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

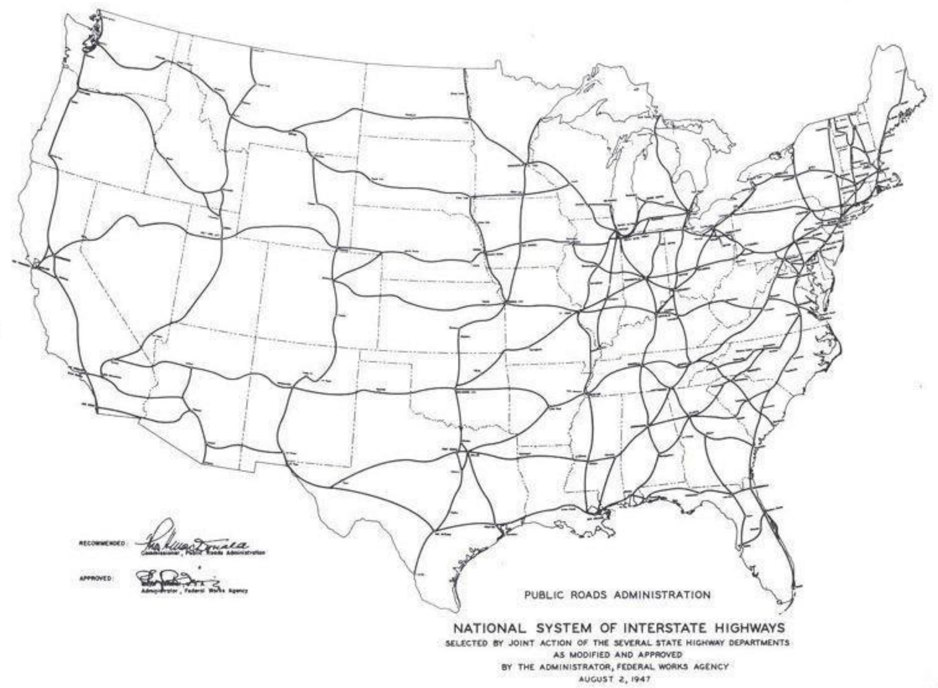
Transportation

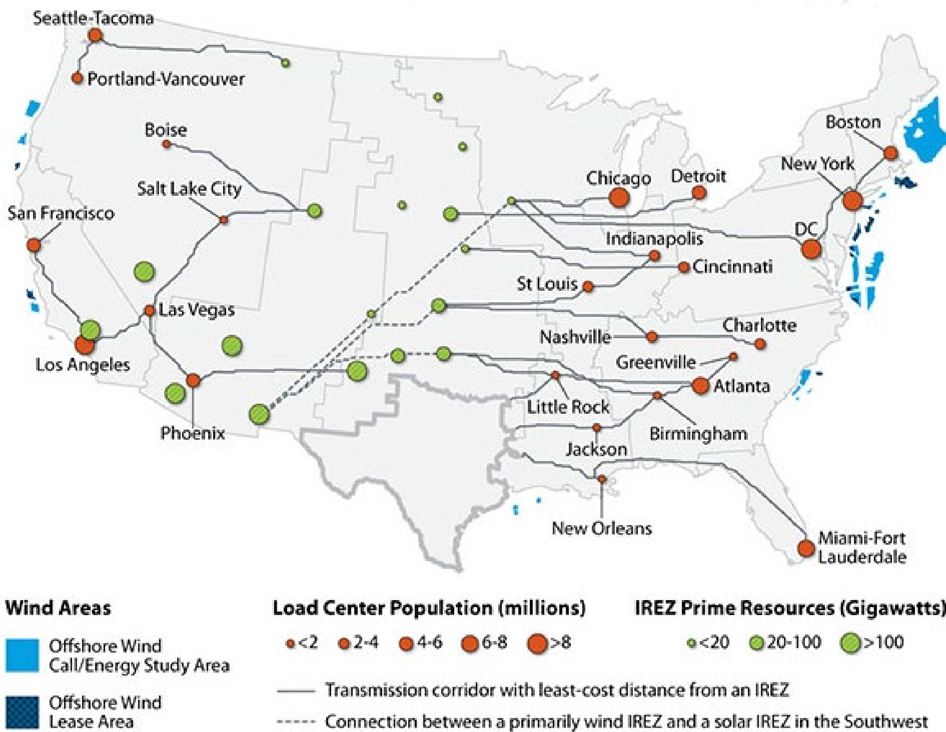
A market for airport slots

Peter Cramton, University of Maryland*

4 November 2024

*In collaboration with 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

Physics

Feasible quantities satisfying network & resource constraints

Lights stay on

Economics

Feasible quantities & prices that maximize social welfare

Least-cost, reliable electricity

Politics

Direct administrative agency to mandate system operator to conduct transparent & efficient market

Enables least-cost, reliable electricity

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

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

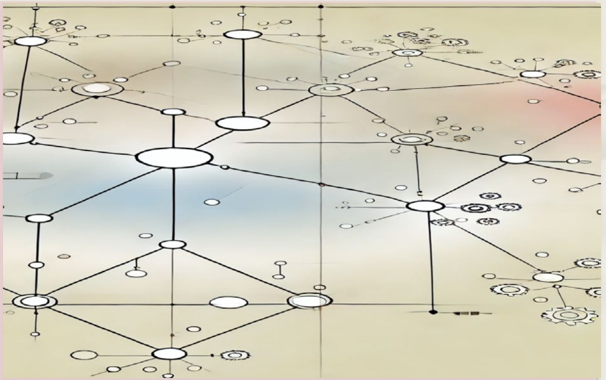
- Flexible climate-friendly generation must be built
- Existing market failures prevent investment without regulatory response

Regulatory response

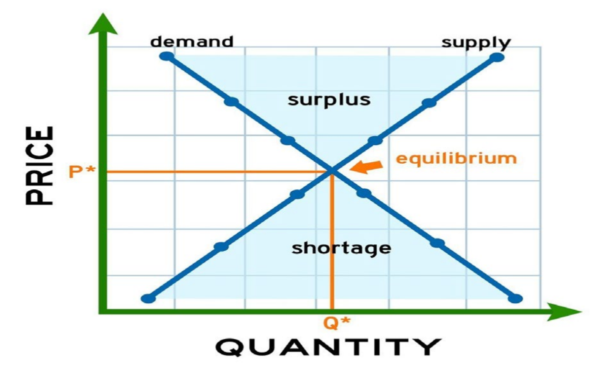
- Procure essential flexible generation consistent with immediate needs
- Fix market failures (incomplete markets, market power, uncertainty, …)
  - For the long run, yielding an efficient, reliability, and resilience electricity market
  - For the near term, yielding a lower-cost, forward-looking procurement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

Centralized vs. Decentralized

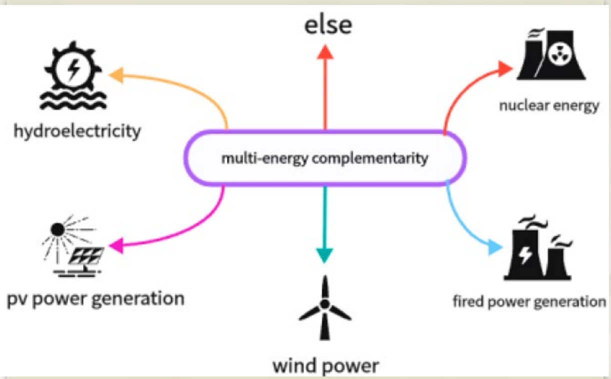
Least-cost reliable electricity requires:



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)

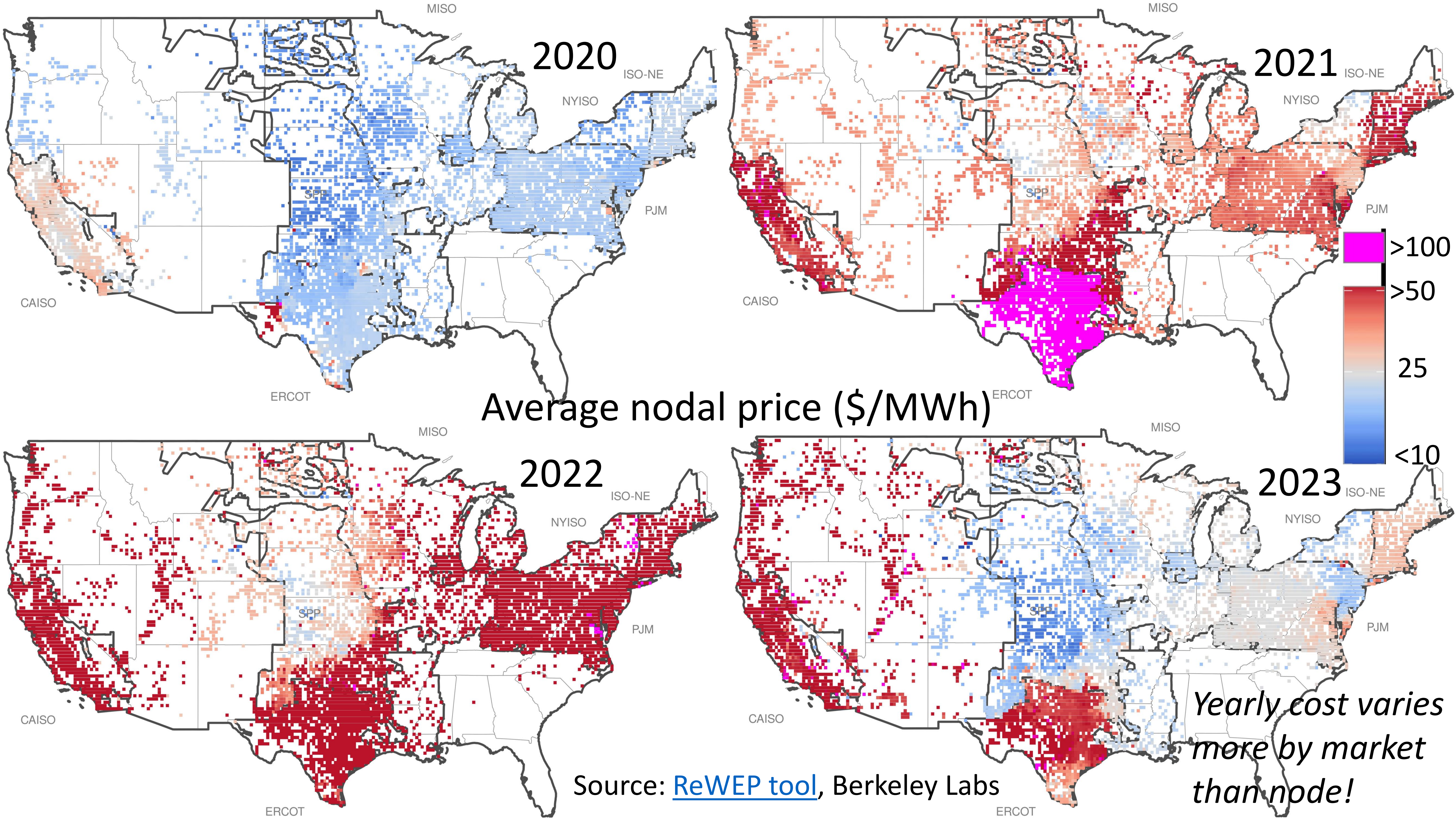
Long-term cost is much greater as payments encourage poor siting

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

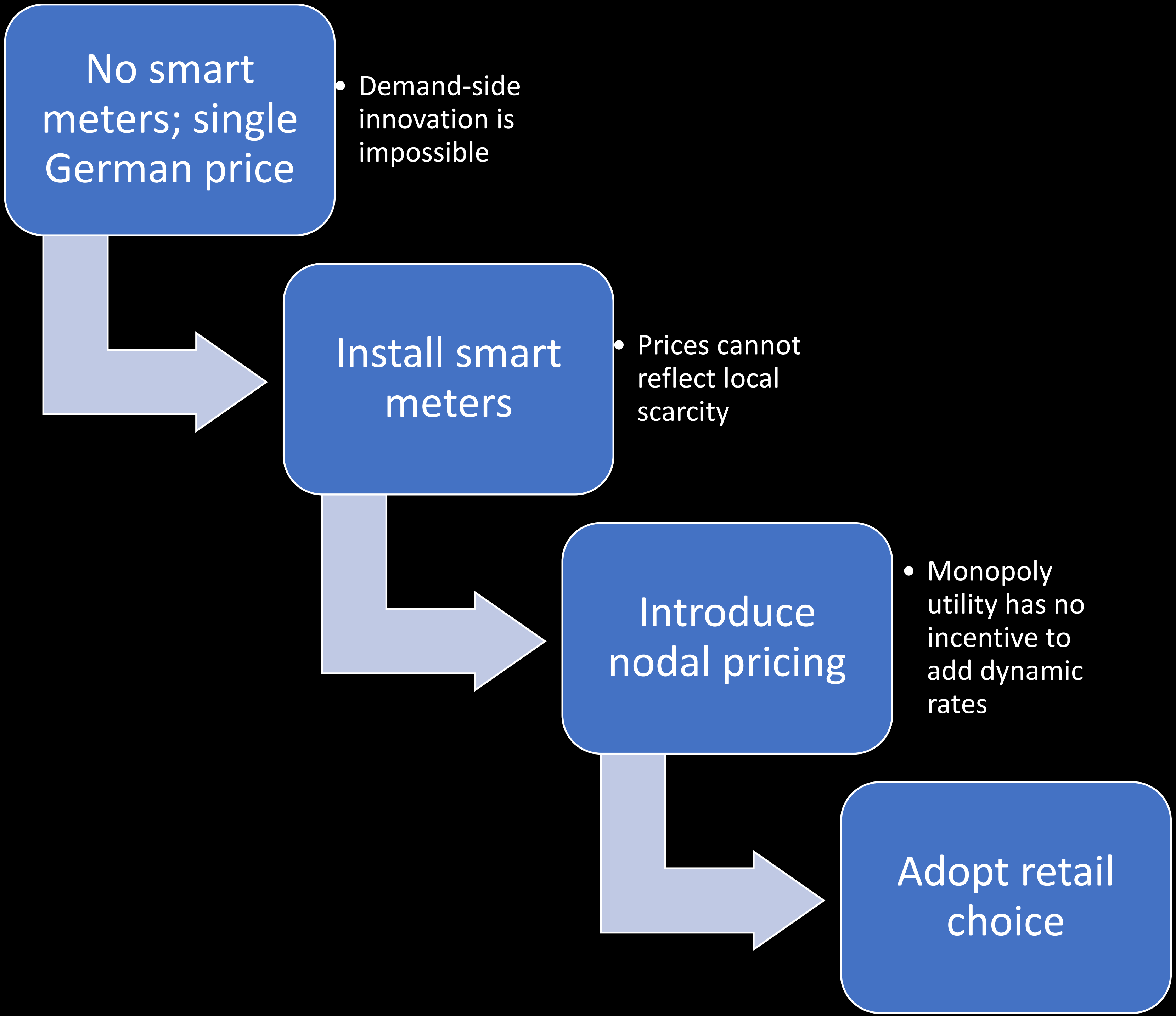
- Constraints vary by time, season, and circumstance; no stable zonal structure



Average nodal price ($/MWh)

Source: ReWEP tool, Berkeley Labs

Yearly cost varies more by market than node!



No smart meters; single German price

- Demand-side innovation is impossible

Install smart meters

- Prices cannot reflect local scarcity

Introduce nodal pricing

- Monopoly utility has no incentive to add dynamic rates

Adopt retail choice

- Innovative service providers offer dynamic rates creating value for EV owners

A Forward Energy Market to Improve Resiliency

Greater need for innovation and flexibility ⇒ efficient price signals increasingly important

7.5 × Tesla Powerwall 3

- 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)

Encourage resiliency

Vibrant forward trade

Forward prices

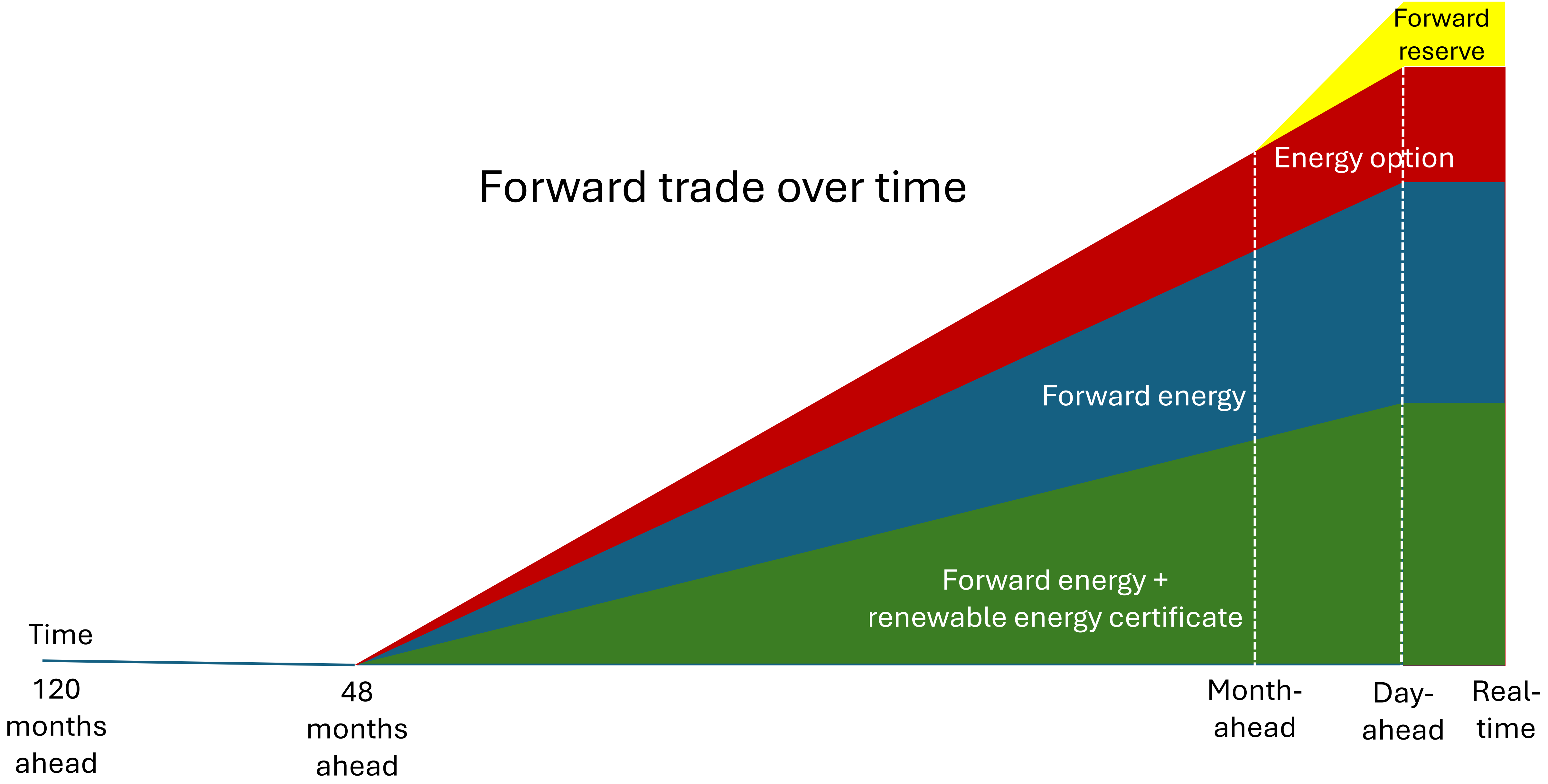
Efficient operation & investment

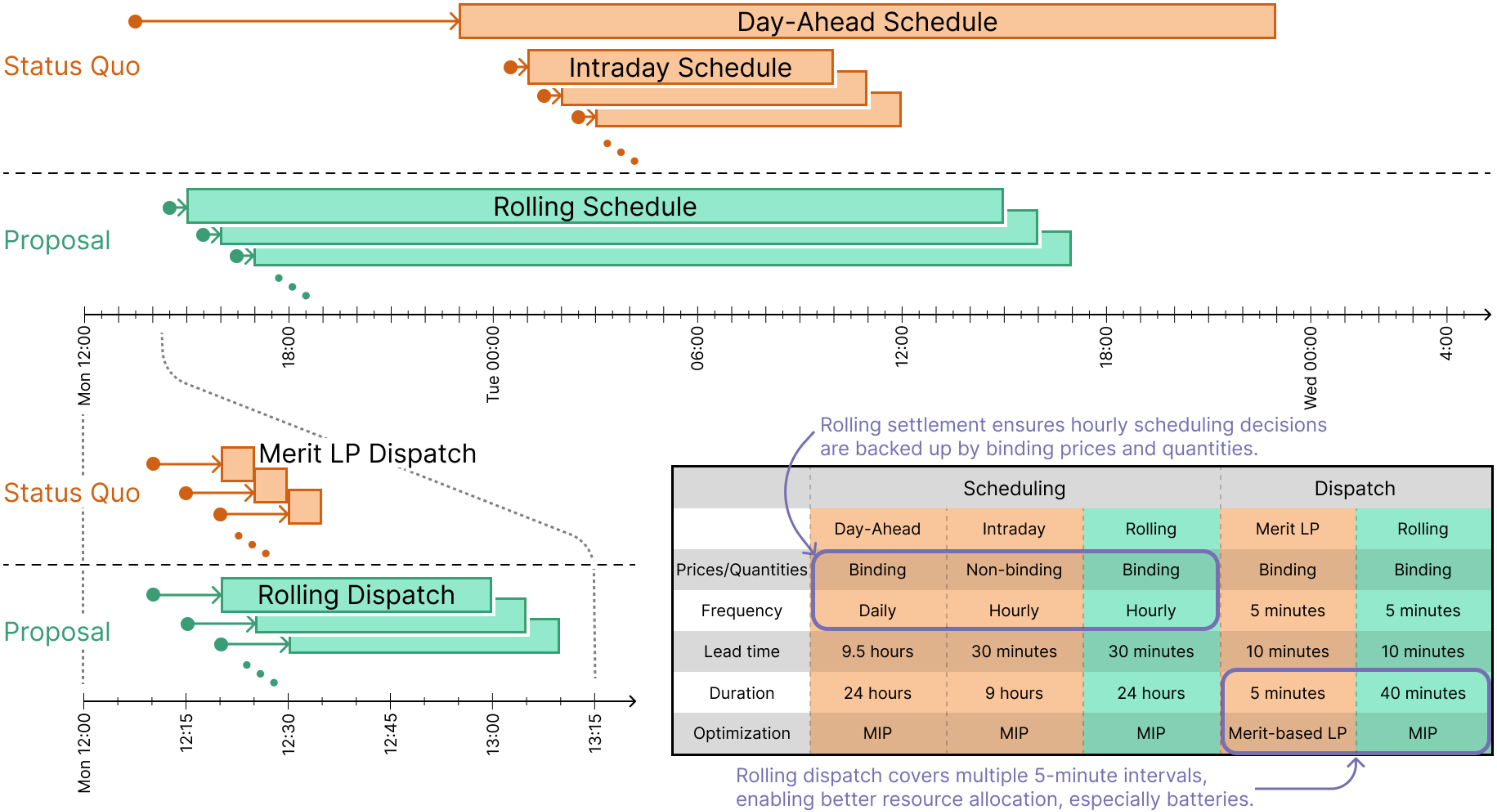
Foster innovation

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





Rolling settlement ensures hourly scheduling decisions are backed up by binding prices and quantities.

	Scheduling			Dispatch	
	Day-Ahead	Intraday	Rolling	Merit LP	Rolling
Prices/Quantities	Binding	Non-binding	Binding	Binding	Binding
Frequency	Daily	Hourly	Hourly	5 minutes	5 minutes
Lead time	9.5 hours	30 minutes	30 minutes	10 minutes	10 minutes
Duration	24 hours	9 hours	24 hours	5 minutes	40 minutes
Optimization	MIP	MIP	MIP	Merit-based LP	MIP

Rolling dispatch covers multiple 5-minute intervals, enabling better resource allocation, especially batteries.

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

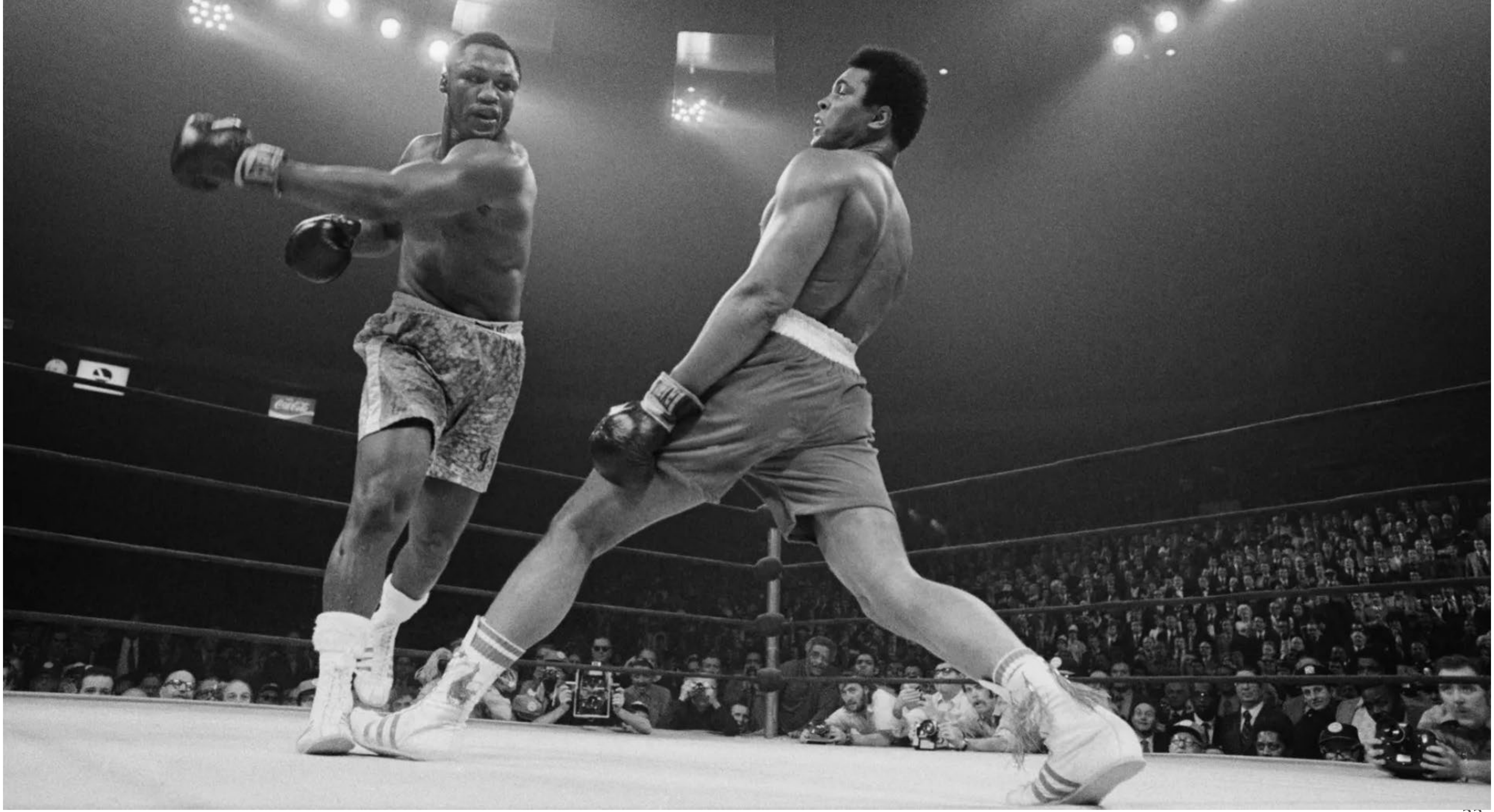
A system's ability to be robust to a wide range of environments

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

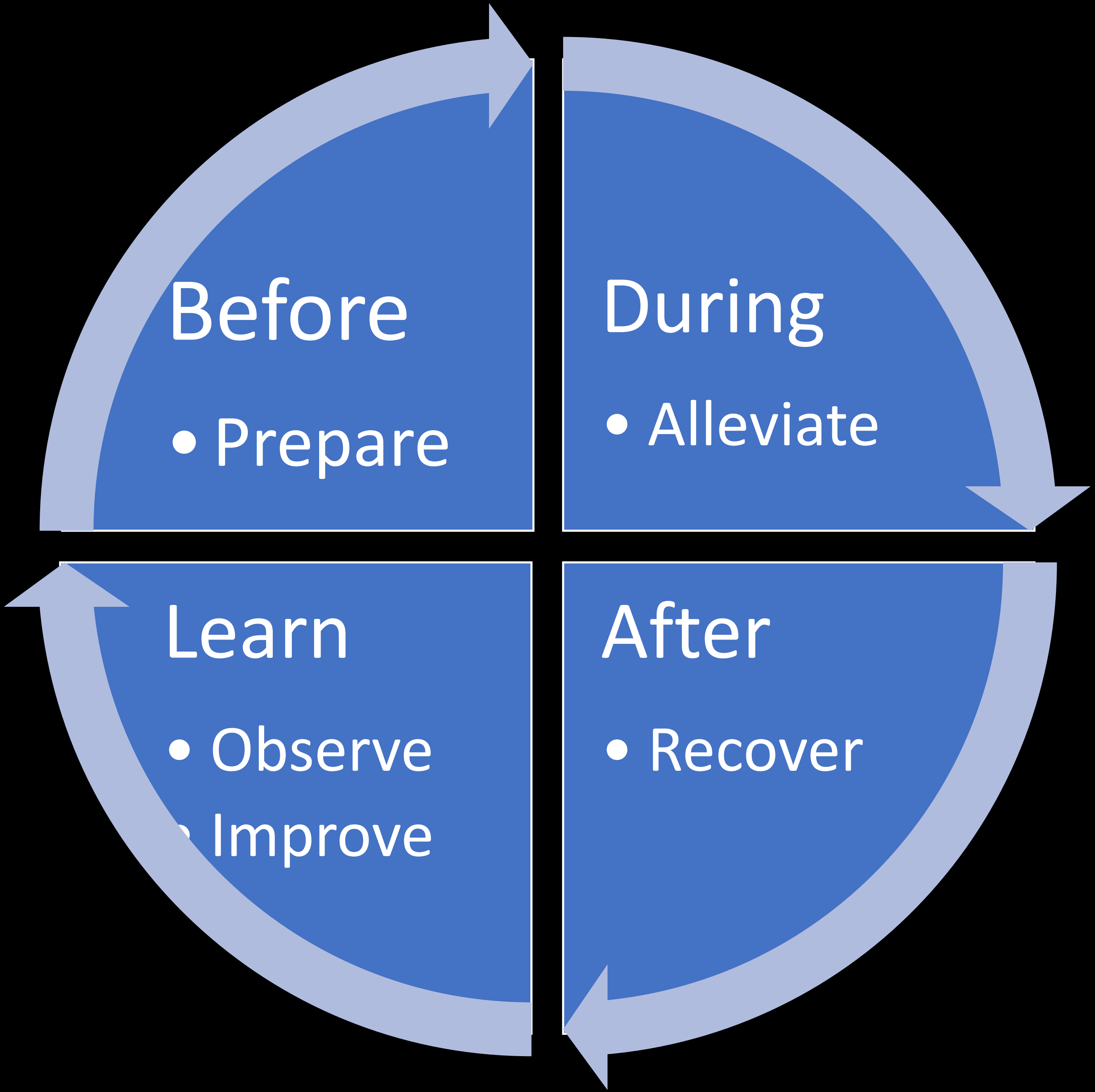
🟥 Resiliency event → Northeast 2003: poor tree trimming, software bug

🟩 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



Before

- Prepare

During

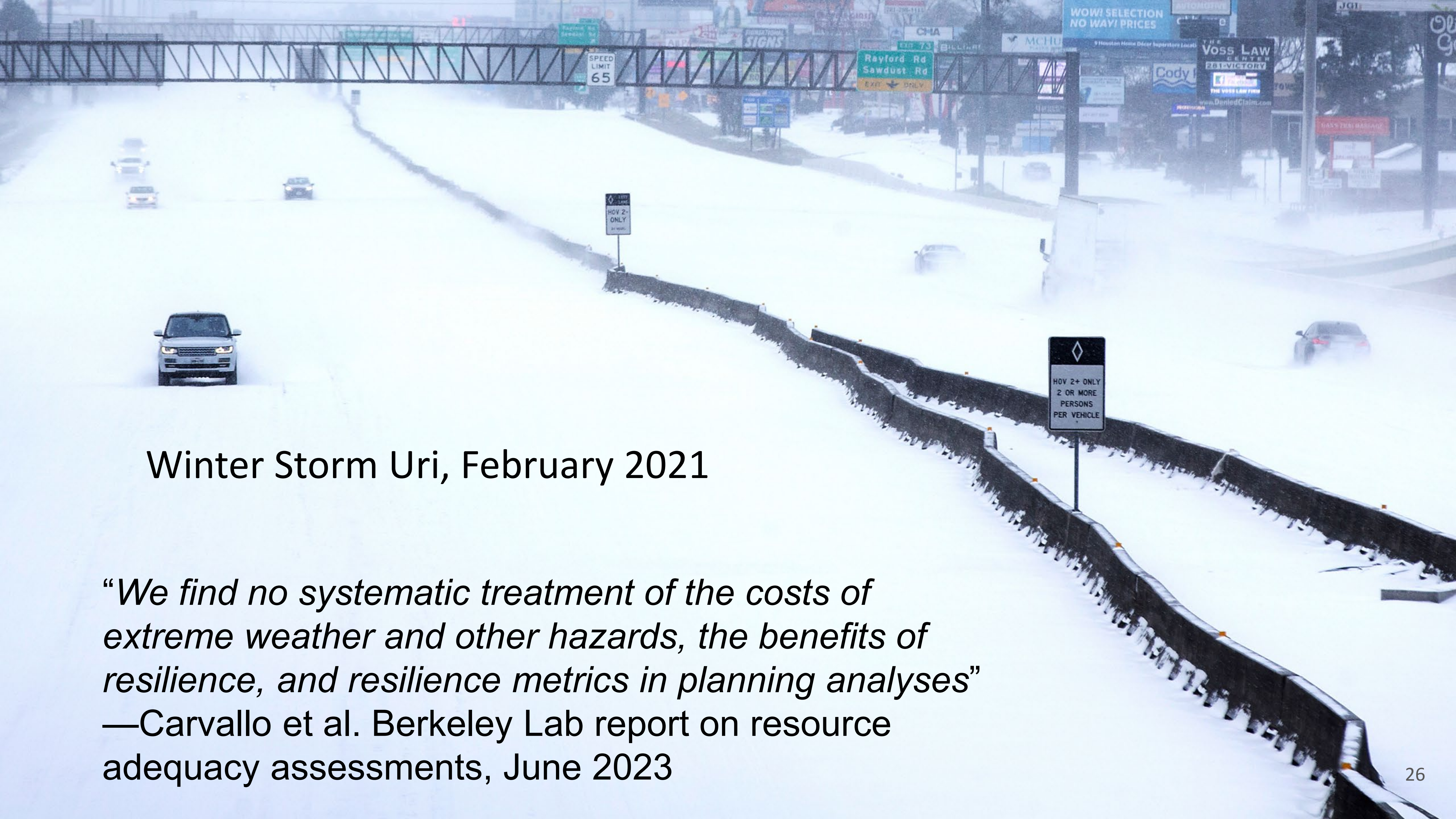
- Alleviate

After

- Recover

Learn

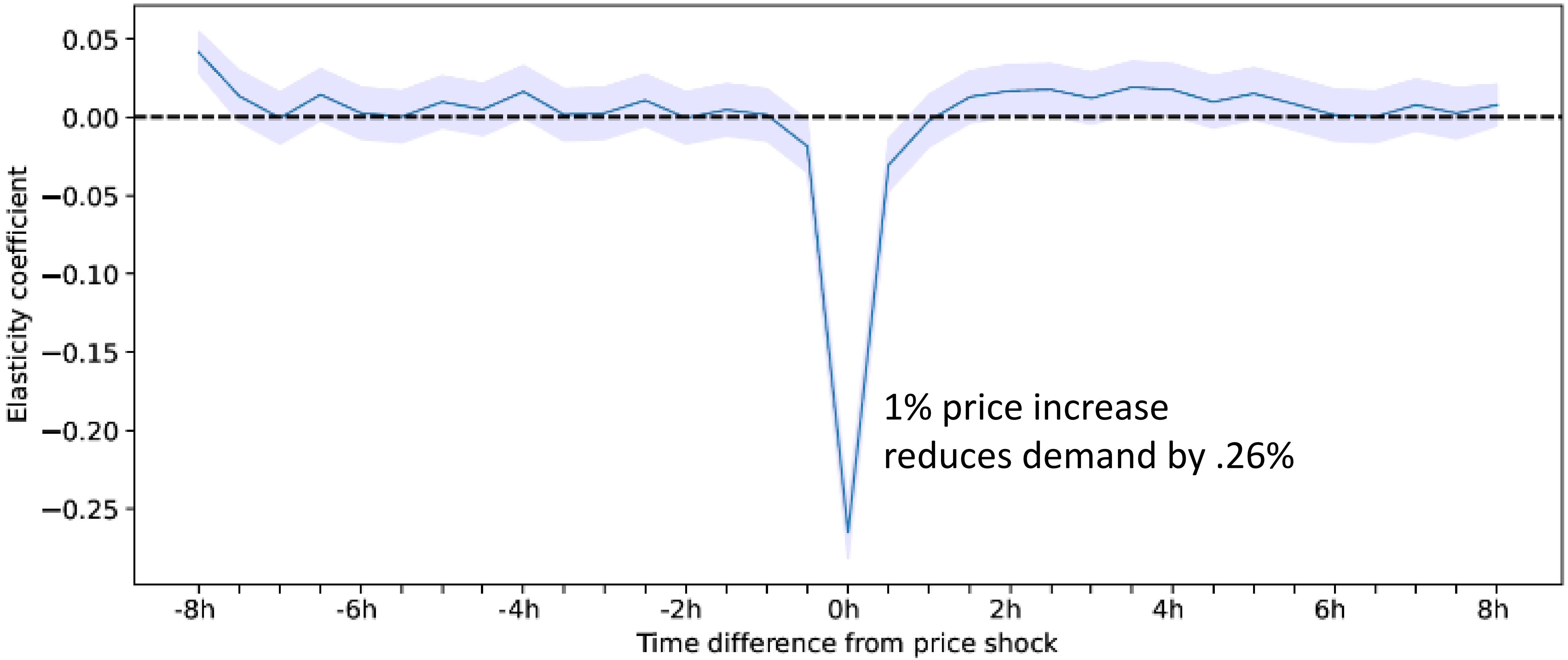
- Observe
- Improve



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

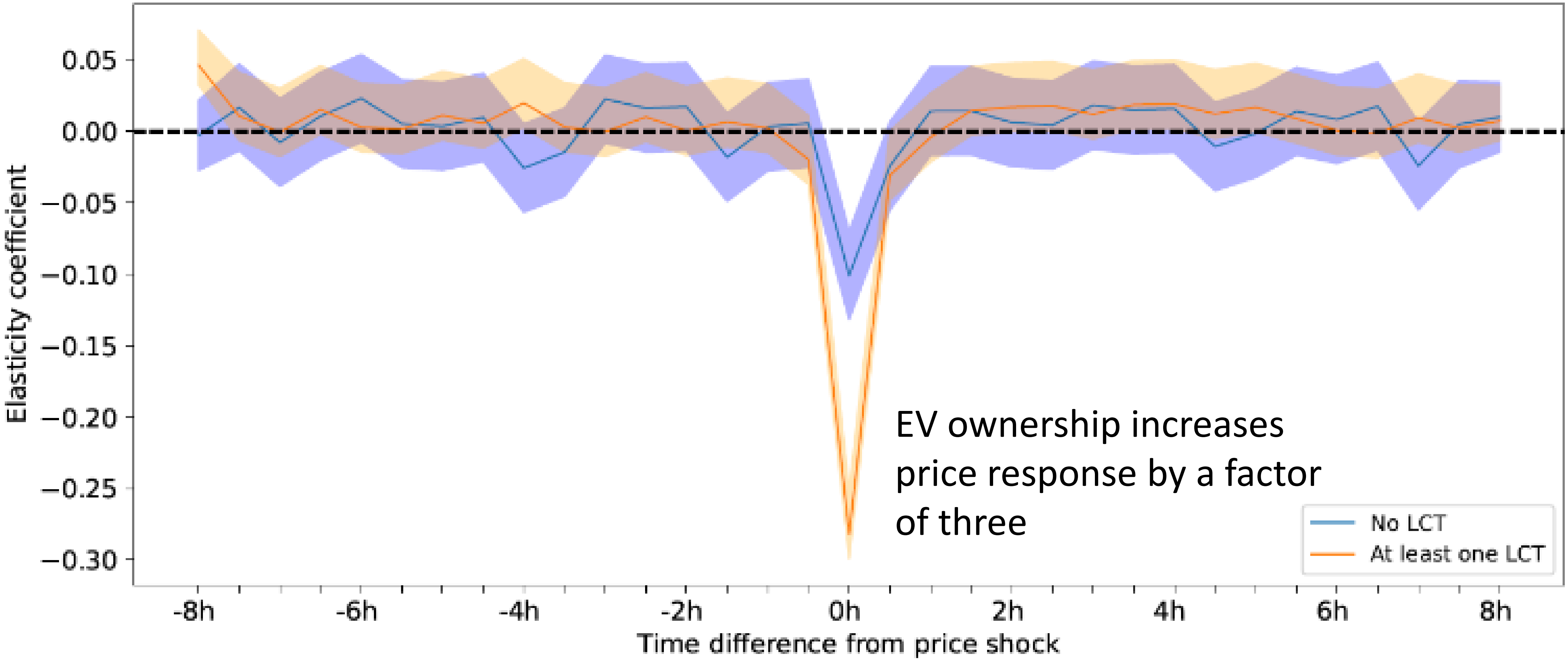
Customers on dynamic rates respond to price, Britain 2020-21



1% price increase
reduces demand by .26%

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.

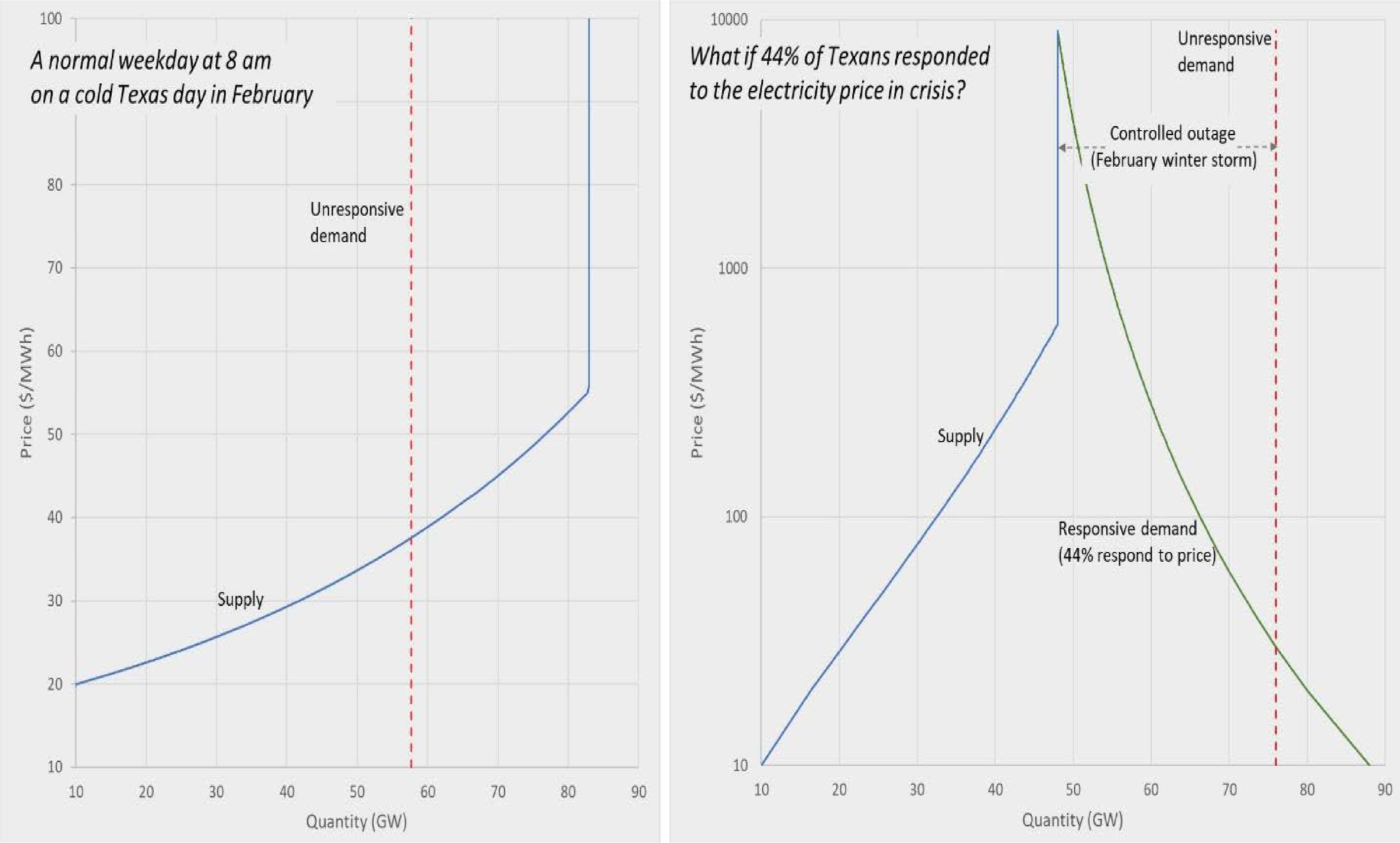
Low-carbon technologies increase price response



EV ownership increases price response by a factor of three

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.

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

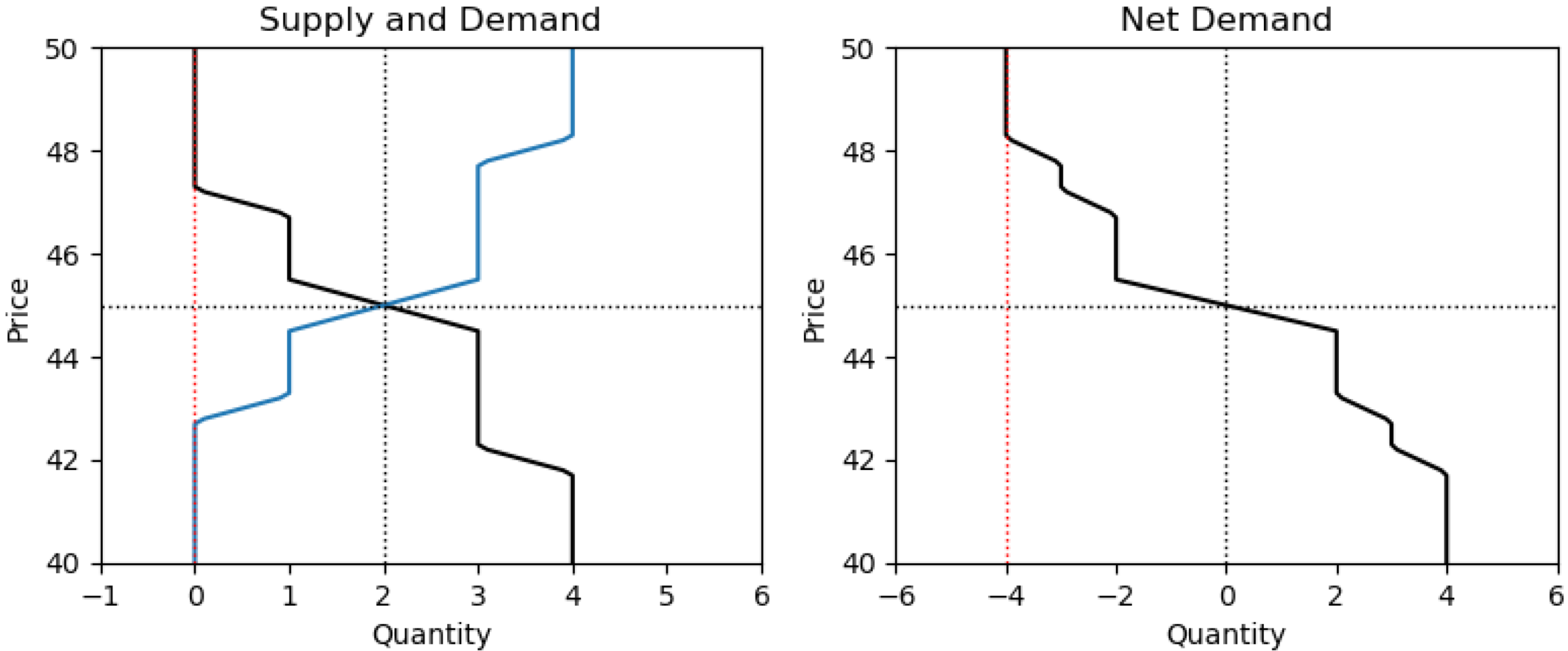
Capacity auction

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

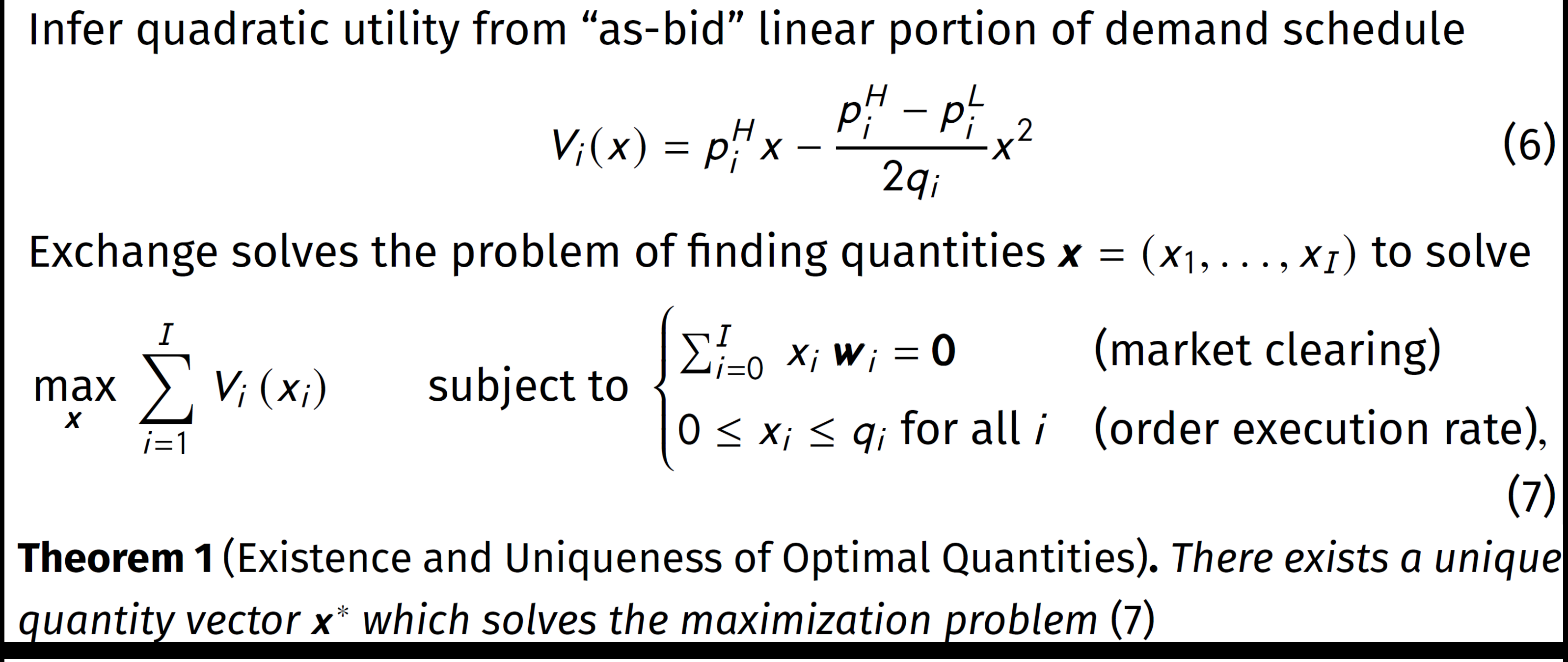
Forward energy market

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 = market participant	Gradual purchase of forward energy, energy options, and renewable energy credits
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



Eric Budish, Peter Cramton, Albert S. Kyle, Jeongmin Lee, and David Malec, "Flow Trading," Working Paper, University of Maryland, March 2023. [Presentation]



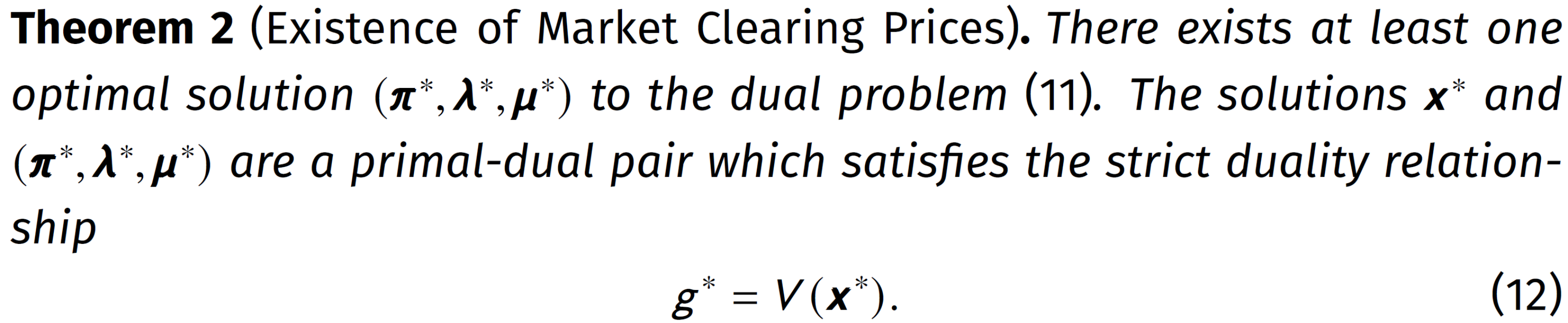
Infer quadratic utility from "as-bid" linear portion of demand schedule

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

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

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

Theorem 1 (Existence and Uniqueness of Optimal Quantities)**.** *There exists a unique quantity vector* $\boldsymbol{x}^*$ *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* $\boldsymbol{x}^*$ *and* $(\boldsymbol{\pi}^*, \boldsymbol{\lambda}^*, \boldsymbol{\mu}^*)$ *are a primal-dual pair which satisfies the strict duality relationship*

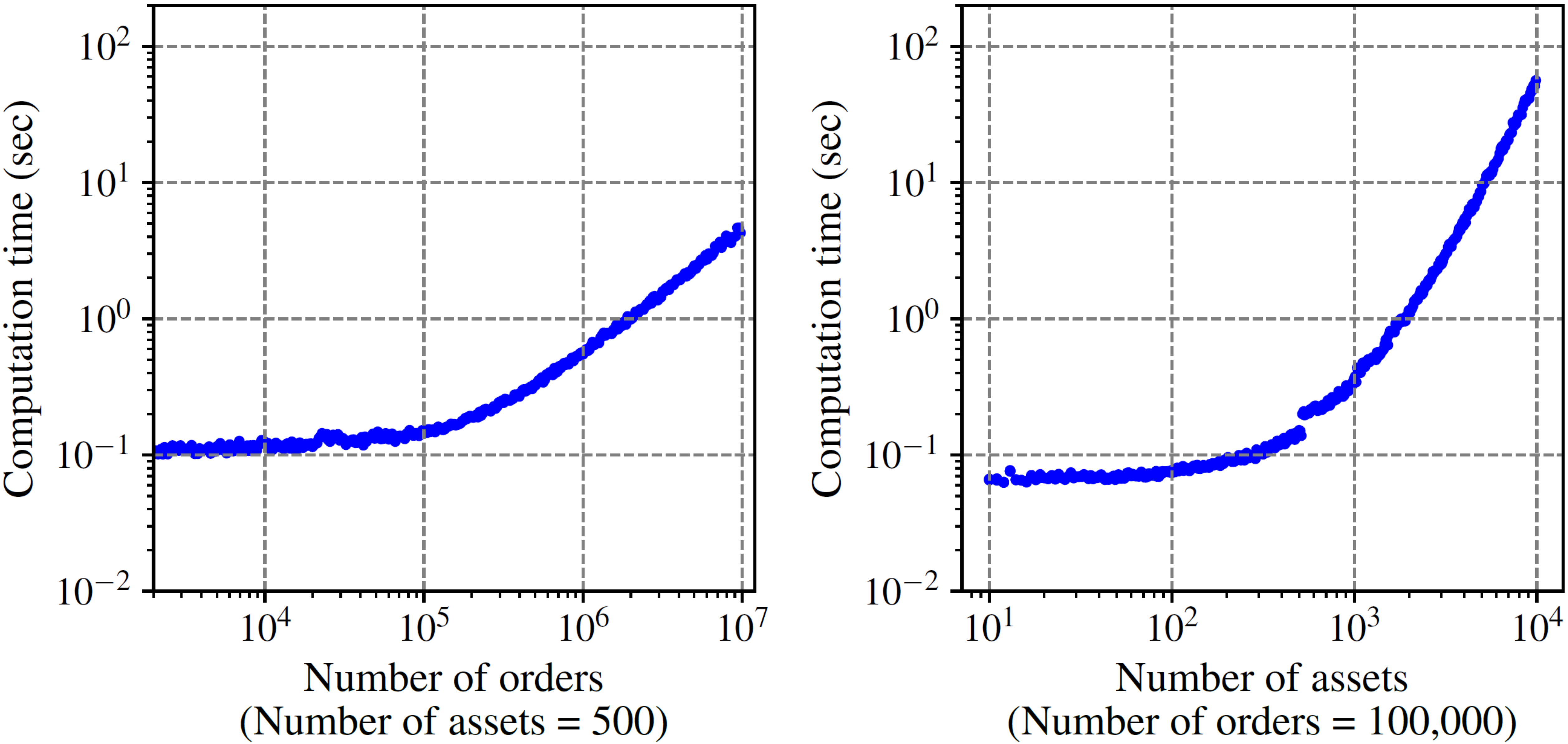
$$g^* = V(\boldsymbol{x}^*). \tag{12}$$

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

Eric Budish, Peter Cramton, Albert S. Kyle, Jeongmin Lee, and David Malec, "Flow Trading," Working Paper, University of Maryland, March 2023. [Presentation]

Can we find unique prices and quantities quickly?

- 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



Eric Budish, Peter Cramton, Albert S. Kyle, Jeongmin Lee, and David Malec, “Flow Trading,” Working Paper, University of Maryland, March 2023. [Presentation]

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)?

Inputs

Risk preference

+

Cost of Capital

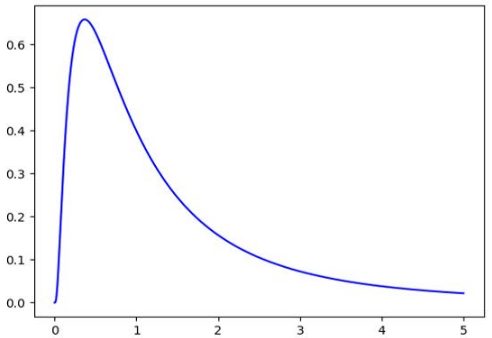
$$C_0 = \frac{C_n}{(1+i)^n}$$

+

Anticipated prices

+

Distribution of hourly net demand



Trade-to-target strategy

Speed of trade

+

Price arbitrage

Arbitrage

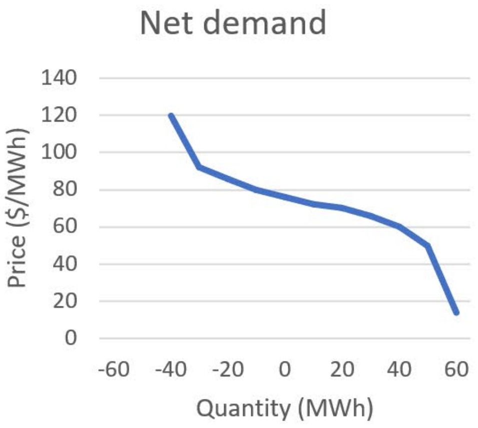
[är-bə-ˌträzh]

The simultaneous purchase and sale of the same asset in different markets in order to profit from tiny differences in the asset's listed price.

Investopedia

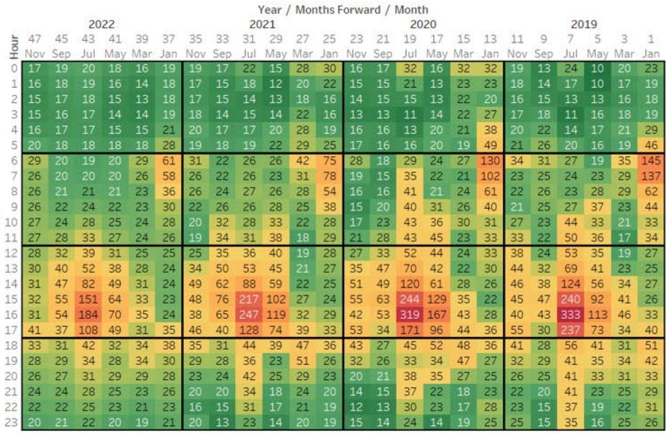
+

Piecewise linear net demand



Outputs

Prices



Year / Months Forward / Month

Hour	2022						2021						2020						2019					
	47	45	43	41	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	7	5	3	1
	Nov	Sep	Jul	May	Mar	Jan	Nov	Sep	Jul	May	Mar	Jan	Nov	Sep	Jul	May	Mar	Jan	Nov	Sep	Jul	May	Mar	Jan
0	17	19	20	18	16	19	19	17	22	15	28	30	16	17	32	16	32	32	19	13	24	10	20	23
1	16	18	19	16	14	18	17	15	18	12	20	22	15	15	21	13	23	23	18	14	17	10	17	19
2	15	17	18	15	13	18	17	15	14	13	18	16	14	15	15	13	22	20	16	15	13	13	16	18
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6	29	20	19	20	29	61	31	22	26	26	42	75	28	18	29	24	27	130	34	31	27	19	35	145
7	26	20	20	20	26	58	26	22	26	23	31	78	19	15	35	22	21	102	23	25	24	23	29	137
8	26	21	21	21	23	36	26	24	27	26	28	54	16	16	41	21	24	61	22	26	23	28	29	62
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15	32	55	151	64	33	23	48	76	217	102	27	24	55	63	244	129	35	22	45	47	240	92	41	26
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23	20	21	22	20	19	21	20	13	23	14	20	19	15	14	24	14	19	25	25	15	35	16	25	26

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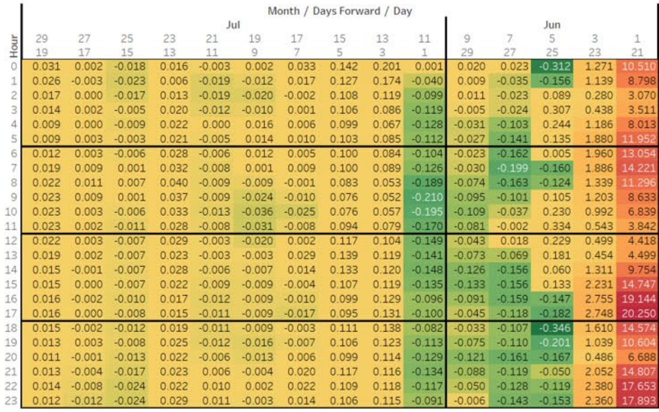
Flow trade rate



Month / Days Forward / Day

Hour	Jul										Jun				
	29	27	25	23	21	19	17	15	13	11	9	7	5	3	1
	19	17	15	13	11	9	7	5	3	1	29	27	25	23	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

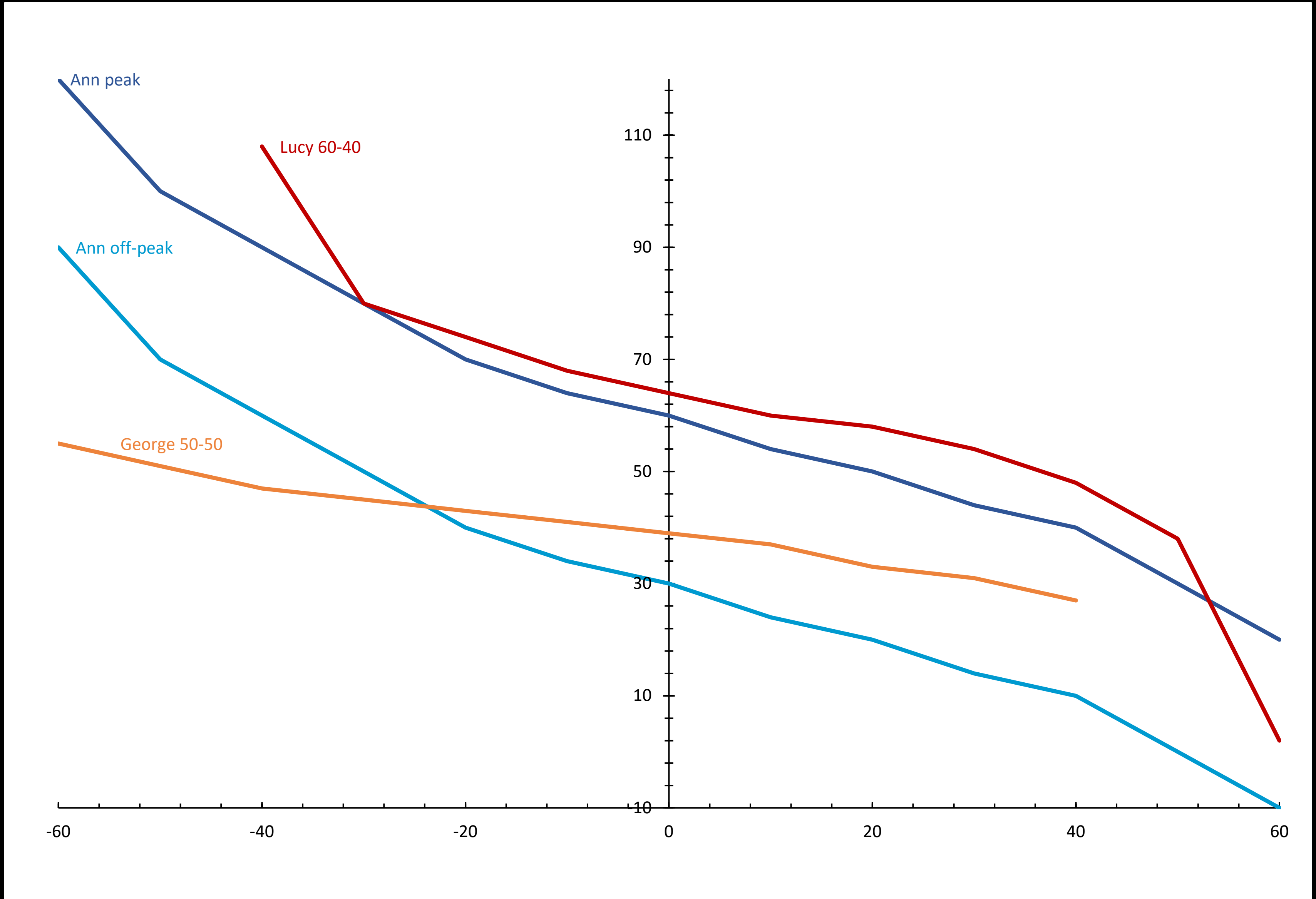
+

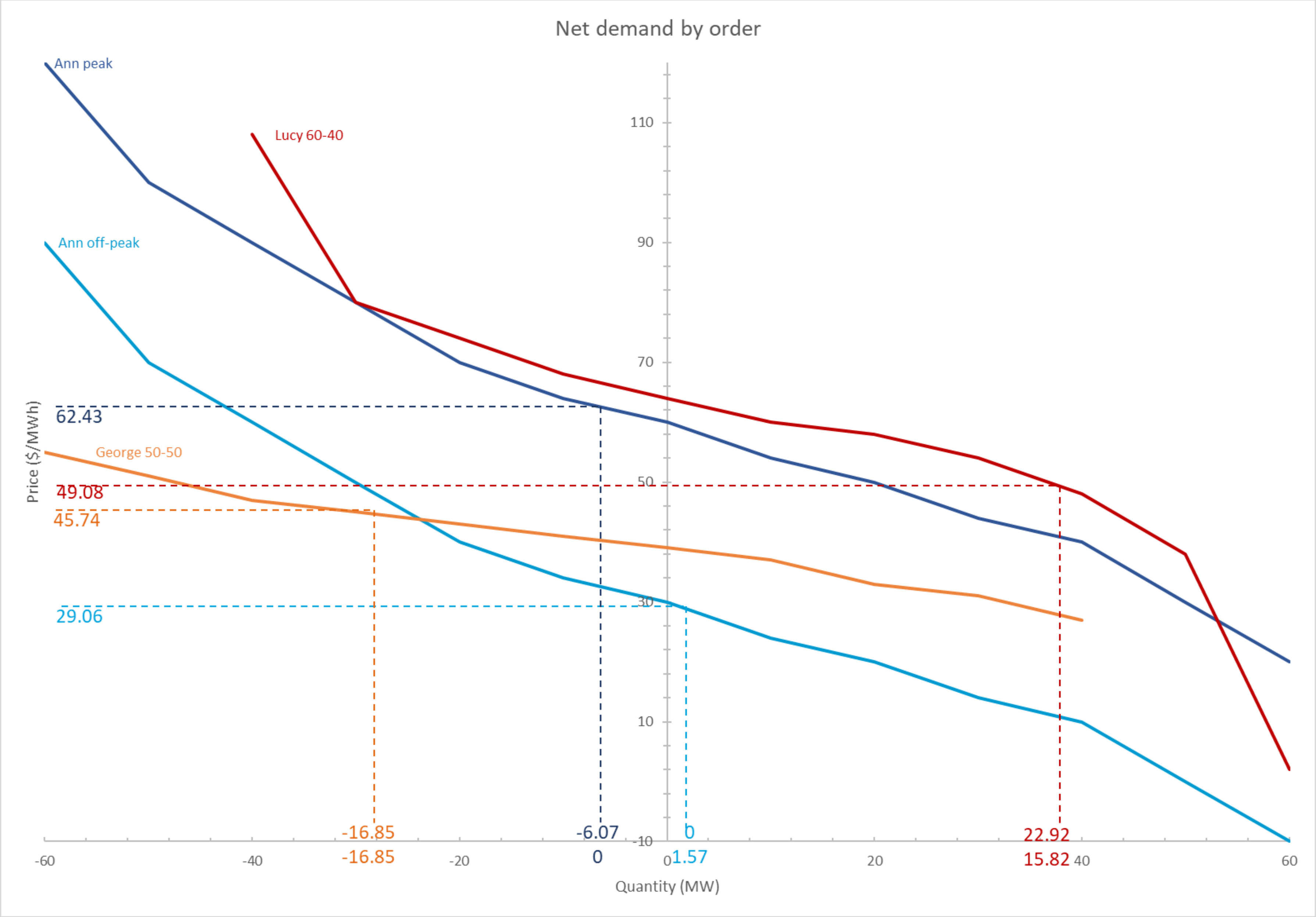
Balanced position

An example:
2 products,
3 participants

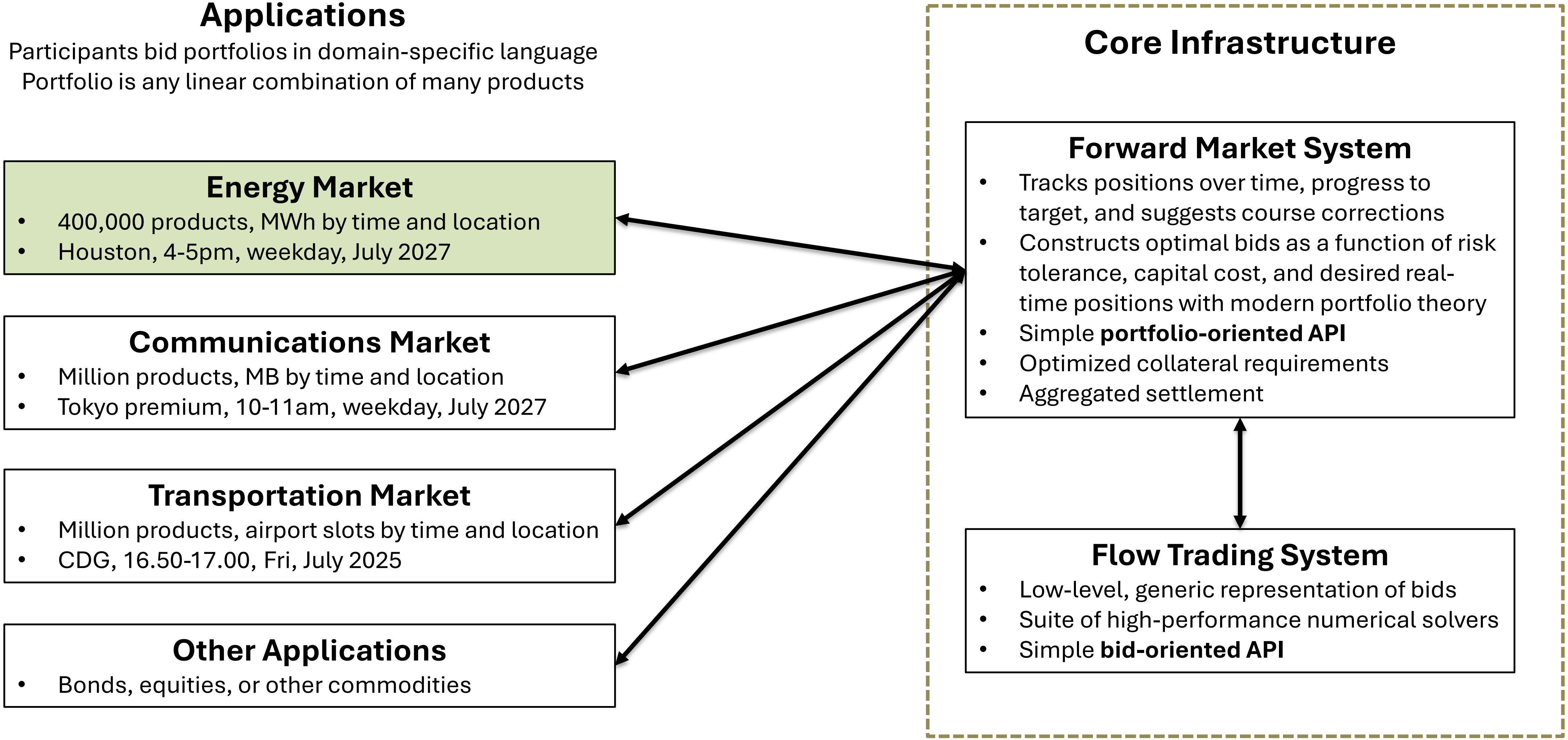
		Price ($/MWh)			
	Quantity MW	Ann peak	Ann off-peak	George 50-50	Lucy 60-40
	-60	120	90	55	
	-50	100	70	51	
Sell	**-40**	90	60	47	108
	-30	80	50	45	80
	-20	70	40	43	74
	-10	64	34	41	68
	0	60	30	39	64
	10	54	24	37	60
	20	50	20	33	58
Buy	**30**	44	14	31	54
	40	40	10	27	48
	50	30	0		38
	60	20	-10		2

[Interactive Demo]


Ann peak
Lucy 60-40
Ann off-peak
George 50-50
110
90
70
50
30
10
-10
-60
-40
-20
0
20
40
60


Net demand by order
Ann peak
Lucy 60-40
Ann off-peak
George 50-50
62.43
49.08
45.74
29.06
110
90
70
50
30
10
-10
Price ($/MWh)
-16.85
-16.85
-6.07
0
0
1.57
22.92
15.82
-60
-40
-20
0
20
40
60
Quantity (MW)

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

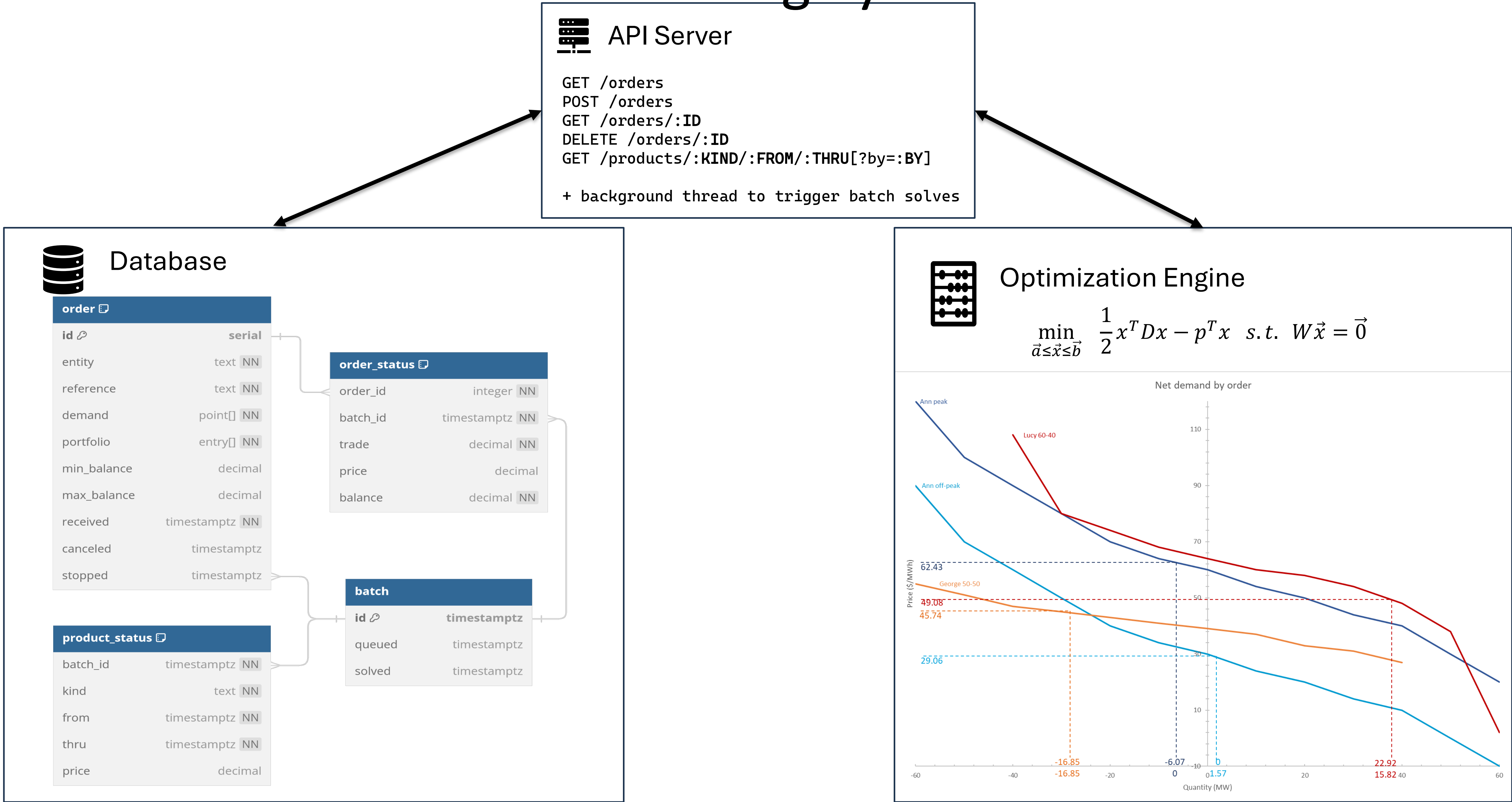
Forward Market System

- 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	timestamptz	NN
canceled	timestamptz	
stopped	timestamptz	

order_status

order_id	integer	NN
batch_id	timestamptz	NN
trade	decimal	NN
price	decimal	
balance	decimal	NN

batch

id	**timestamptz**
queued	timestamptz
solved	timestamptz

product_status

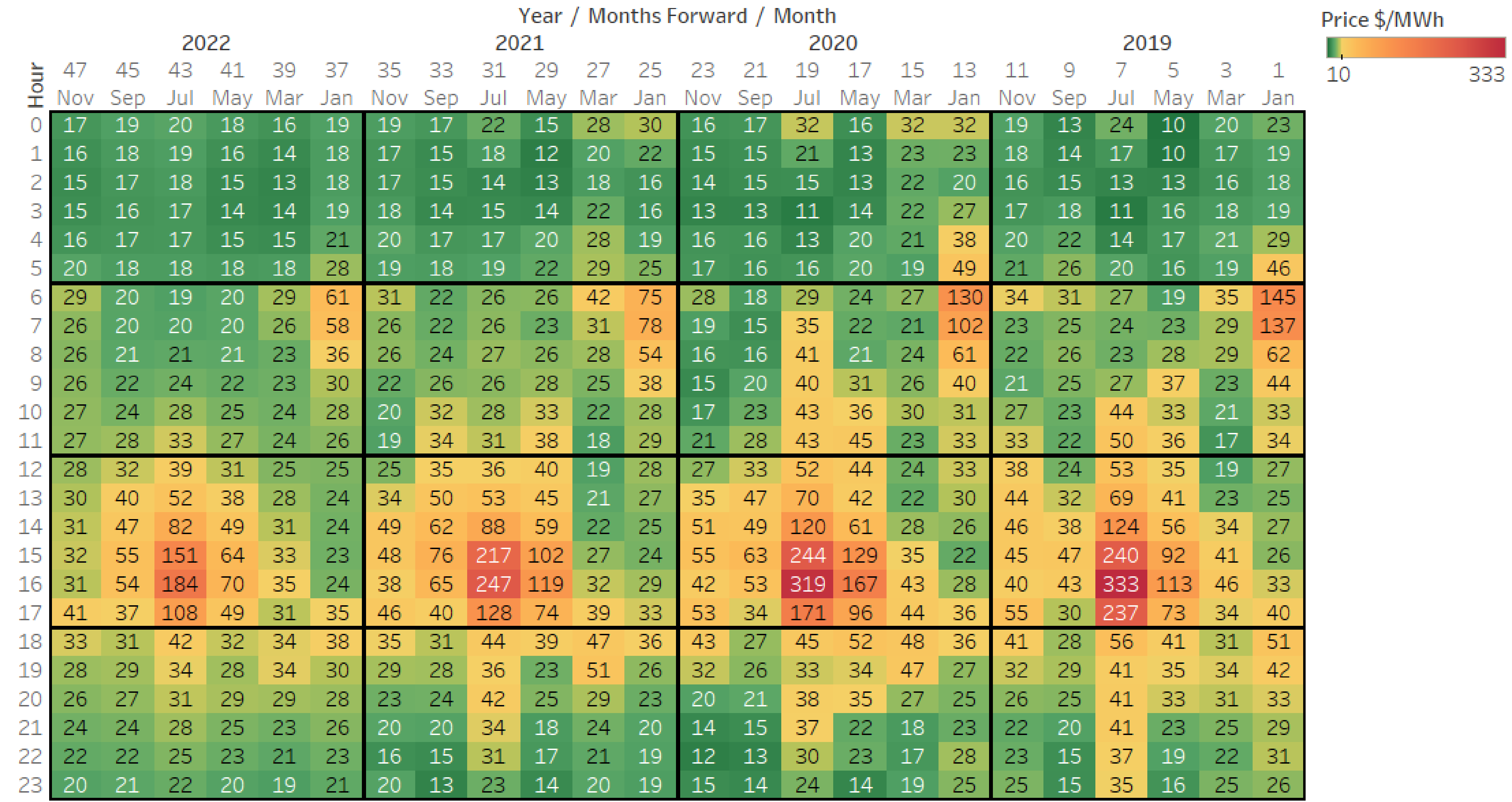
batch_id	timestamptz	NN
kind	text	NN
from	timestamptz	NN
thru	timestamptz	NN
price	decimal	

Optimization Engine

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

Net demand by order

Monthly forward prices, Houston, weekday ($/MWh)
48 to 1 month ahead (48 × 24 = 1152 monthly products per load zone)

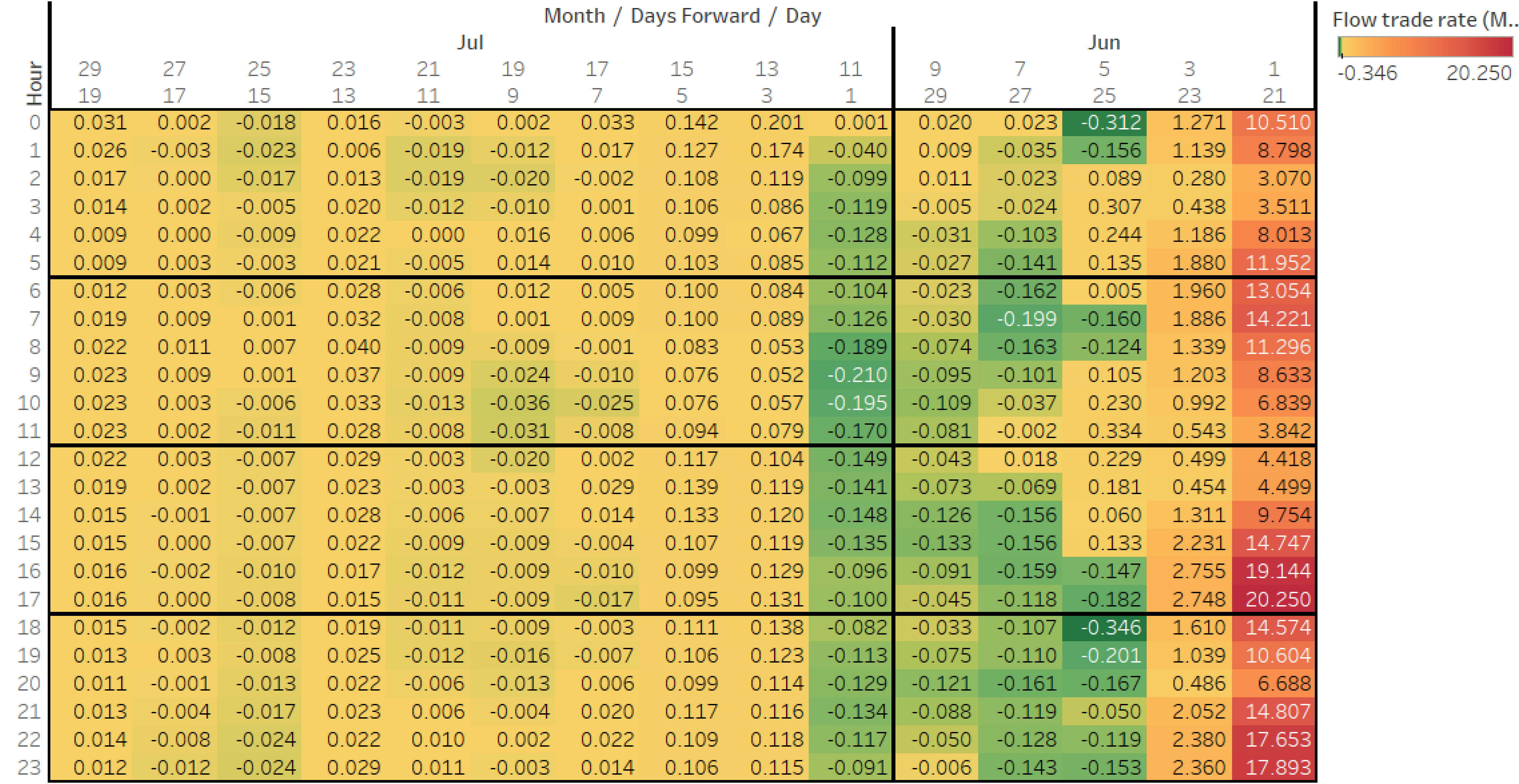


Year / Months Forward / Month

Hour	2022						2021						2020						2019					
	47	45	43	41	39	37	35	33	31	29	27	25	23	21	19	17	15	13	11	9	7	5	3	1
	Nov	Sep	Jul	May	Mar	Jan	Nov	Sep	Jul	May	Mar	Jan	Nov	Sep	Jul	May	Mar	Jan	Nov	Sep	Jul	May	Mar	Jan
0	17	19	20	18	16	19	19	17	22	15	28	30	16	17	32	16	32	32	19	13	24	10	20	23
1	16	18	19	16	14	18	17	15	18	12	20	22	15	15	21	13	23	23	18	14	17	10	17	19
2	15	17	18	15	13	18	17	15	14	13	18	16	14	15	15	13	22	20	16	15	13	13	16	18
3	15	16	17	14	14	19	18	14	15	14	22	16	13	13	11	14	22	27	17	18	11	16	18	19
4	16	17	17	15	15	21	20	17	17	20	28	19	16	16	13	20	21	38	20	22	14	17	21	29
5	20	18	18	18	18	28	19	18	19	22	29	25	17	16	16	20	19	49	21	26	20	16	19	46
6	29	20	19	20	29	61	31	22	26	26	42	75	28	18	29	24	27	130	34	31	27	19	35	145
7	26	20	20	20	26	58	26	22	26	23	31	78	19	15	35	22	21	102	23	25	24	23	29	137
8	26	21	21	21	23	36	26	24	27	26	28	54	16	16	41	21	24	61	22	26	23	28	29	62
9	26	22	24	22	23	30	22	26	26	28	25	38	15	20	40	31	26	40	21	25	27	37	23	44
10	27	24	28	25	24	28	20	32	28	33	22	28	17	23	43	36	30	31	27	23	44	33	21	33
11	27	28	33	27	24	26	19	34	31	38	18	29	21	28	43	45	23	33	33	22	50	36	17	34
12	28	32	39	31	25	25	25	35	36	40	19	28	27	33	52	44	24	33	38	24	53	35	19	27
13	30	40	52	38	28	24	34	50	53	45	21	27	35	47	70	42	22	30	44	32	69	41	23	25
14	31	47	82	49	31	24	49	62	88	59	22	25	51	49	120	61	28	26	46	38	124	56	34	27
15	32	55	151	64	33	23	48	76	217	102	27	24	55	63	244	129	35	22	45	47	240	92	41	26
16	31	54	184	70	35	24	38	65	247	119	32	29	42	53	319	167	43	28	40	43	333	113	46	33
17	41	37	108	49	31	35	46	40	128	74	39	33	53	34	171	96	44	36	55	30	237	73	34	40
18	33	31	42	32	34	38	35	31	44	39	47	36	43	27	45	52	48	36	41	28	56	41	31	51
19	28	29	34	28	34	30	29	28	36	23	51	26	32	26	33	34	47	27	32	29	41	35	34	42
20	26	27	31	29	29	28	23	24	42	25	29	23	20	21	38	35	27	25	26	25	41	33	31	33
21	24	24	28	25	23	26	20	20	34	18	24	20	14	15	37	22	18	23	22	20	41	23	25	29
22	22	22	25	23	21	23	16	15	31	17	21	19	12	13	30	23	17	28	23	15	37	19	22	31
23	20	21	22	20	19	21	20	13	23	14	20	19	15	14	24	14	19	25	25	15	35	16	25	26

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

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

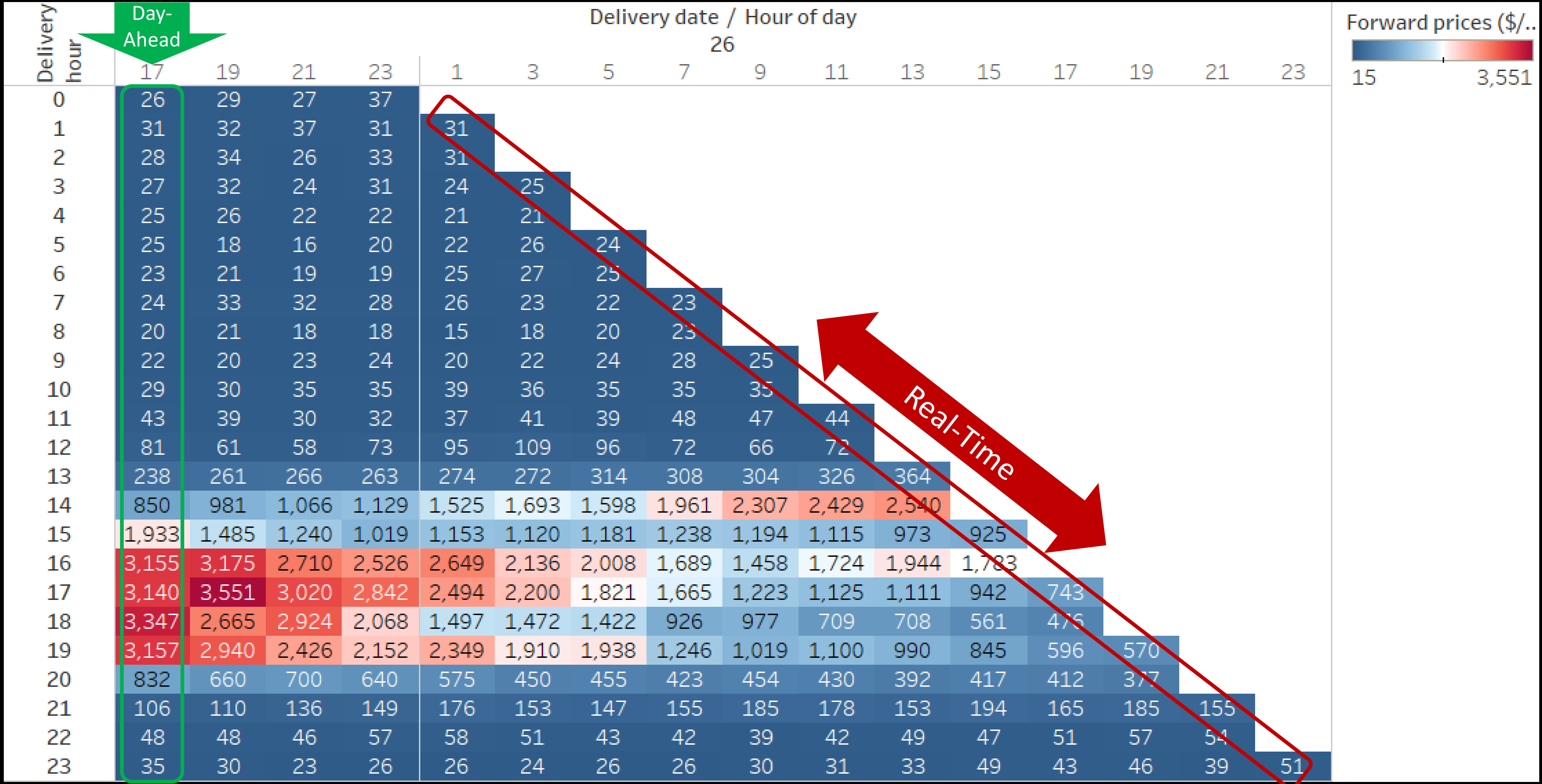


Month / Days Forward / Day

Hour	Jul										Jun				
	29	27	25	23	21	19	17	15	13	11	9	7	5	3	1
	19	17	15	13	11	9	7	5	3	1	29	27	25	23	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 × 7 + 23 + 22 + … + 1 = 444 new prices)



Delivery date / Hour of day

					26											
Delivery hour	17	19	21	23	1	3	5	7	9	11	13	15	17	19	21	23
0	26	29	27	37												
1	31	32	37	31	31											
2	28	34	26	33	31											
3	27	32	24	31	24	25										
4	25	26	22	22	21	21										
5	25	18	16	20	22	26	24									
6	23	21	19	19	25	27	25									
7	24	33	32	28	26	23	22	23								
8	20	21	18	18	15	18	20	23								
9	22	20	23	24	20	22	24	28	25							
10	29	30	35	35	39	36	35	35	35							
11	43	39	30	32	37	41	39	48	47	44						
12	81	61	58	73	95	109	96	72	66	72						
13	238	261	266	263	274	272	314	308	304	326	364					
14	850	981	1,066	1,129	1,525	1,693	1,598	1,961	2,307	2,429	2,540					
15	1,933	1,485	1,240	1,019	1,153	1,120	1,181	1,238	1,194	1,115	973	925				
16	3,155	3,175	2,710	2,526	2,649	2,136	2,008	1,689	1,458	1,724	1,944	1,783				
17	3,140	3,551	3,020	2,842	2,494	2,200	1,821	1,665	1,223	1,125	1,111	942	743			
18	3,347	2,665	2,924	2,068	1,497	1,472	1,422	926	977	709	708	561	476			
19	3,157	2,940	2,426	2,152	2,349	1,910	1,938	1,246	1,019	1,100	990	845	596	570		
20	832	660	700	640	575	450	455	423	454	430	392	417	412	377		
21	106	110	136	149	176	153	147	155	185	178	153	194	165	185	155	
22	48	48	46	57	58	51	43	42	39	42	49	47	51	57	54	
23	35	30	23	26	26	24	26	26	30	31	33	49	43	46	39	51

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