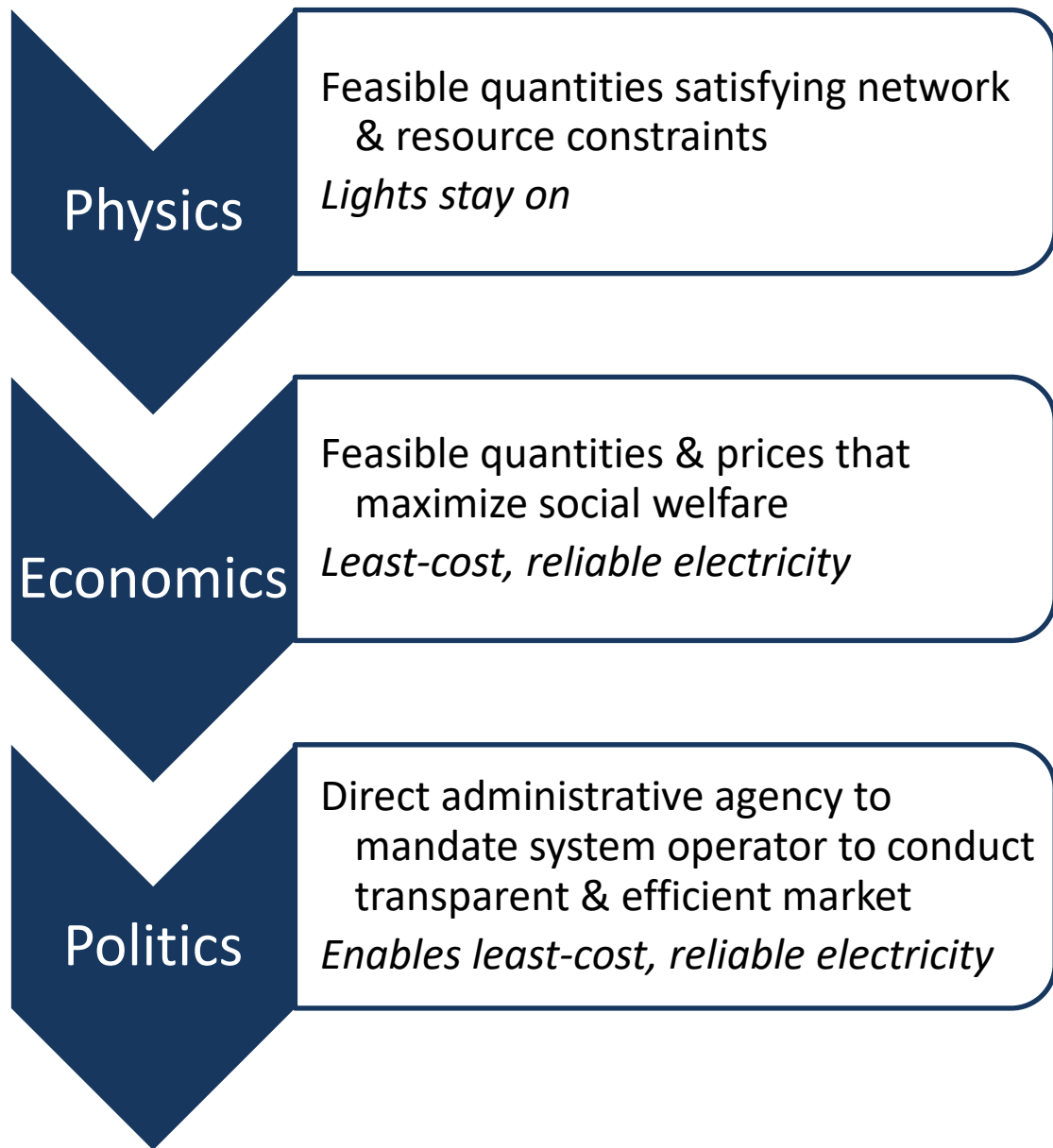
Prisoner's dilemma

Incomplete markets

Market power

Adverse selection and moral hazard

# Governance



Administrative agency  
*Approves market rules*  
*Selects key parameters (price cap...)*

System operator independent board  
*Approves market rules to send to AA*

System operator  
*Develops & implements market rules*

Technical advisory committee  
*Helps develop market rules*

Independent market monitor  
*Analyzes market, identifies problems*



# Market Design for Germany's Power Station Strategy

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Peter Cramton and Axel Ockenfels  
July 2024

Peter Cramton is a professor of Economics at the University of Maryland, USA. Axel Ockenfels is a professor of Economics at the University of Cologne and Director of the Max Planck Institute for Research on Collective Goods in Bonn, Germany.





# Background and motivation

## Decarbonization brings change

- Expansion of intermittent renewable energy
- Phase-out of coal
- Growing demand

## Market implication

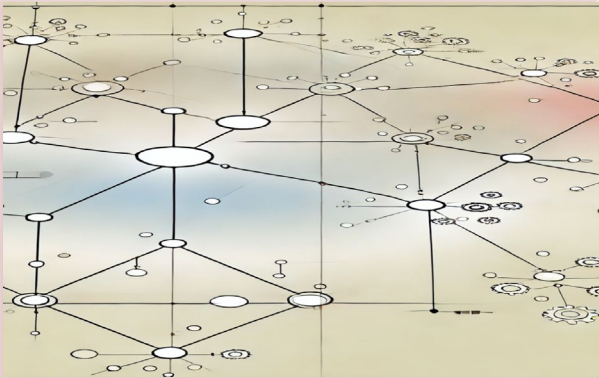
- Flexible climate-friendly generation must be built
- Existing market failures prevent investment without regulatory response

## Regulatory response

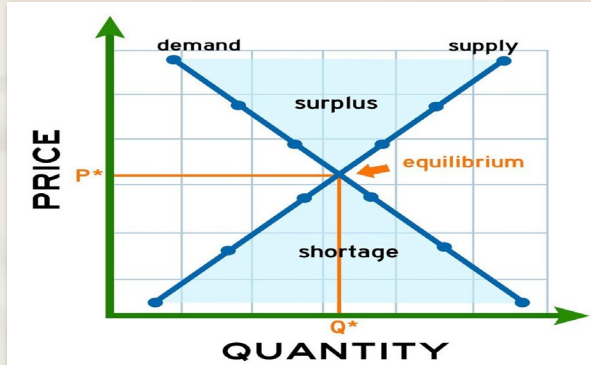
- Procure essential flexible generation consistent with immediate needs
- Fix market failures (incomplete markets, market power, uncertainty, ...)
  - For the long run, yielding an efficient, reliability, and resilience electricity market
  - For the near term, yielding a lower-cost, forward-looking procurement of immediate needs

# Centralized vs. Decentralized

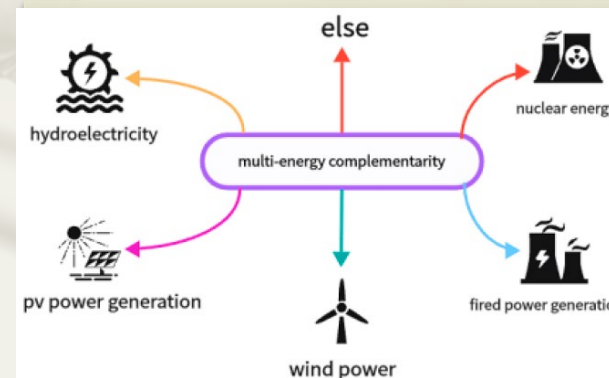
*Least-cost reliable electricity requires:*



*Decentralized* decision-making by market participants in efficient and transparent markets



*Centralized* forward market for efficient operation and investment



*Centralized* scheduling for efficient intraday operation



*Centralized* dispatch for efficient real-time operation

# Factors to consider in electricity market design

- Measure real-time use and encourage competitive prices  
*price = marginal social cost = marginal social value → max social welfare*
- Complete market with time and location derivative forward products  
*efficient performance; deviations settled at real-time prices*





# One German price is unsustainable

## Even today, one price is false

- Dispatch must respect transmission constraints
- Redispatch payments impose large distortion in payments
- German redispatch cost €7.2 billion for 2020-22 (9% higher generation cost)

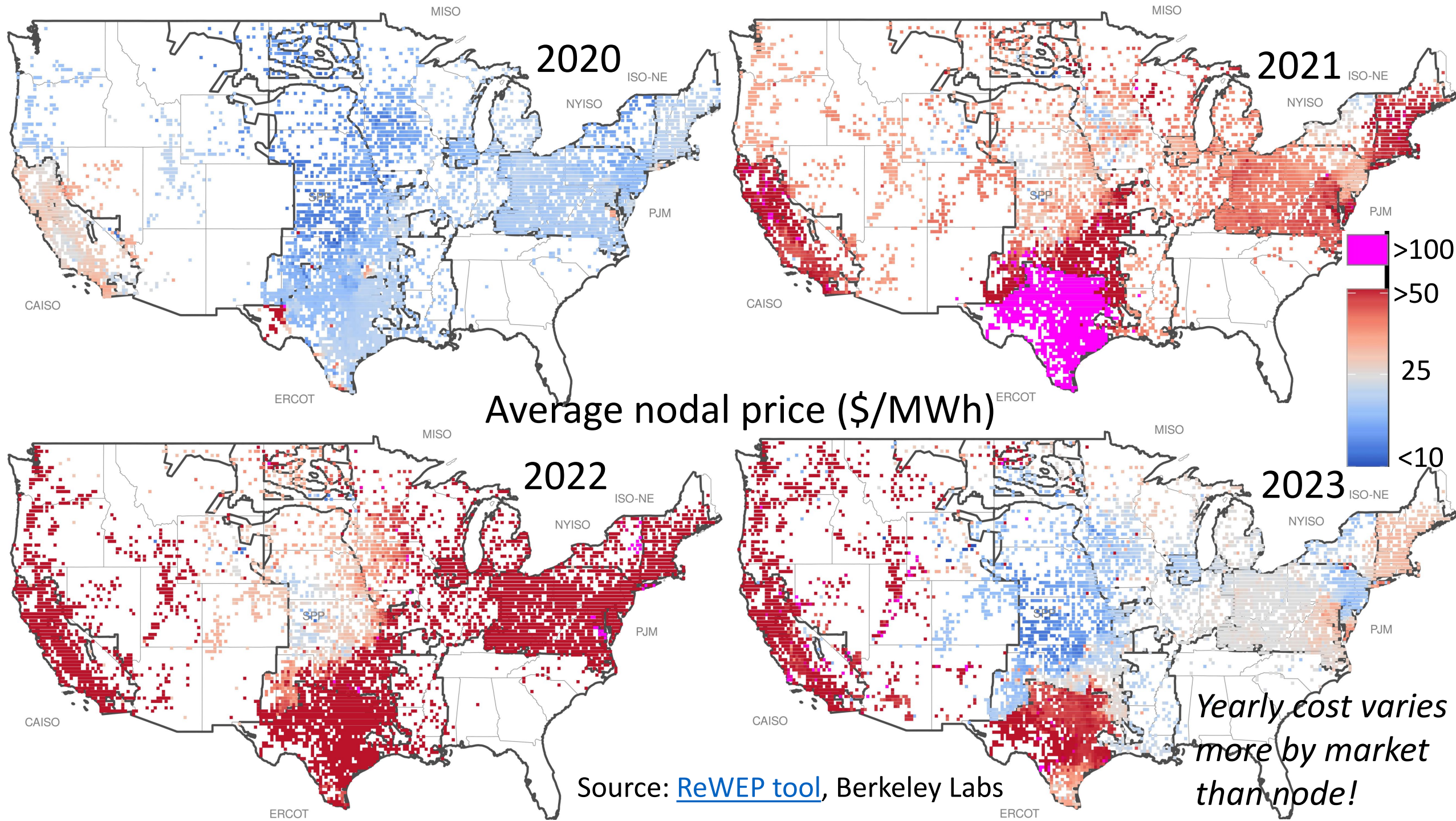
## Long-term cost is much greater as payments encourage poor siting

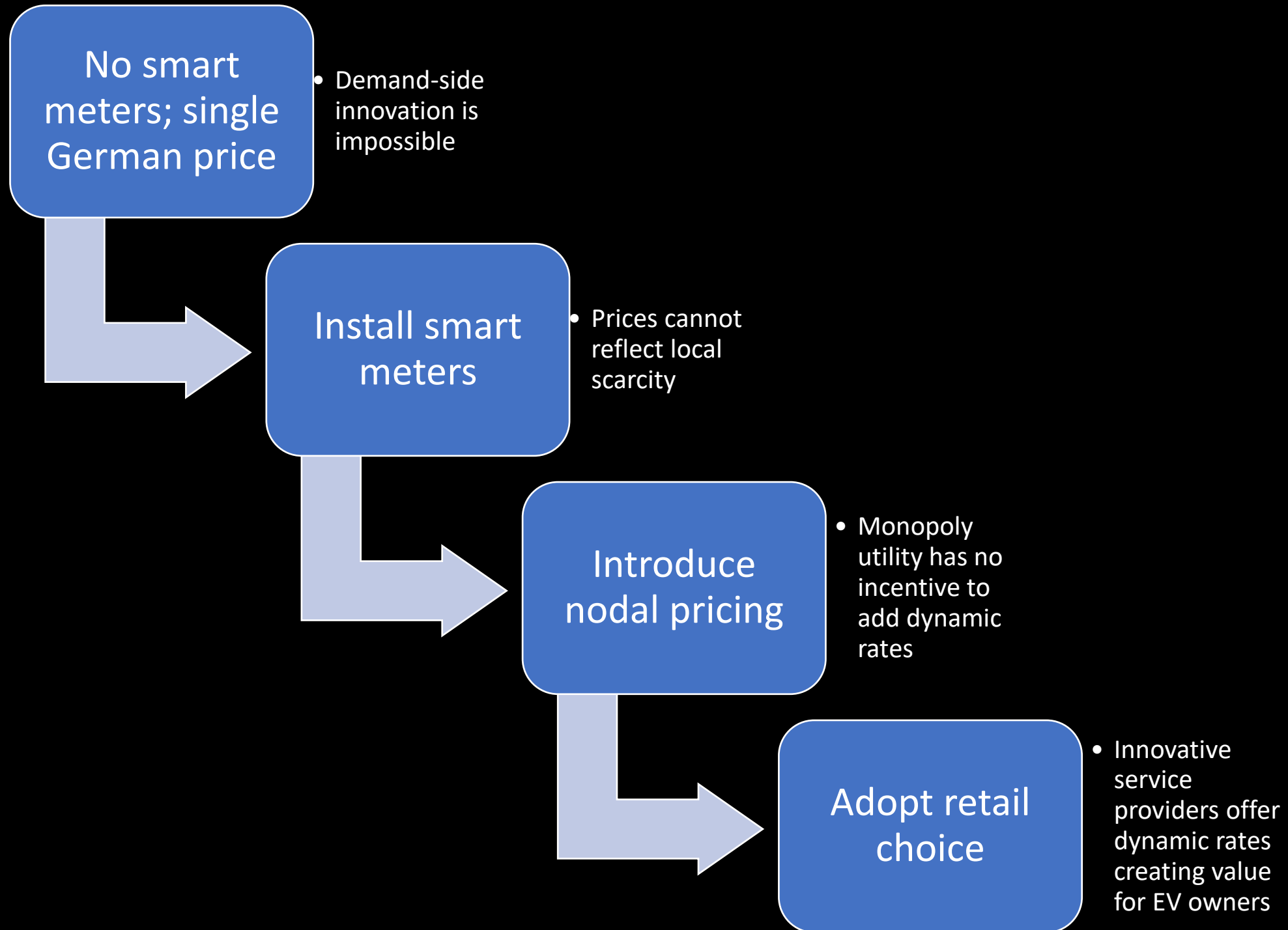
## German climate goals and one German price destroy the market

- Goals
  - Net zero, 100 % electric vehicles, high renewable penetration
- One price
  - Zero marginal cost for more than 90 percent of capacity
  - No price-responsive demand despite the huge quantity of batteries that would create and receive huge value to the system if price varied by time and location

## Zonal pricing does not work; only nodal supports least-cost dispatch

- Constraints vary by time, season, and circumstance; no stable zonal structure









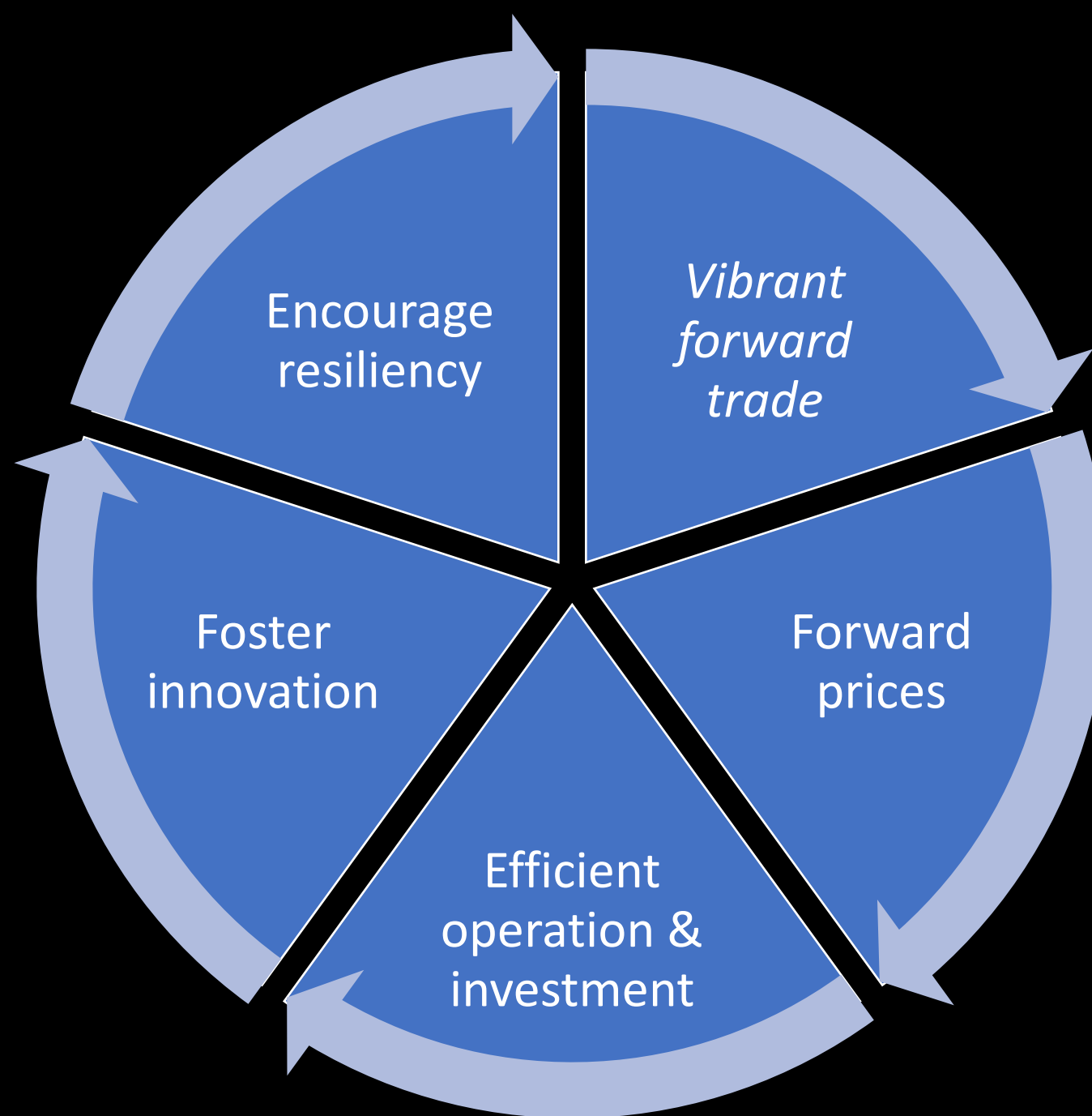
# A Forward Energy Market to Improve Resiliency



# Greater need for innovation and flexibility $\Rightarrow$ efficient price signals increasingly important

- Real-time market: security constrained economic dispatch (physical market)
  - Network and resources fully modeled
  - Co-optimize energy and reserves to maximize as-bid social welfare subject to network and resource constraints
  - High shortage price (e.g., \$5,000/MWh during reserve shortage) to provide sufficient incentives for operation and investment
  - Nodal pricing to reflect scarcity at time and location
    - Pretending no congestion does not work
      - German redispatch cost of €1.5 billion in 2018; wrong price signal; poor location incentives
- Day-ahead (posted 4pm) and intraday (every hour until real-time) market
  - Financial market with physical report of plans
  - Network and resources modeled for unit commitment (mixed-integer non-convex optimization)
  - Co-optimize energy and reserves to maximize as-bid social welfare subject to network and resource constraints
  - Intraday: re-optimize every hour to reflect current system state
    - Rolling intraday settlement
  - Nodal pricing to reflect scarcity at time and location
- Forward energy market (48 months to 1 day ahead)
  - Purely financial market
  - Network and resources are not modeled
  - Product is delivered energy in some future hour (MWh)
  - Delivery point may be an aggregation of withdrawal nodes into a load zone (as in done today in all markets)
  - For risk management, operation, and investment (resource adequacy)

*7.5 × Tesla Powerwall 3*

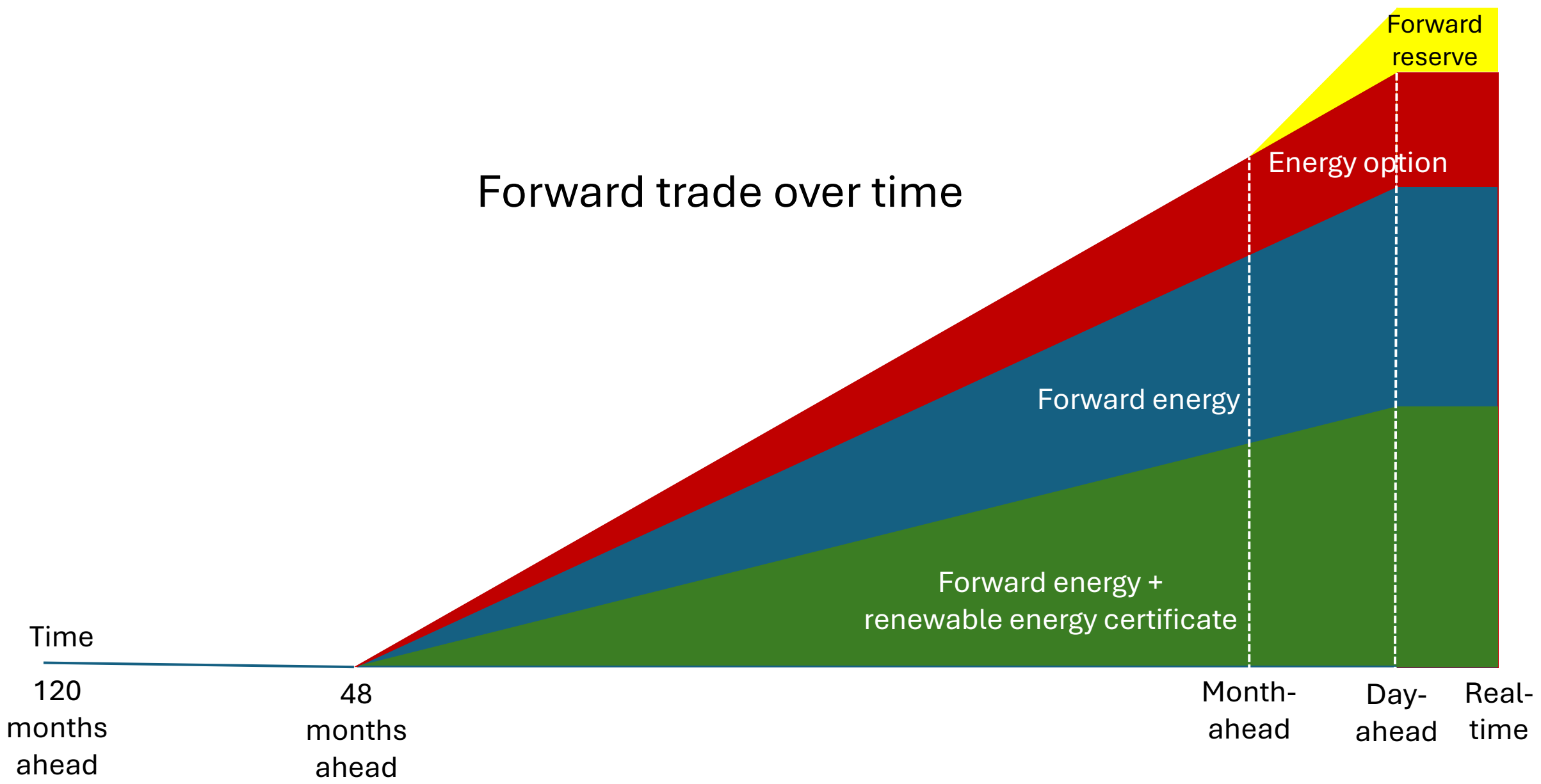


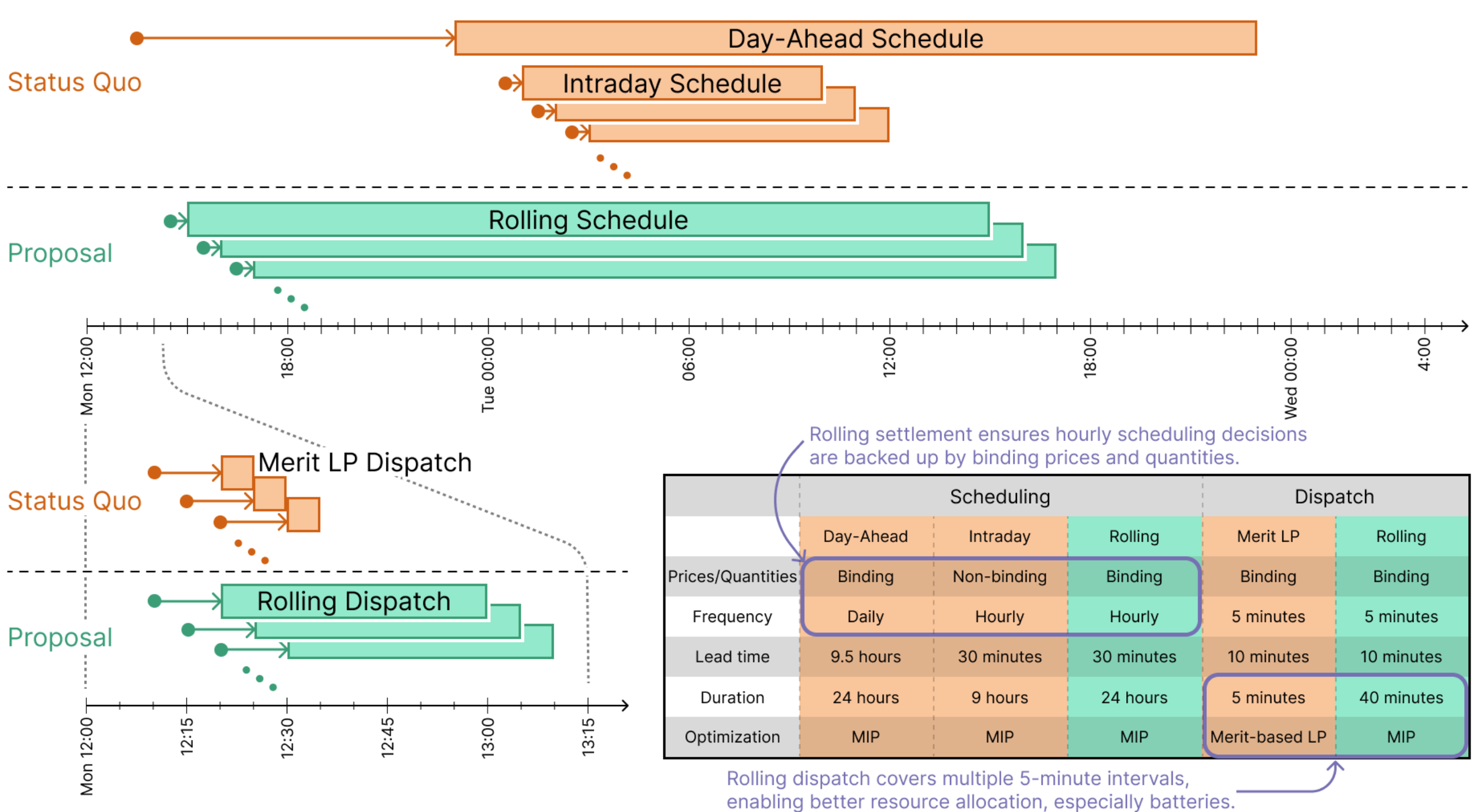


# Forward energy market

- Derivative of day-ahead energy (hourly)
- Monthly forward energy (up to 48 months forward)
  - Hourly, weekday or weekend, load zones
- Hourly forward energy (up to 30 days forward)
  - Hourly, load zones
  - Could also include hourly reserves by load zone
- Flow trading (Budish-Cramton-Kyle-Lee-Malec)
  - Persistent piecewise linear net demand for any product portfolio (rate of trade in MW as a function of price)
  - Cleared hourly
  - Unique prices and quantities, trivial computation
- Single key mandatory element
  - Load-serving entity obligation to buy *real-time demand* increases from 0% 48 months ahead to 100% day-ahead
  - Fulfilled with portfolio of forward energy + energy options
  - Energy options with high strike price (\$1000/MWh) provide hedge for price spikes from unanticipated demand during extreme events
- Conducted and settled by the system operator
- Transparent forward pricing and positions
- Flexible way to manage risk, operation, and investment
  - Participant moves smoothly from current position to target

# Forward trade over time







# Transparent forward prices updated hourly with ample liquidity



## Promote efficient investment

- Complete markets
- Reduce uncertainty
- Improve predictions



## Foster innovation

- Reduce risk
- Improve investment
- Improve operation
- Enhance competition



## Encourage resiliency

- Improve response to scarcity
  - More resources
  - Lower entry barriers
  - Higher price cap
- More innovation
  - Demand
  - Supply

# Reliability

Electricity system's ability to satisfy 100 percent of demand

Measures frequency, duration, and magnitude of shortage events

- system average interruption duration
- system average interruption frequency

Outages are short and localized, caused by routine events that cause demand to spike and supply to drop

- Failure of large units on a windless hot summer day

# Resilience

A system's ability to be robust to a wide range of environments

Events are rare and involve systemic failure of many elements

- Cyber attack, extreme cold, etc.

Drop in supply and spike in demand triggered by the same event

Events are system-wide, long in duration, and have implications for other critical infrastructure.



Mohammad Ali demonstrated resilience to Joe Frazier in 1971





## Electricity crises in North America and Europe since 2000

Resiliency event

California 2000-2001: arid year, unhedged utilities

Resiliency event

Northeast 2003: poor tree trimming, software bug

Resiliency event

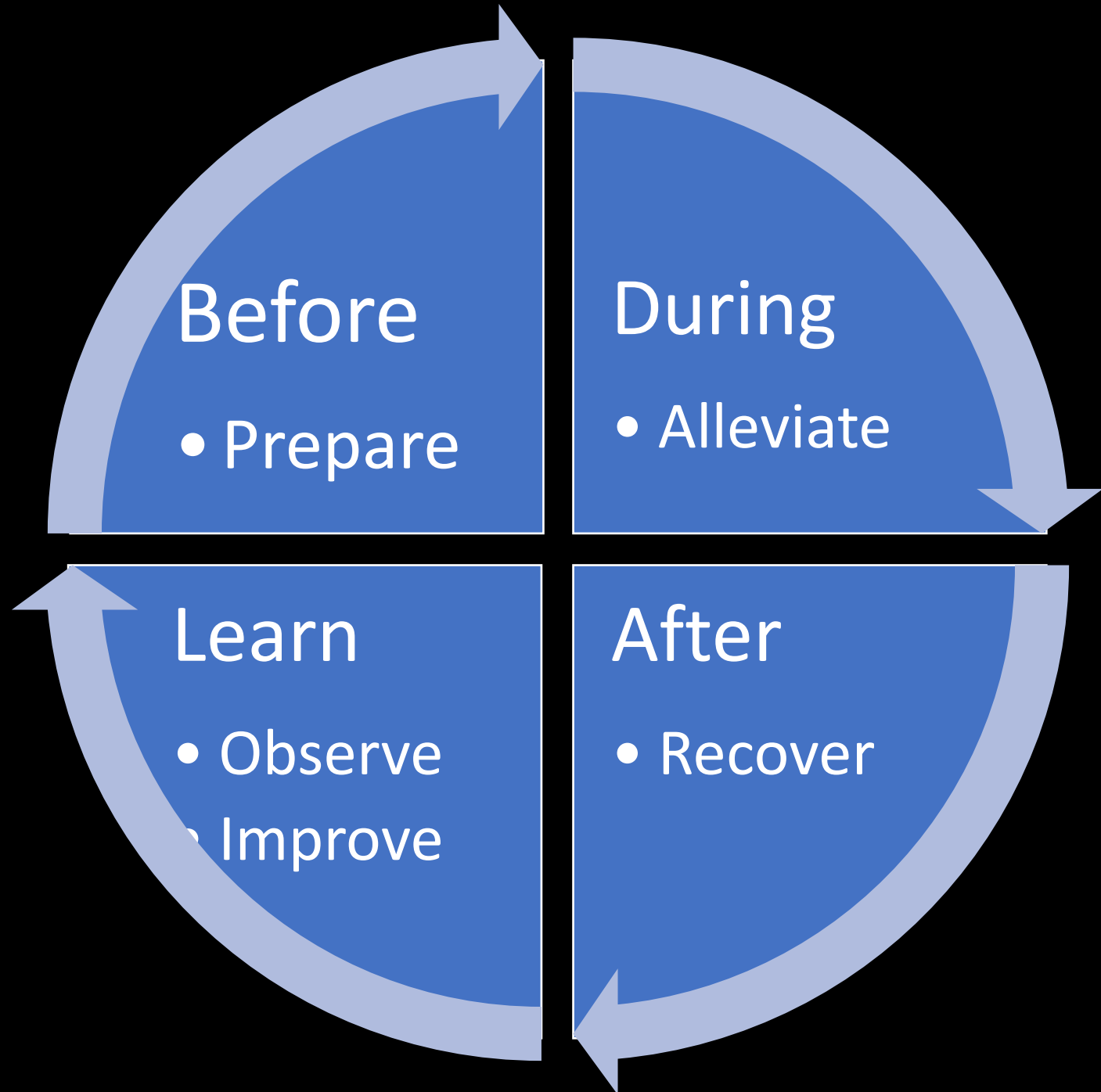
Texas February 2021: cold snap, electric heat, little gas

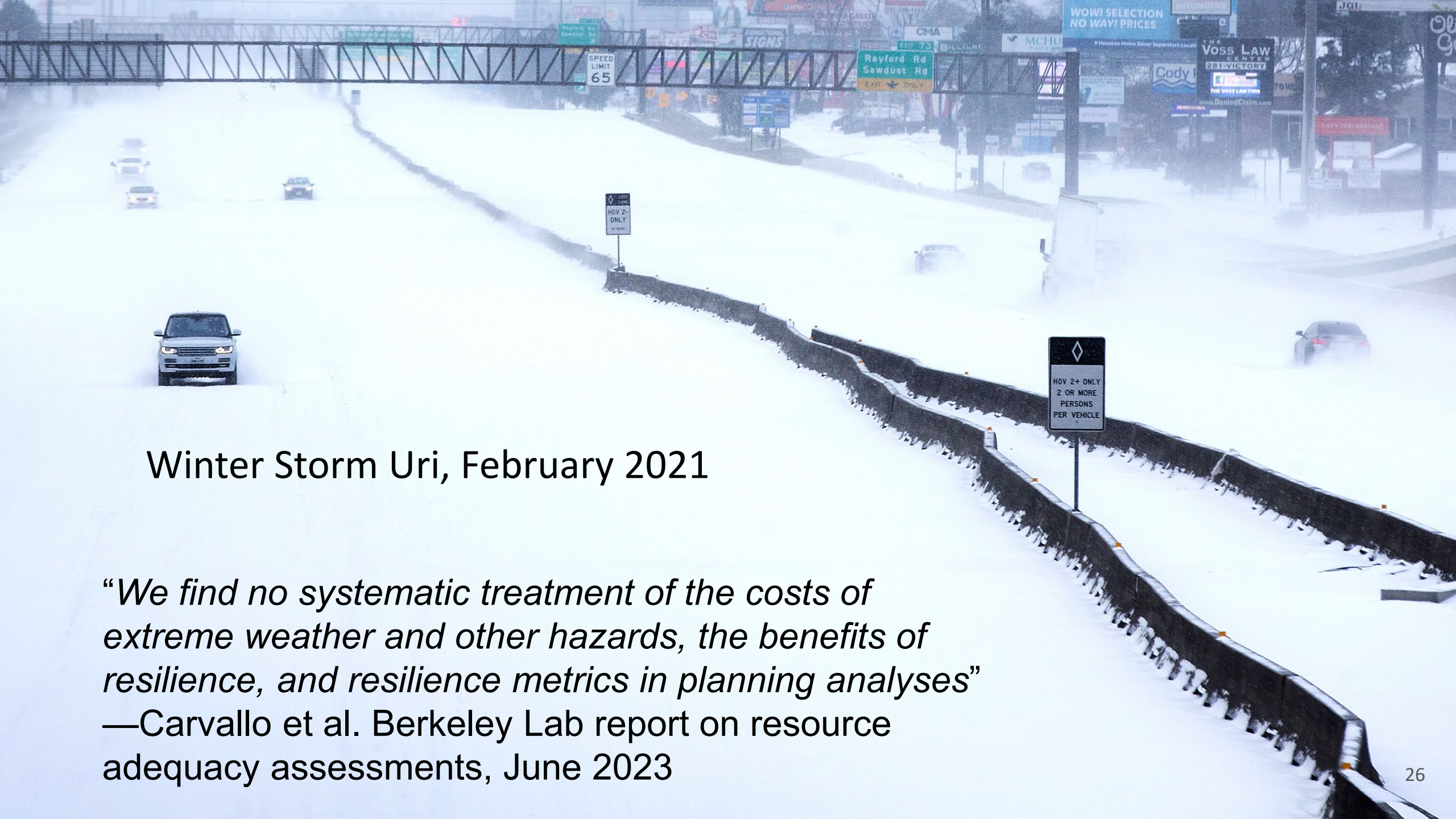
Resiliency event

Europe 2022: Russia's invasion of Ukraine, poor hedging

*Traditional resource adequacy eliminates none of these events!*

# Resilience



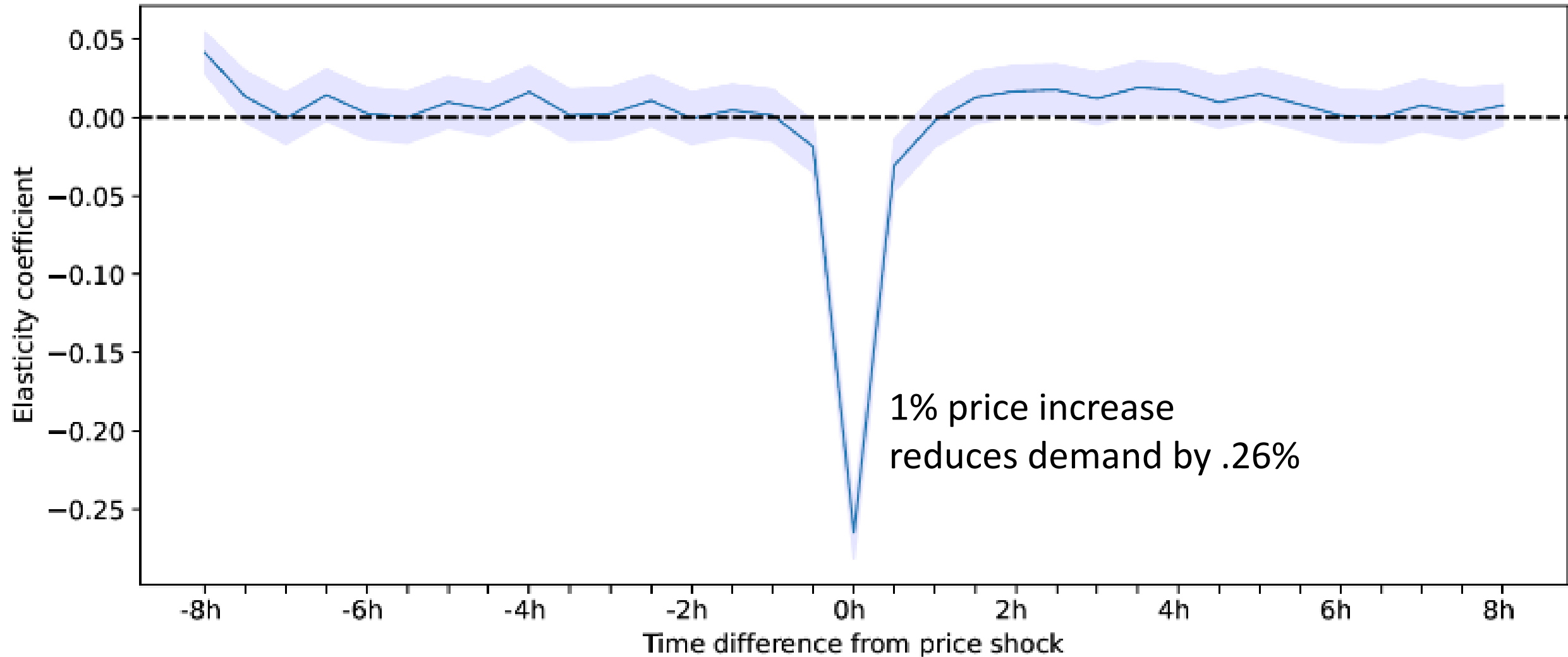


## Winter Storm Uri, February 2021

*“We find no systematic treatment of the costs of extreme weather and other hazards, the benefits of resilience, and resilience metrics in planning analyses”*  
—Carvallo et al. Berkeley Lab report on resource adequacy assessments, June 2023



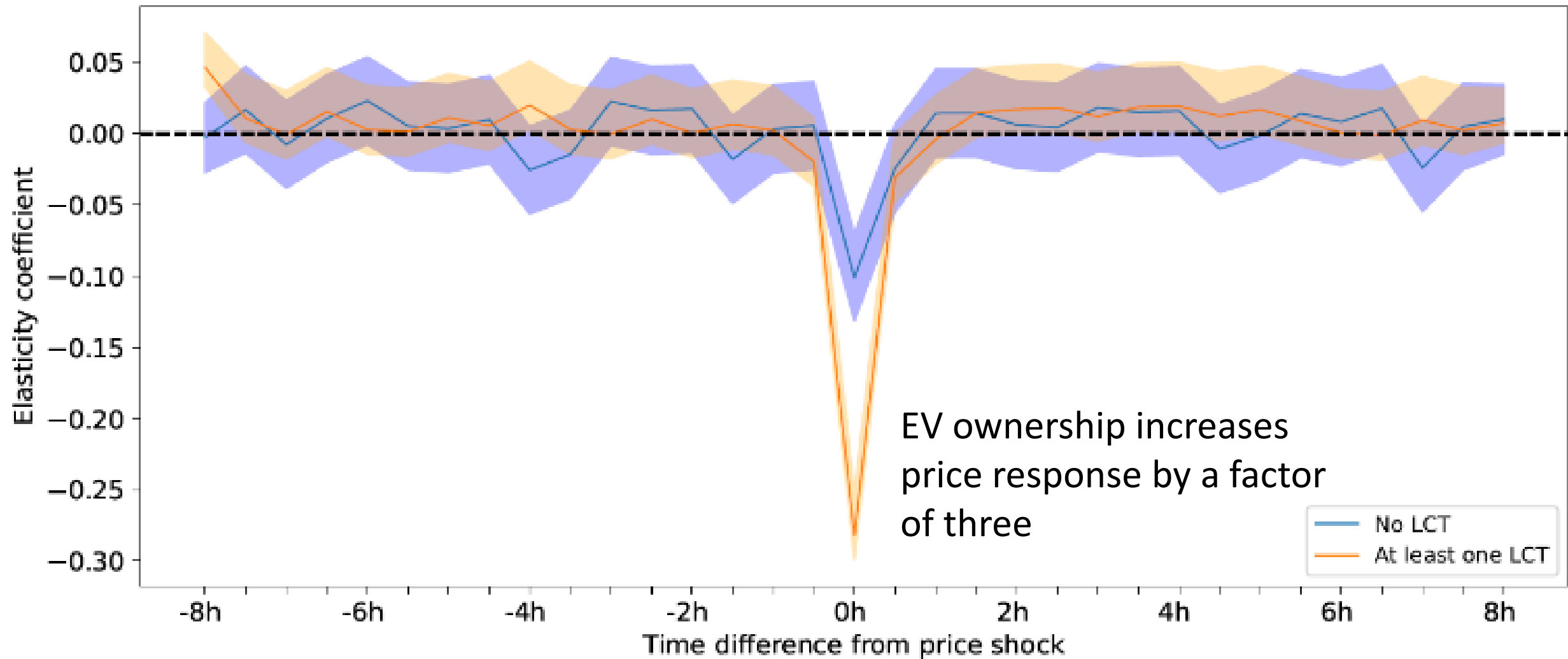
## Customers on dynamic rates respond to price, Britain 2020-21



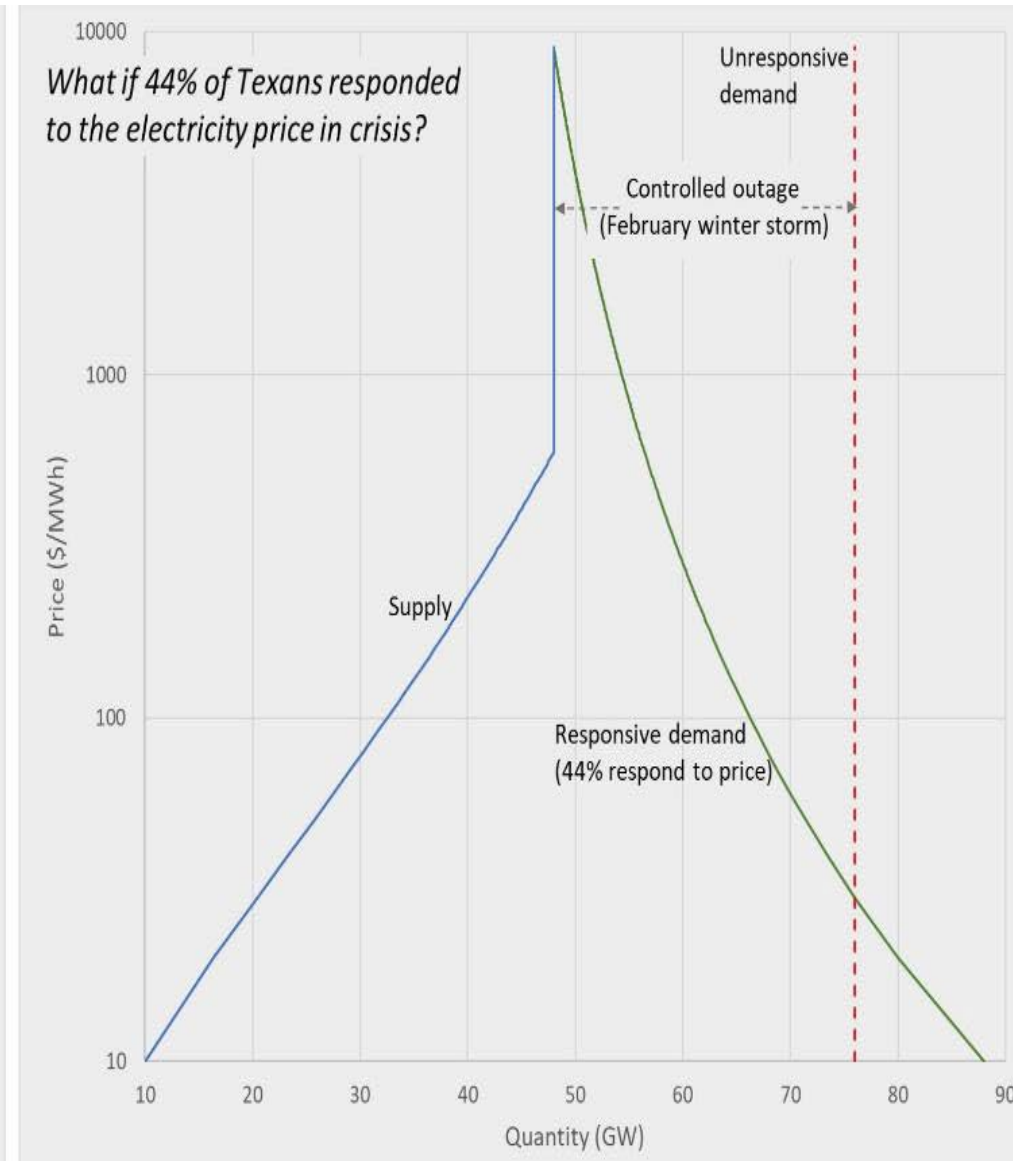
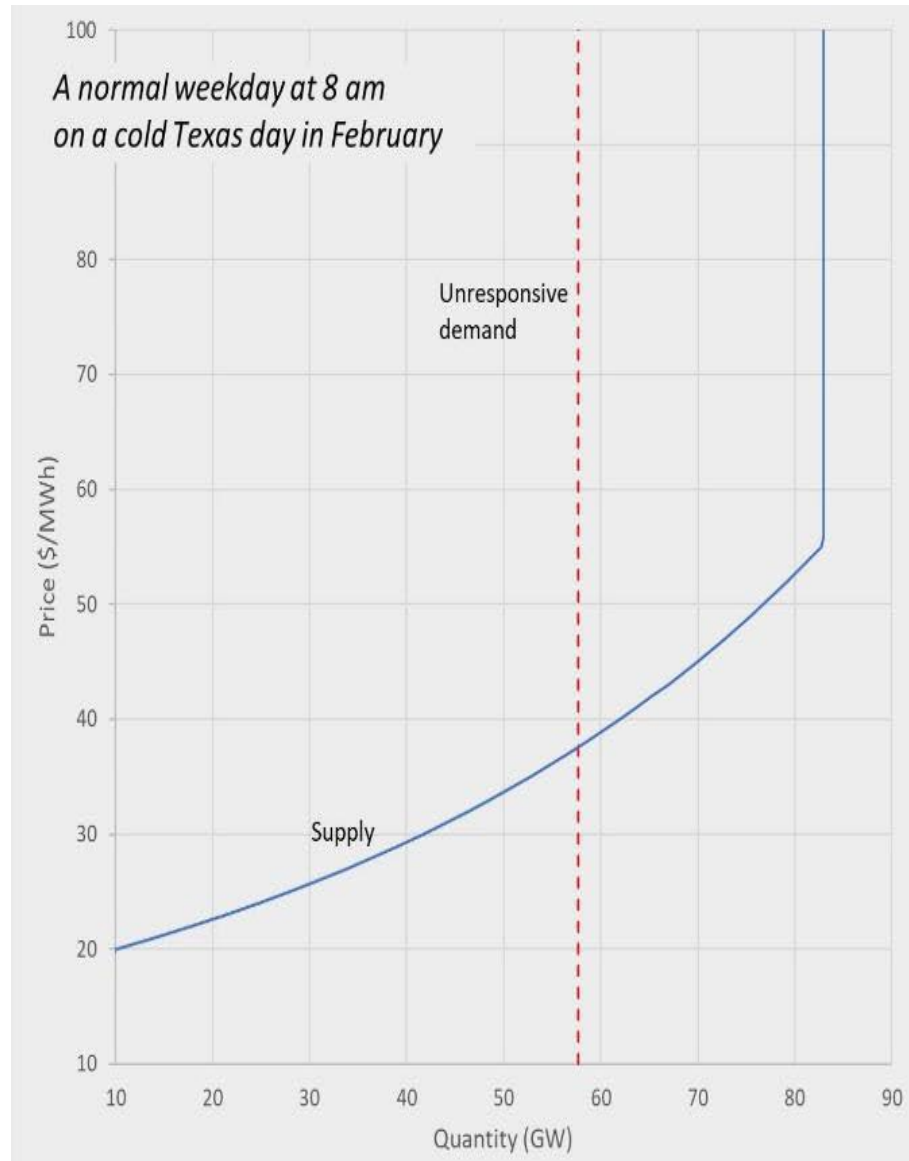
Emmanuele Bobbio, Simon Brandkamp, Stephanie Chan, Peter Cramton, David Malec, and Lucy Yu,  
[“Resilient Electricity Requires Consumer Engagement,”](#) Working Paper, University of Maryland, August 2023.



## Low-carbon technologies increase price response



## Price-responsive demand improves resiliency



Emmanuele Bobbio, Simon Brandkamp, Stephanie Chan, Peter Cramton, David Malec, and Lucy Yu, [“Resilient Electricity Requires Consumer Engagement,”](#) Working Paper, University of Maryland, August 2023.

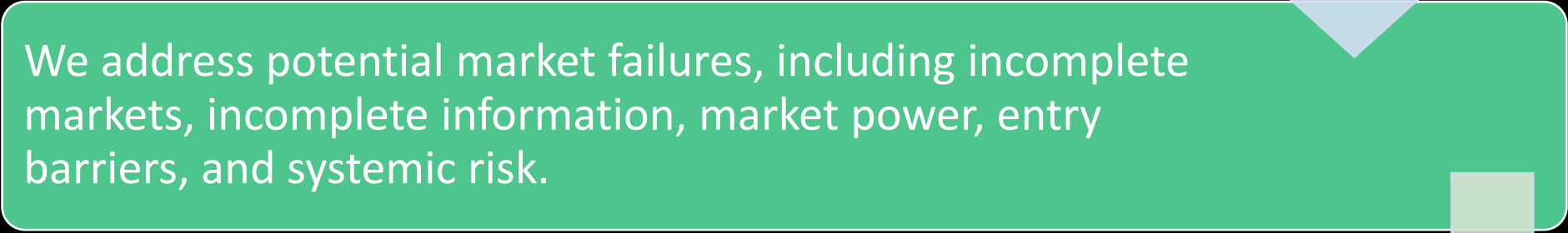
# System Operator Mission + Translation

ERCOT mission:

“We serve the public by ensuring a reliable grid, efficient electricity markets, open access, and retail choice.”



We address potential market failures, including incomplete markets, incomplete information, market power, entry barriers, and systemic risk.



We conduct transparent and efficient markets by pricing energy and ancillary services to maximize social welfare subject to network and resource constraints.



# Why the system operator should conduct the market

- Zero transaction costs (included in existing fees)
- Complements day-ahead and real-time markets, emphasizing transparency and efficiency
- Leverages information already maintained by system operator
- Accommodates many products
- Allows parties to manage climate goals or jurisdiction-specific requirements
- Allows system operator to establish highly optimized collateral requirements that would maximize the resiliency of the market to systemic events with minimal collateral based on deviations from balanced positions
- Addresses resource adequacy, eliminating the need for a capacity market
  - Modest LSE obligation to buy coordinates trade





# Key features

## Fine granularity in time and location

- Flexibility to trade consistent with needs and capabilities

## Gradual coordinated trade

- Reduces risk and market power
- Robust clearing prices

## Persistent portfolio flow orders

- Easy participation with effective trade-to-target strategies



## Capacity auction

ISO "Big event" annual auction, three years ahead

ISO Administrative quantity for 100% of forecast

ISO Administrative cost of new entry to set price

ISO Administrative capacity value to set quantity

ISO Administrative demand curve with floor and ceiling on offers

ISO Administrative money transfer from load-serving entities to generators



## Forward energy market

ISO Hourly auctions, up to four years ahead with fine granularity in time and location

ISO Optimized collateral based on position imbalance to minimize default risk

MP = Gradual purchase of forward energy, energy options, and renewable energy credits

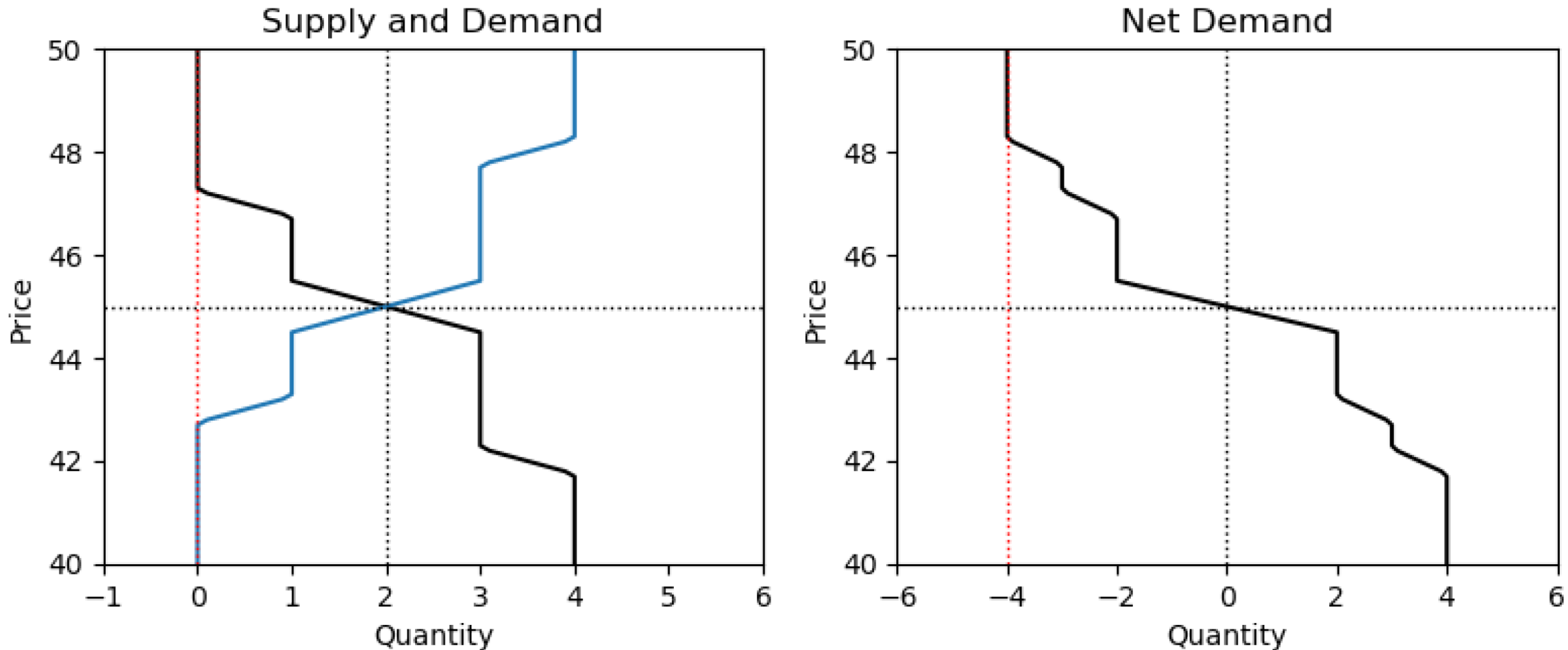
market participant

MP Increasing obligation on load-serving entities to purchase realized load by day-ahead

MP Flexibility to purchase when and what you need to best manage risk and position

MP Robust prices for innovation and efficient investment and operation

# Market design, properties, and feasibility



Infer quadratic utility from “as-bid” linear portion of demand schedule

$$V_i(x) = p_i^H x - \frac{p_i^H - p_i^L}{2q_i} x^2 \quad (6)$$

Exchange solves the problem of finding quantities  $\mathbf{x} = (x_1, \dots, x_I)$  to solve

$$\max_{\mathbf{x}} \sum_{i=1}^I V_i(x_i) \quad \text{subject to} \quad \begin{cases} \sum_{i=0}^I x_i \mathbf{w}_i = \mathbf{0} & \text{(market clearing)} \\ 0 \leq x_i \leq q_i \text{ for all } i & \text{(order execution rate),} \end{cases} \quad (7)$$

**Theorem 1** (Existence and Uniqueness of Optimal Quantities). *There exists a unique quantity vector  $\mathbf{x}^*$  which solves the maximization problem (7)*

**Theorem 2** (Existence of Market Clearing Prices). *There exists at least one optimal solution  $(\boldsymbol{\pi}^*, \boldsymbol{\lambda}^*, \boldsymbol{\mu}^*)$  to the dual problem (11). The solutions  $\mathbf{x}^*$  and  $(\boldsymbol{\pi}^*, \boldsymbol{\lambda}^*, \boldsymbol{\mu}^*)$  are a primal-dual pair which satisfies the strict duality relationship*

$$\mathbf{g}^* = V(\mathbf{x}^*). \quad (12)$$

*Corollary 1 Uniqueness of quantities and prices.* Prices and quantities are unique with the closest-to-prior-prices rule.

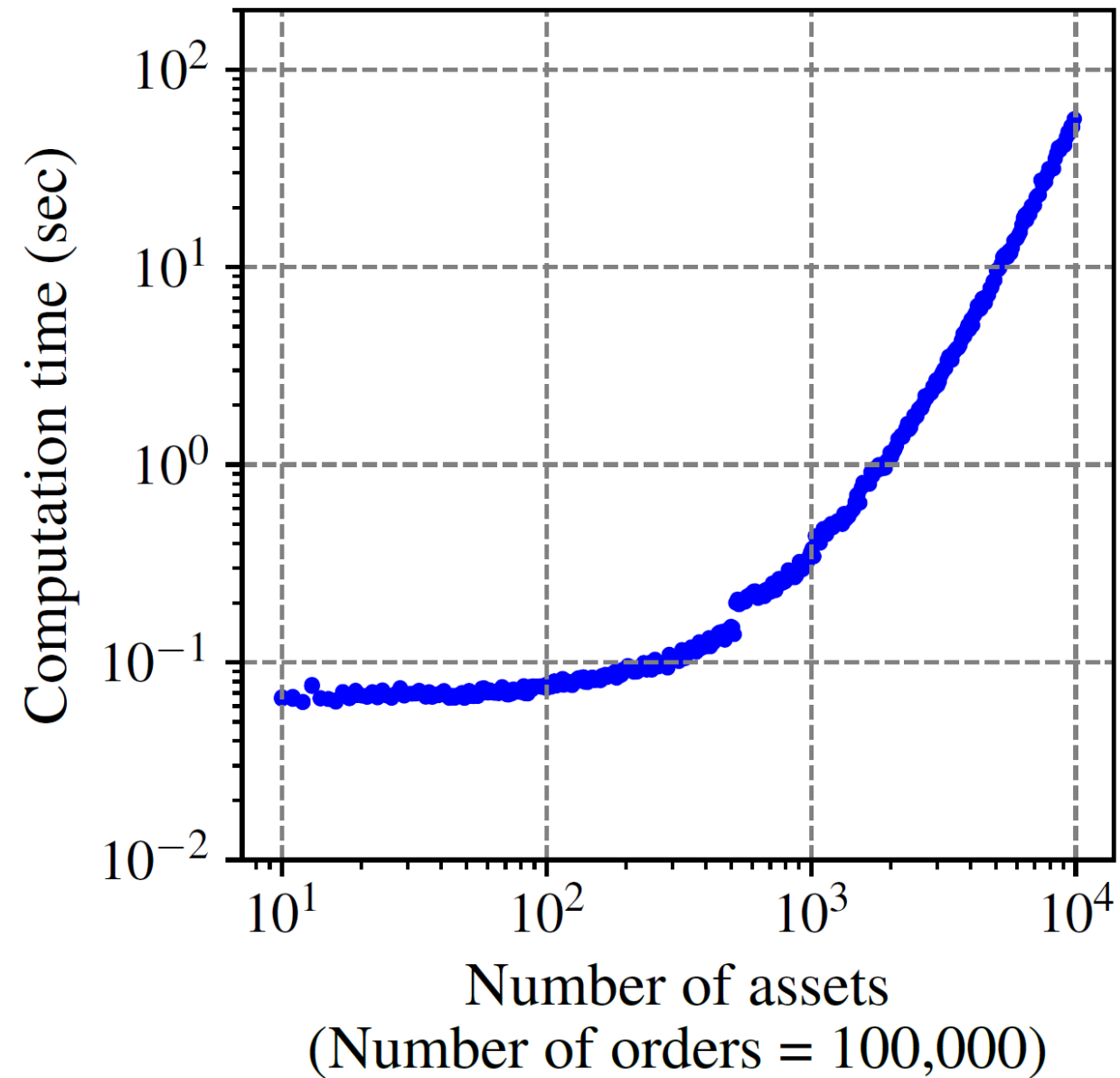
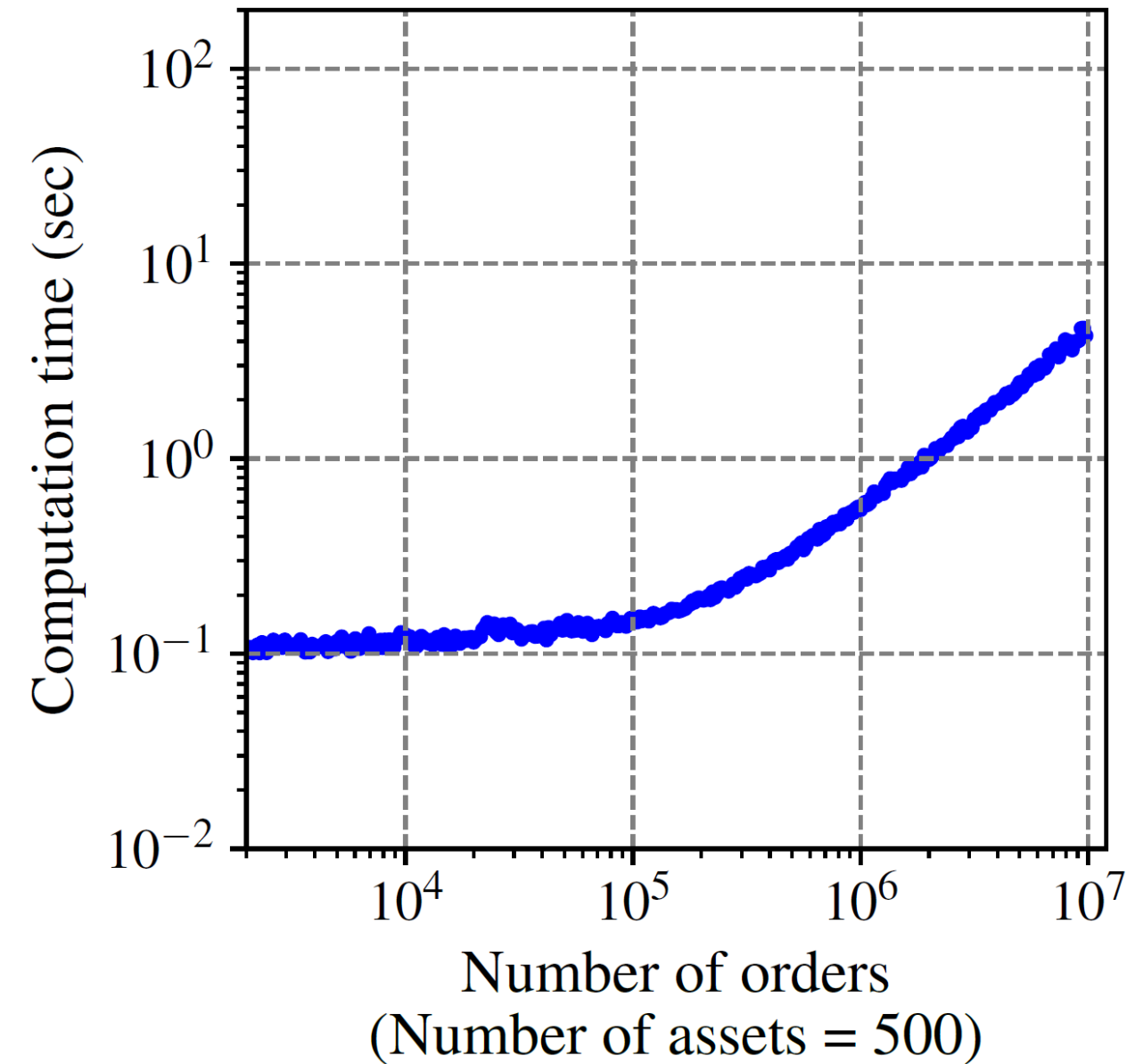




# Can we find unique prices and quantities quickly?

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- Quadratic optimization with linear constraints and near-separability (product-by-product optimization is close to optimal)
- Problem is nearly identical each hour
- Strategy
  - Warm start from prior solution
  - Use alternating direction method of multipliers (Boyd et al. 2011)  
(interior point methods also work well but are harder to warm start)
- We are performing large problem tests to confirm computational feasibility



# Participating in market is straightforward

- Inputs
  - Current position
  - Expected net demand by hour
  - Net demand by hour in extreme event
  - Expected day-ahead energy price by hour
  - Risk attitude and cost of capital
- Trade-to-target strategy
  - Adjustment to reach target (MWh)
  - Flow rate to reach target (MW)
  - Slope of net demand curve: how much does flow rate increase with a \$1/MWh price decrease (MW)?







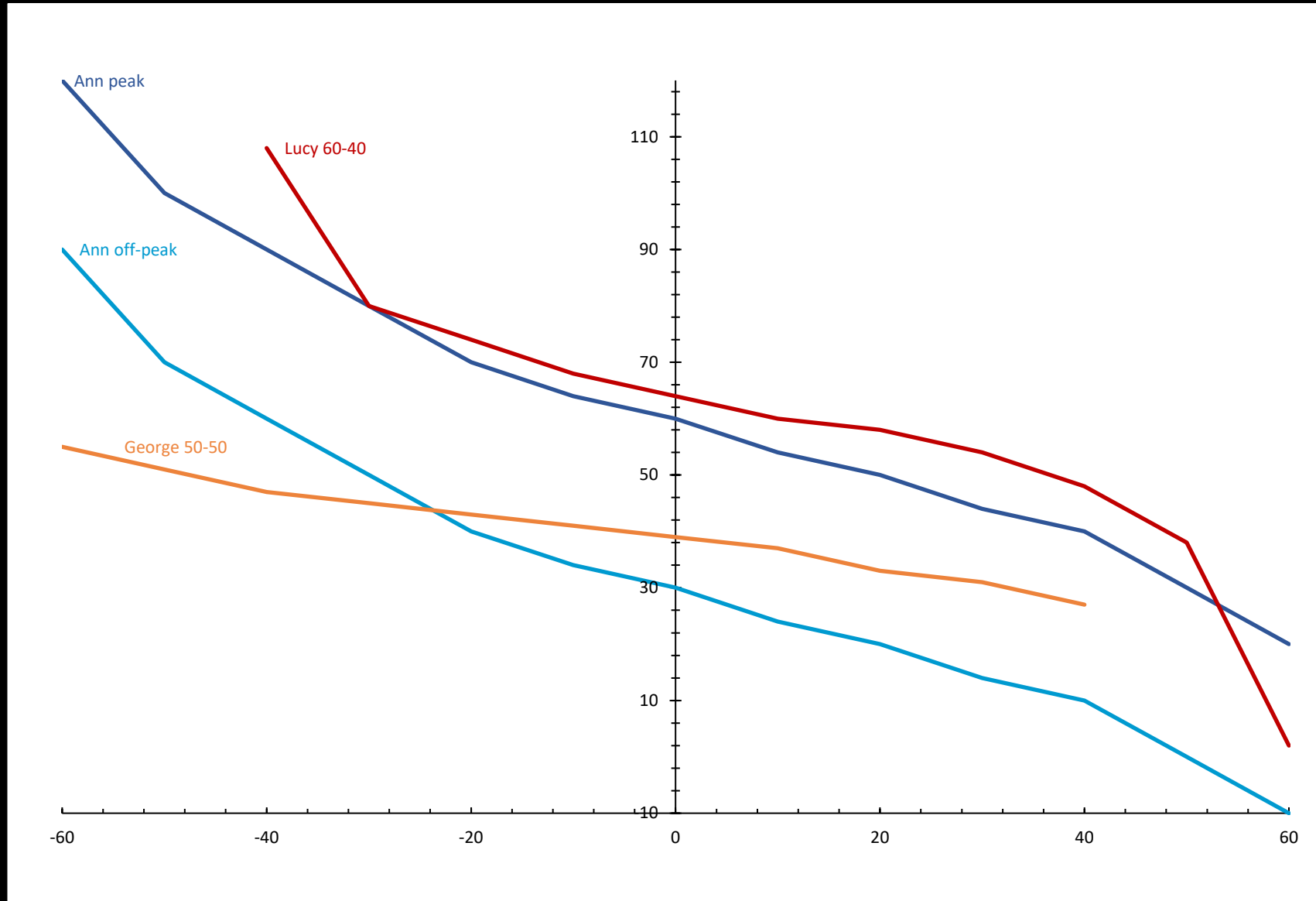
An example:  
2 products,  
3 participants

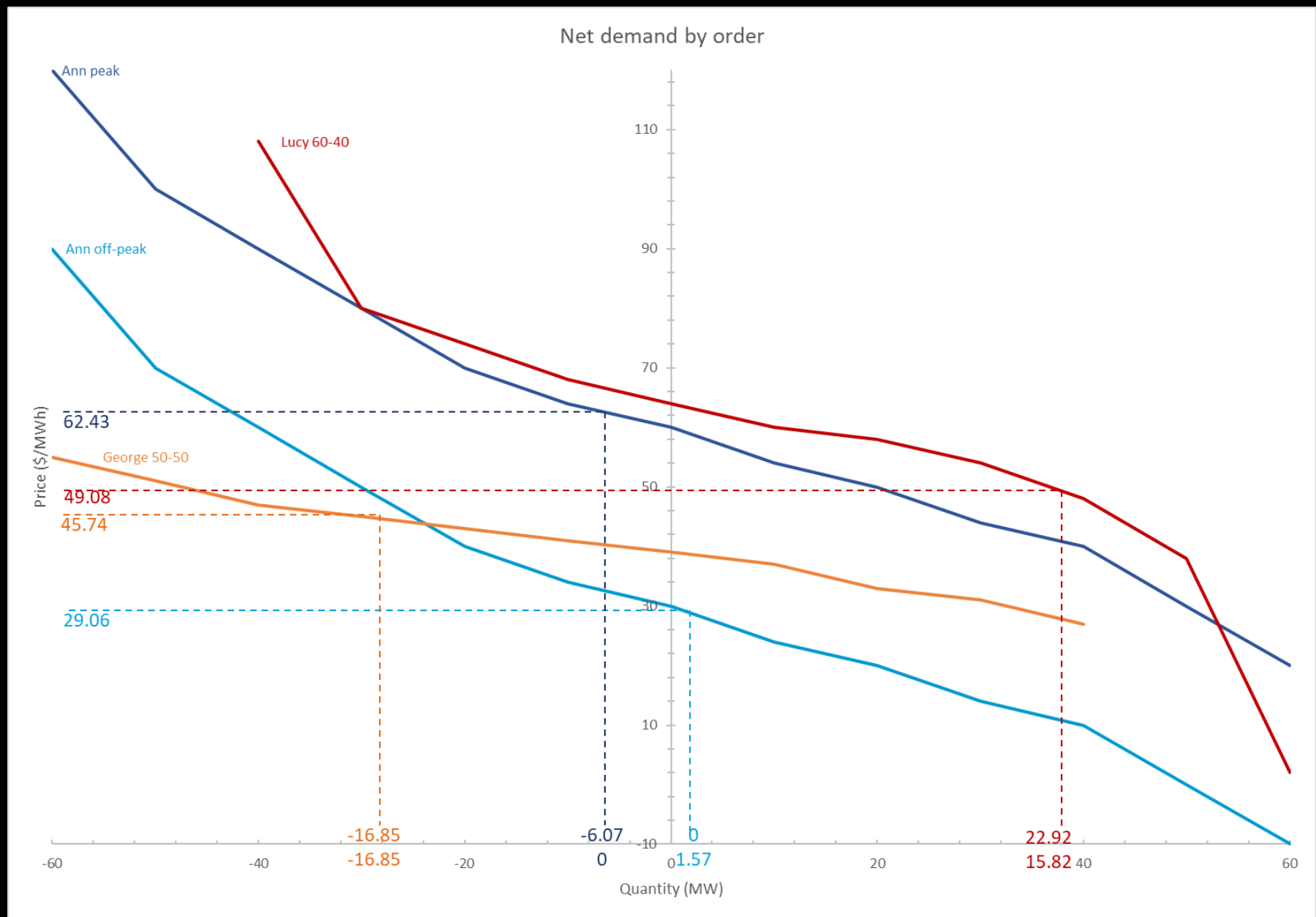
Sell

Buy

	Price (\$/MWh)			
Quantity MW	Ann peak	Ann off-peak	George 50-50	Lucy 60-40
-60	120	90	55	
-50	100	70	51	
-40	90	60	47	108
-30	80	50	45	80
-20	70	40	43	74
-10	64	34	41	68
0	60	30	39	64
10	54	24	37	60
20	50	20	33	58
30	44	14	31	54
40	40	10	27	48
50	30	0		38
60	20	-10		2

[Interactive Demo]





# Architecture

## Applications

Participants bid portfolios in domain-specific language  
Portfolio is any linear combination of many products

### Energy Market

- 400,000 products, MWh by time and location
- Houston, 4-5pm, weekday, July 2027

### Communications Market

- Million products, MB by time and location
- Tokyo premium, 10-11am, weekday, July 2027

### Transportation Market

- Million products, airport slots by time and location
- CDG, 16.50-17.00, Fri, July 2025

### Other Applications

- Bonds, equities, or other commodities

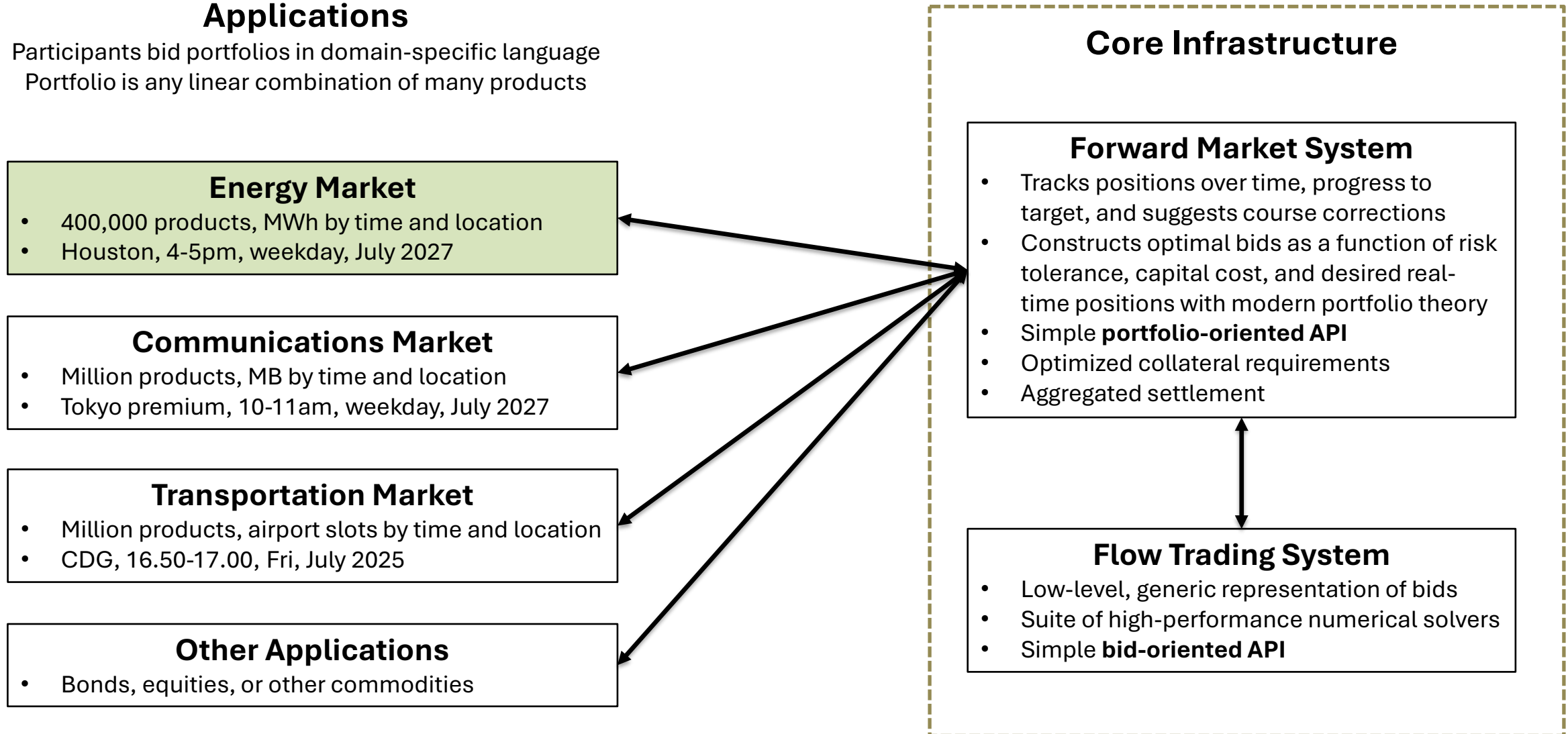
## Core Infrastructure

### Forward Market System

- Tracks positions over time, progress to target, and suggests course corrections
- Constructs optimal bids as a function of risk tolerance, capital cost, and desired real-time positions with modern portfolio theory
- Simple **portfolio-oriented API**
- Optimized collateral requirements
- Aggregated settlement

### Flow Trading System

- Low-level, generic representation of bids
- Suite of high-performance numerical solvers
- Simple **bid-oriented API**





# Flow Trading System



## API Server

GET /orders  
POST /orders  
GET /orders/:ID  
DELETE /orders/:ID  
GET /products/:KIND/:FROM/:THRU[?by=:BY]

+ background thread to trigger batch solves



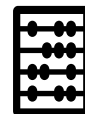
## Database

order	
id	serial
entity	text NN
reference	text NN
demand	point[] NN
portfolio	entry[] NN
min_balance	decimal
max_balance	decimal
received	timestampz NN
canceled	timestampz
stopped	timestampz

order_status	
order_id	integer NN
batch_id	timestampz NN
trade	decimal NN
price	decimal
balance	decimal NN

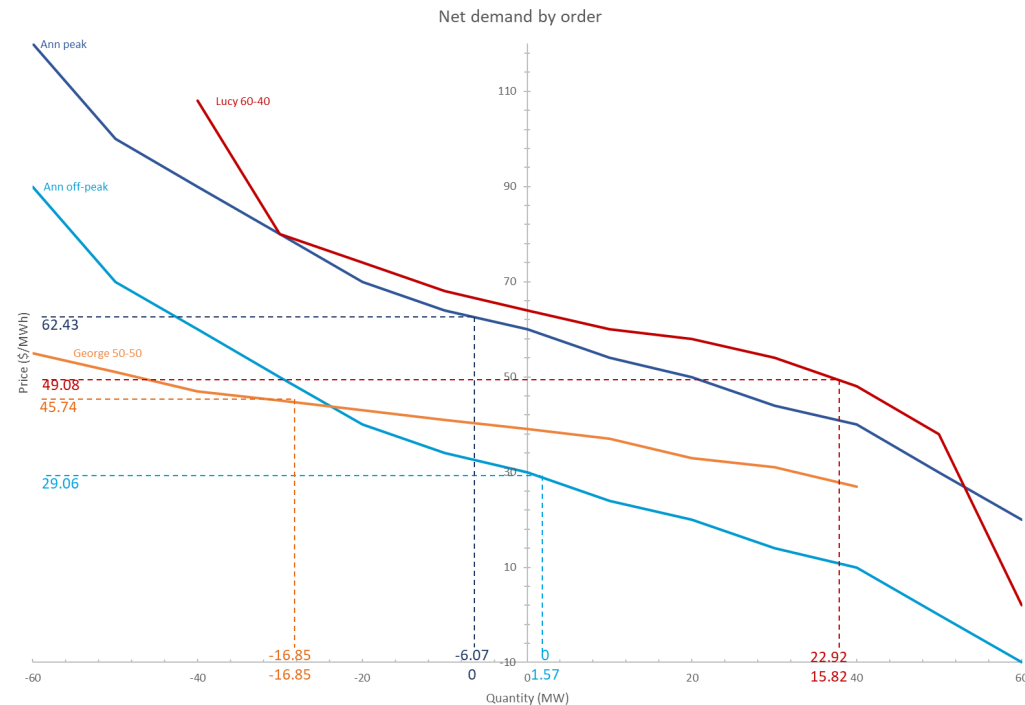
product_status	
batch_id	timestampz NN
kind	text NN
from	timestampz NN
thru	timestampz NN
price	decimal

batch	
id	timestampz
queued	timestampz
solved	timestampz



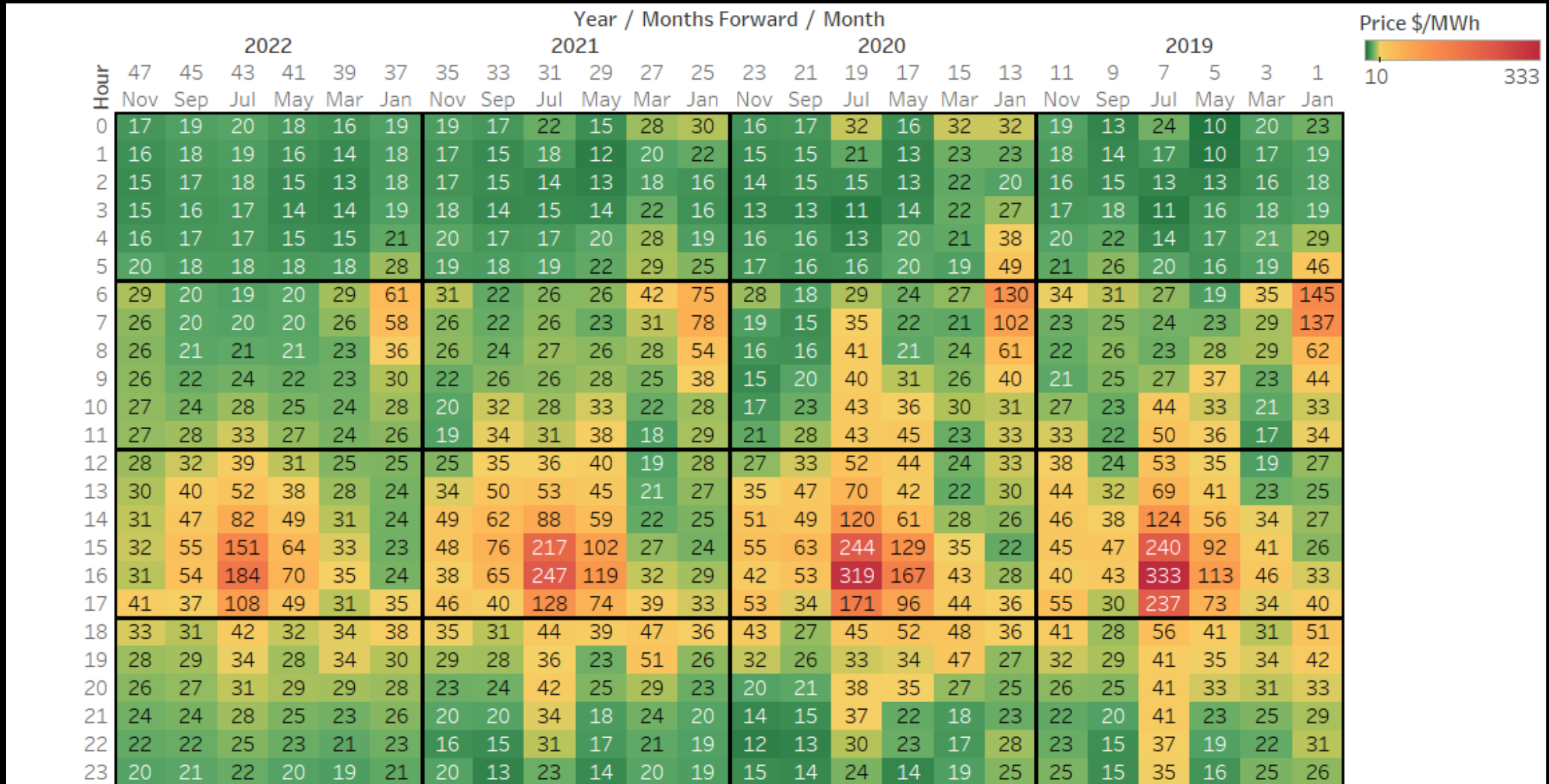
## Optimization Engine

$$\min_{\vec{a} \leq \vec{x} \leq \vec{b}} \frac{1}{2} x^T D x - p^T x \quad s.t. \quad W \vec{x} = \vec{0}$$



# Monthly forward prices, Houston, weekday (\$/MWh)

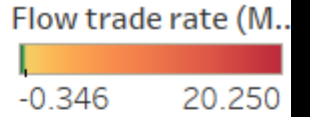
48 to 1 month ahead ( $48 \times 24 = 1152$  monthly products per load zone)



*Prices are highest at 4pm in July (seasonal and hourly effects)*

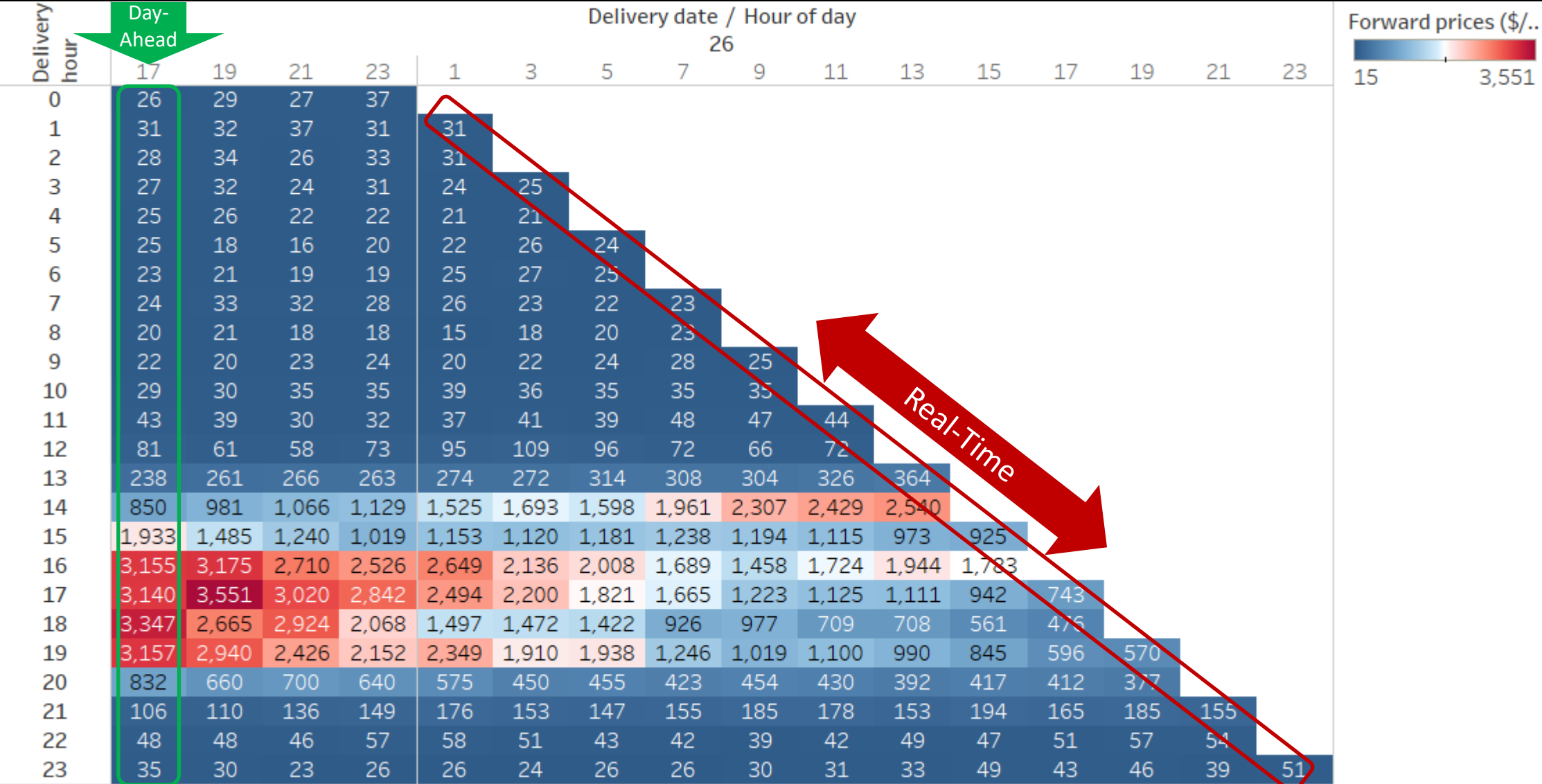
# Flow trade rate (MW) of 4GW Load Serving Entity using straightforward strategy

Hour	Month / Days Forward / Day														
	Jul										Jun				
	29 19	27 17	25 15	23 13	21 11	19 9	17 7	15 5	13 3	11 1	9 29	7 27	5 25	3 23	1 21
0	0.031	0.002	-0.018	0.016	-0.003	0.002	0.033	0.142	0.201	0.001	0.020	0.023	-0.312	1.271	10.510
1	0.026	-0.003	-0.023	0.006	-0.019	-0.012	0.017	0.127	0.174	-0.040	0.009	-0.035	-0.156	1.139	8.798
2	0.017	0.000	-0.017	0.013	-0.019	-0.020	-0.002	0.108	0.119	-0.099	0.011	-0.023	0.089	0.280	3.070
3	0.014	0.002	-0.005	0.020	-0.012	-0.010	0.001	0.106	0.086	-0.119	-0.005	-0.024	0.307	0.438	3.511
4	0.009	0.000	-0.009	0.022	0.000	0.016	0.006	0.099	0.067	-0.128	-0.031	-0.103	0.244	1.186	8.013
5	0.009	0.003	-0.003	0.021	-0.005	0.014	0.010	0.103	0.085	-0.112	-0.027	-0.141	0.135	1.880	11.952
6	0.012	0.003	-0.006	0.028	-0.006	0.012	0.005	0.100	0.084	-0.104	-0.023	-0.162	0.005	1.960	13.054
7	0.019	0.009	0.001	0.032	-0.008	0.001	0.009	0.100	0.089	-0.126	-0.030	-0.199	-0.160	1.886	14.221
8	0.022	0.011	0.007	0.040	-0.009	-0.009	-0.001	0.083	0.053	-0.189	-0.074	-0.163	-0.124	1.339	11.296
9	0.023	0.009	0.001	0.037	-0.009	-0.024	-0.010	0.076	0.052	-0.210	-0.095	-0.101	0.105	1.203	8.633
10	0.023	0.003	-0.006	0.033	-0.013	-0.036	-0.025	0.076	0.057	-0.195	-0.109	-0.037	0.230	0.992	6.839
11	0.023	0.002	-0.011	0.028	-0.008	-0.031	-0.008	0.094	0.079	-0.170	-0.081	-0.002	0.334	0.543	3.842
12	0.022	0.003	-0.007	0.029	-0.003	-0.020	0.002	0.117	0.104	-0.149	-0.043	0.018	0.229	0.499	4.418
13	0.019	0.002	-0.007	0.023	-0.003	-0.003	0.029	0.139	0.119	-0.141	-0.073	-0.069	0.181	0.454	4.499
14	0.015	-0.001	-0.007	0.028	-0.006	-0.007	0.014	0.133	0.120	-0.148	-0.126	-0.156	0.060	1.311	9.754
15	0.015	0.000	-0.007	0.022	-0.009	-0.009	-0.004	0.107	0.119	-0.135	-0.133	-0.156	0.133	2.231	14.747
16	0.016	-0.002	-0.010	0.017	-0.012	-0.009	-0.010	0.099	0.129	-0.096	-0.091	-0.159	-0.147	2.755	19.144
17	0.016	0.000	-0.008	0.015	-0.011	-0.009	-0.017	0.095	0.131	-0.100	-0.045	-0.118	-0.182	2.748	20.250
18	0.015	-0.002	-0.012	0.019	-0.011	-0.009	-0.003	0.111	0.138	-0.082	-0.033	-0.107	-0.346	1.610	14.574
19	0.013	0.003	-0.008	0.025	-0.012	-0.016	-0.007	0.106	0.123	-0.113	-0.075	-0.110	-0.201	1.039	10.604
20	0.011	-0.001	-0.013	0.022	-0.006	-0.013	0.006	0.099	0.114	-0.129	-0.121	-0.161	-0.167	0.486	6.688
21	0.013	-0.004	-0.017	0.023	0.006	-0.004	0.020	0.117	0.116	-0.134	-0.088	-0.119	-0.050	2.052	14.807
22	0.014	-0.008	-0.024	0.022	0.010	0.002	0.022	0.109	0.118	-0.117	-0.050	-0.128	-0.119	2.380	17.653
23	0.012	-0.012	-0.024	0.029	0.011	-0.003	0.014	0.106	0.115	-0.091	-0.006	-0.143	-0.153	2.360	17.893



*Flow trade rate is tiny until one day before day-ahead!*

Intraday Prices, Houston, 26 August 2023 (\$/MWh), odd hours  
( $24 \times 7 + 23 + 22 + \dots + 1 = 444$  new prices)



*Rolling settlement especially important on summer net peak days!*



# Detailed market simulation (to be done)

- Backcast for ERCOT, 2011-2023
  - Forecast load and renewable production (net load)
  - Forecast day-ahead price on forward basis
  - Develop parameterized trade-to-target strategies for natural buyers and sellers
    - LSEs have target positions increasing from 0% to 100% from 48 months to day-ahead, including portfolio of forward energy + energy options
    - LSEs deviate from target positions based on slope parameter (net demand)
    - Generators have target positions increasing from 0% to 100% from 48 months to day-ahead
    - Generators deviate from target positions based on slope parameter (net demand)
  - Optimize parameters to determine equilibrium (approximate best responses)
  - Evaluate risk relative to unhedged positions except day-ahead market hedges real-time price risk
  - Develop collateral requirements that assure resiliency
- Forecast same market but with simulated spot market using estimated resource structure
  - Midway through the energy transition (2040?)
  - At the end of the energy transition (2060?)

## Computation at secure umd.edu facility

- Compute is handled by three 96-core AMD EPYC 4th gen servers
  - 288 cores total running at 2.4GHz base / 3.7GHz boost
  - 1,152GB of DDR5 RAM total running at 4800MT/s (2GB per core)
  - Platform supports 512-bit advanced vector operations (AVX-512)
- High per-server core density lets us trade off speed and efficiency:
  - Assign many cores per problem: fastest time-to-solution, fewer solutions/hour
  - Assign one core per problem: Most solutions/hour, slower time-to-solution
- Data management handled by a dedicated database server
  - 36 cores and 768GB of RAM to support desired scale of simultaneous simulations
  - 10Gb networking throughout to ensure fast data transfers







*Proof-of-concept simulation and market tools*

Today's resource structure (backcast)

Mid-transition resource structure

Net Zero resource structure