A Forward Energy Market to Improve Resiliency

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[Latest FAQ] [Latest Presentation] [Interactive Demo] [Seminar 18 Dec 2023]

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Greater need for innovation and flexibility ⇒ 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)

Over one dozen
Tesla Powerwalls

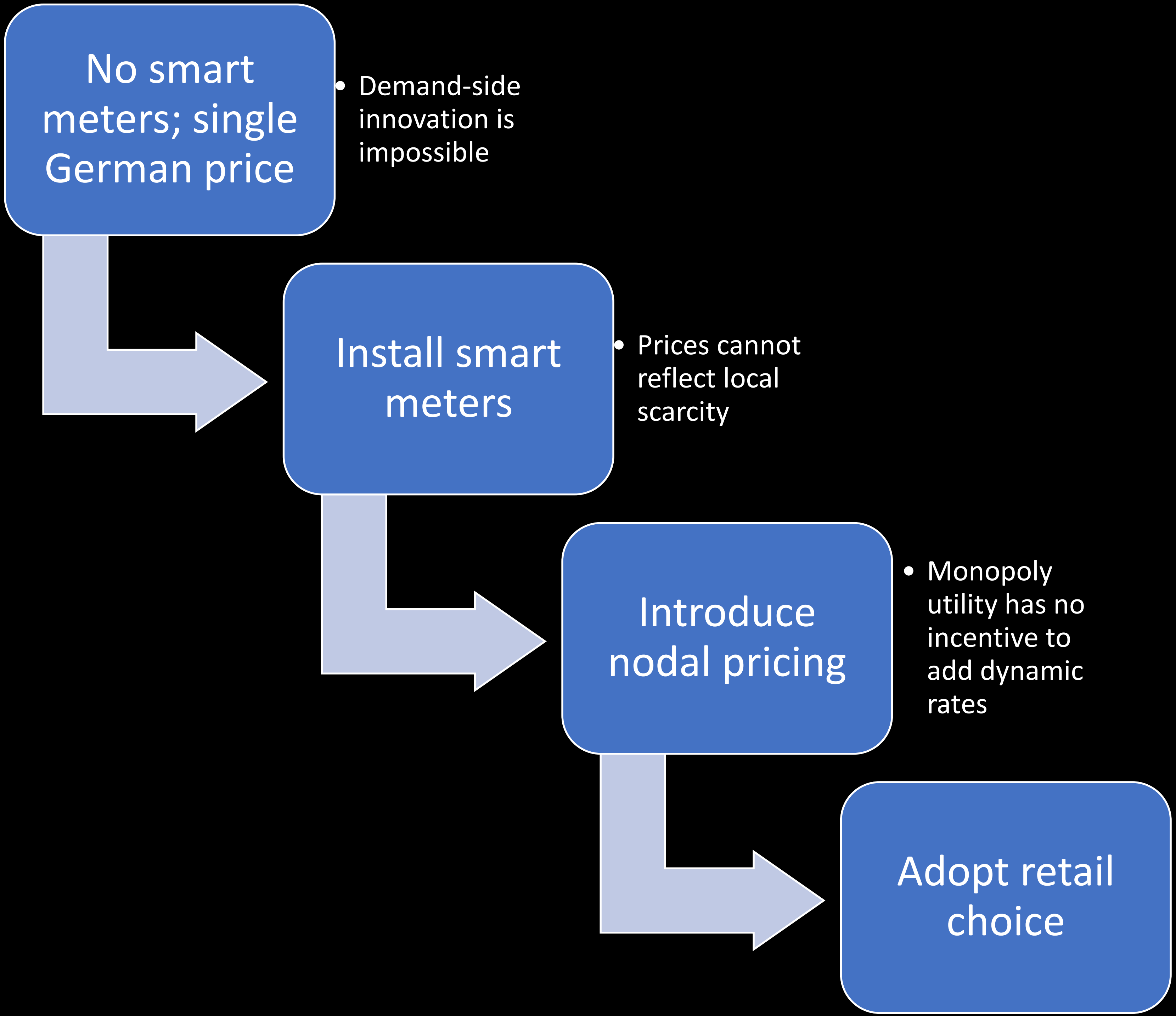
Encourage resiliency

Vibrant forward trade

Forward prices

Efficient operation & investment

Foster innovation



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

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

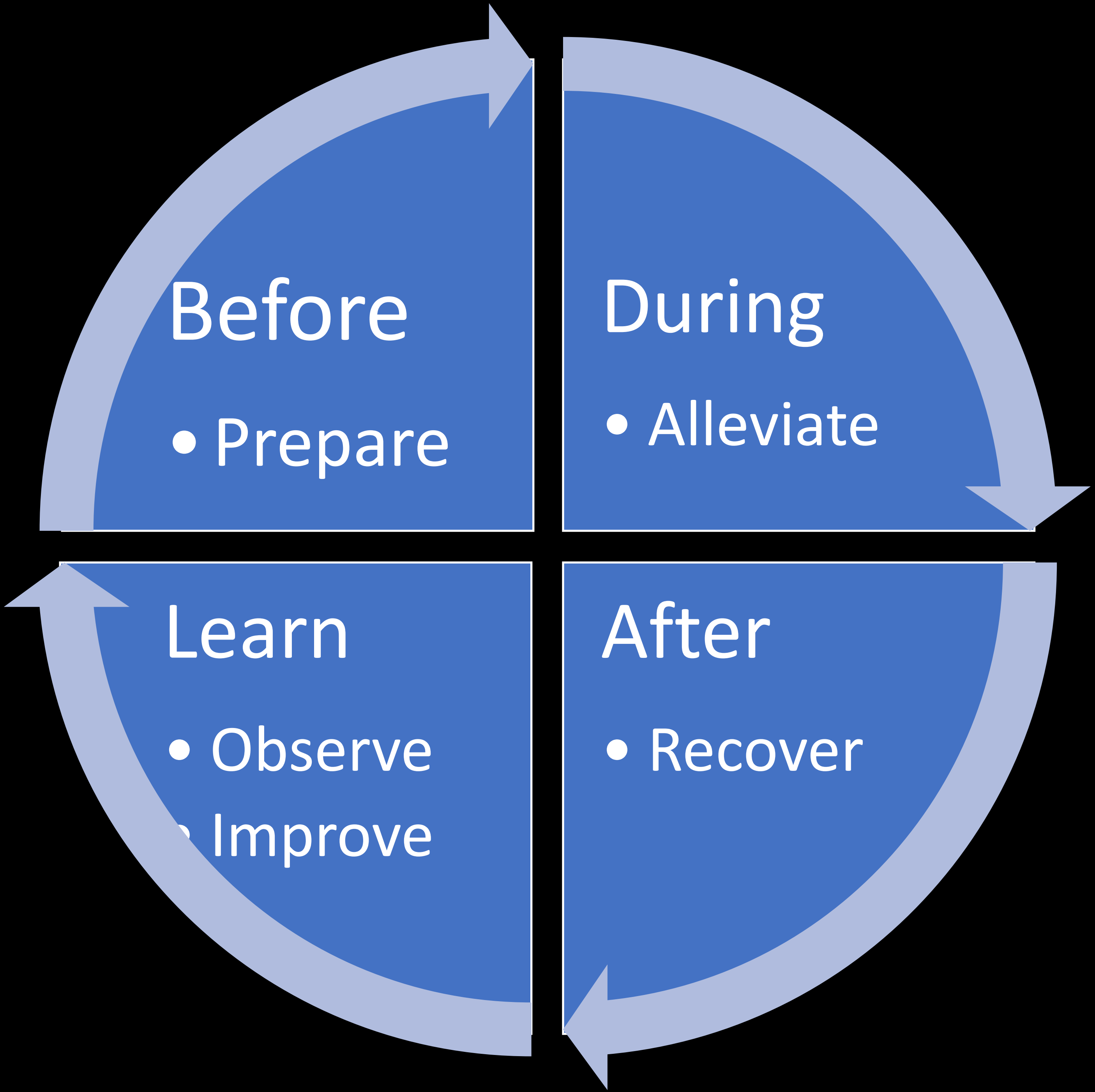
Events are system-wide, long in duration, and have implications for other critical infrastructure.

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

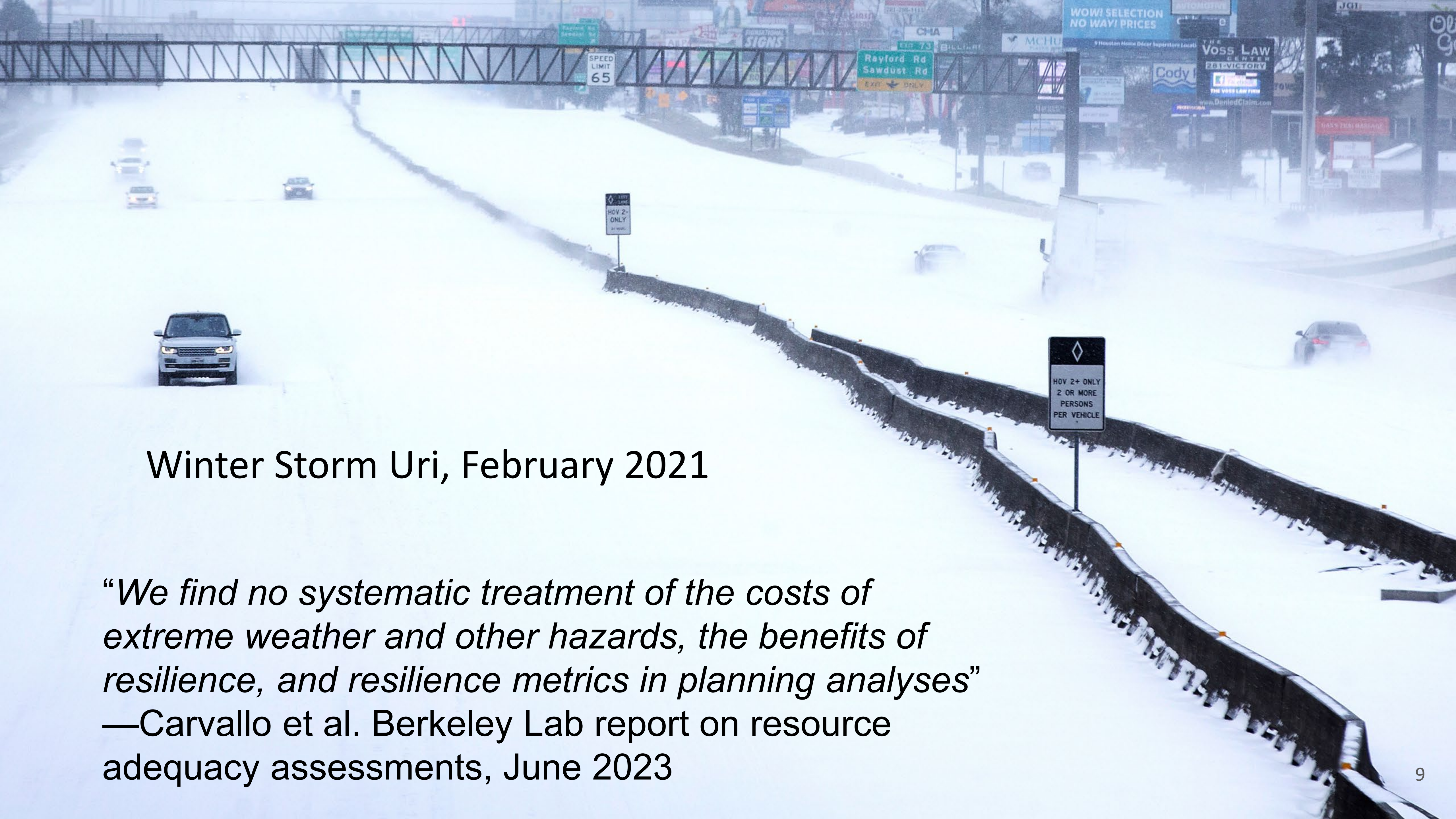
- Alleviate

After

- Recover

Learn

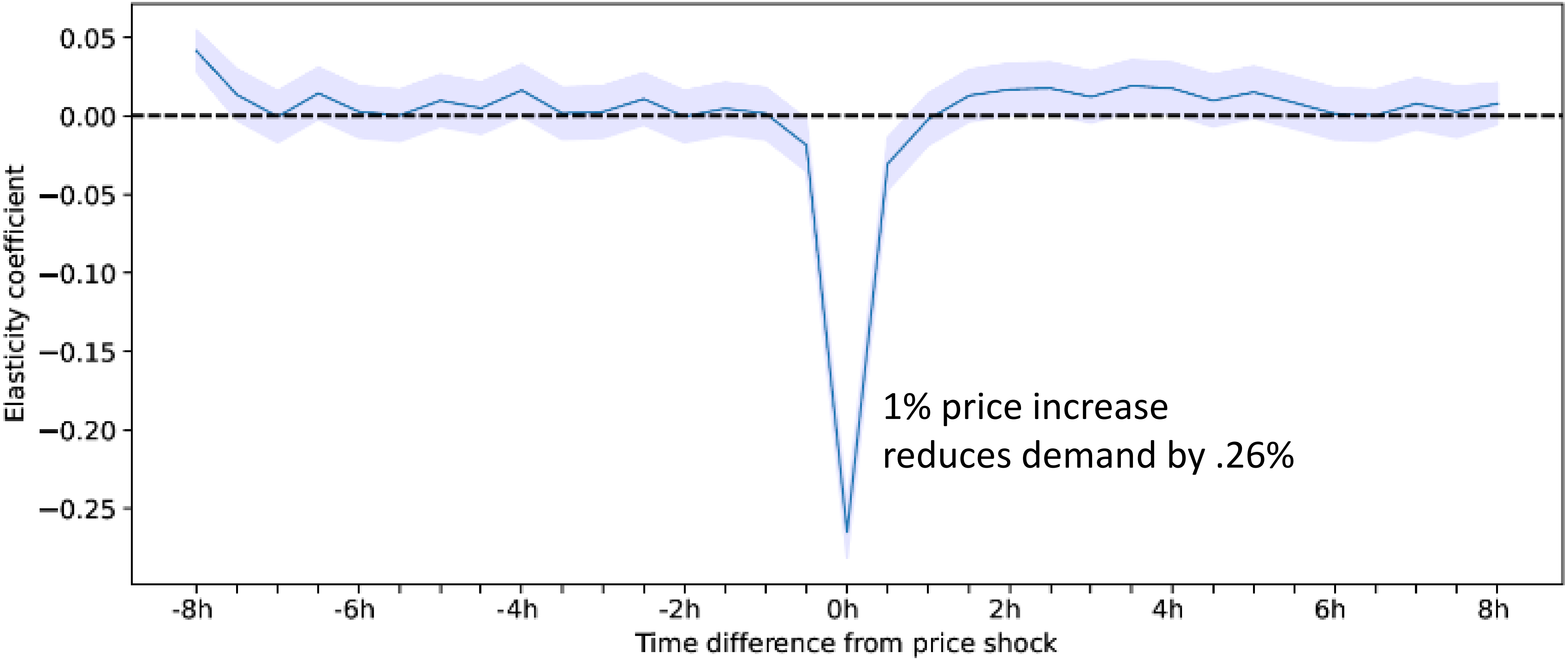
- Observe
- Improve



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

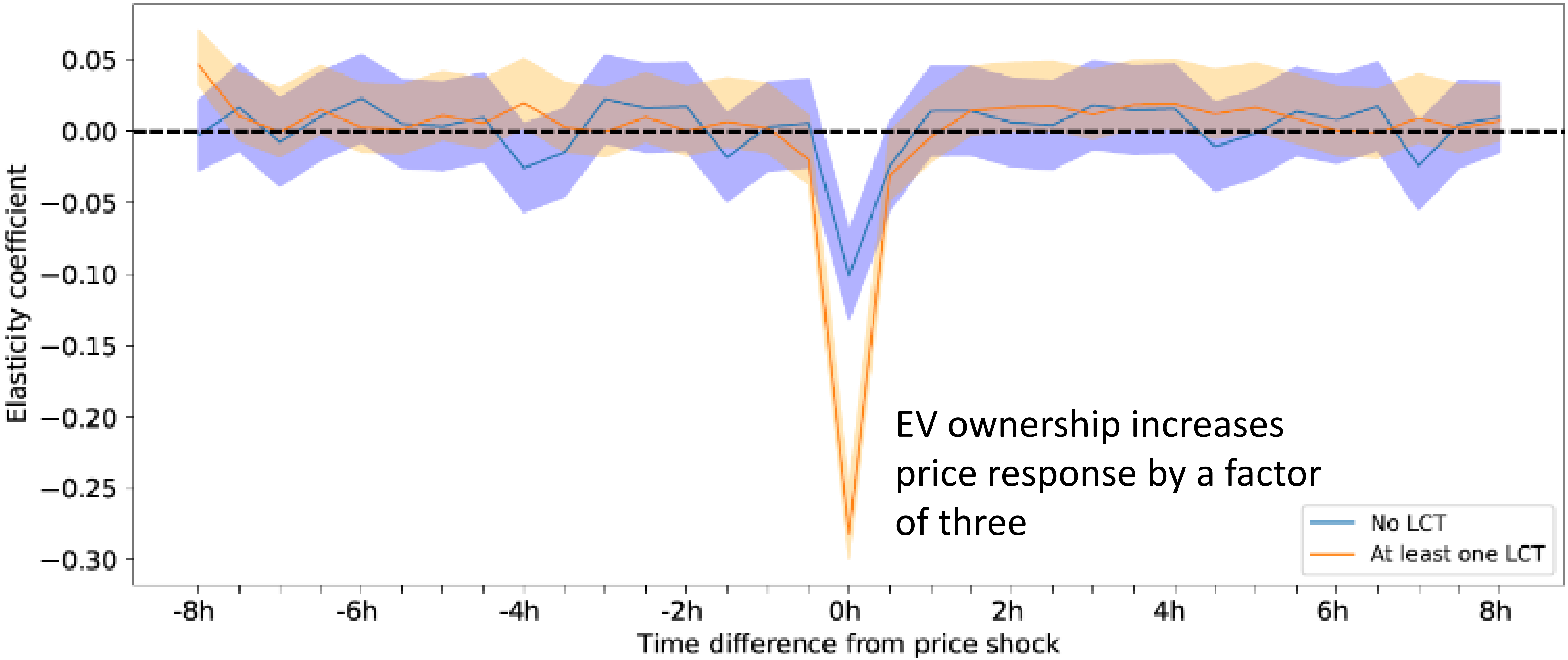
Customers on dynamic rates respond to price, Britain 2020-21



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.

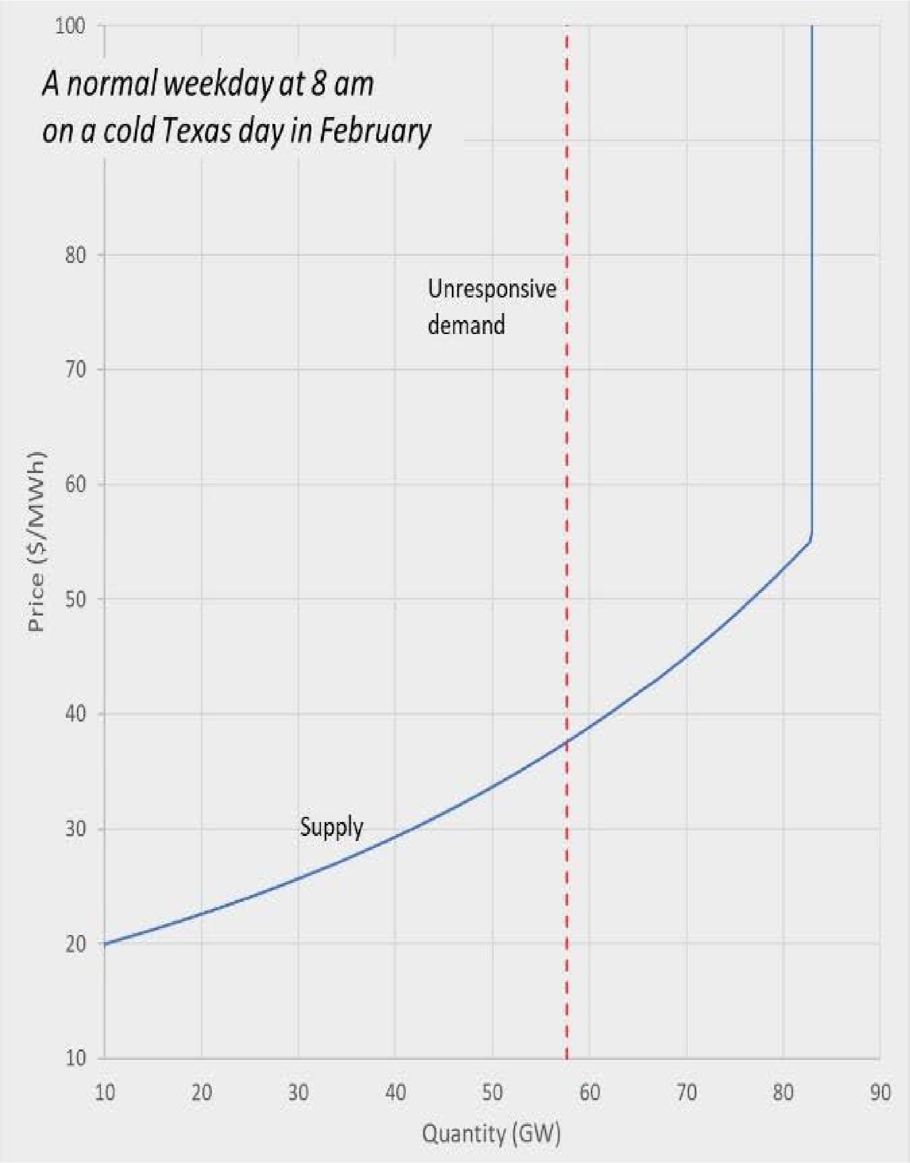
Low-carbon technologies increase price response

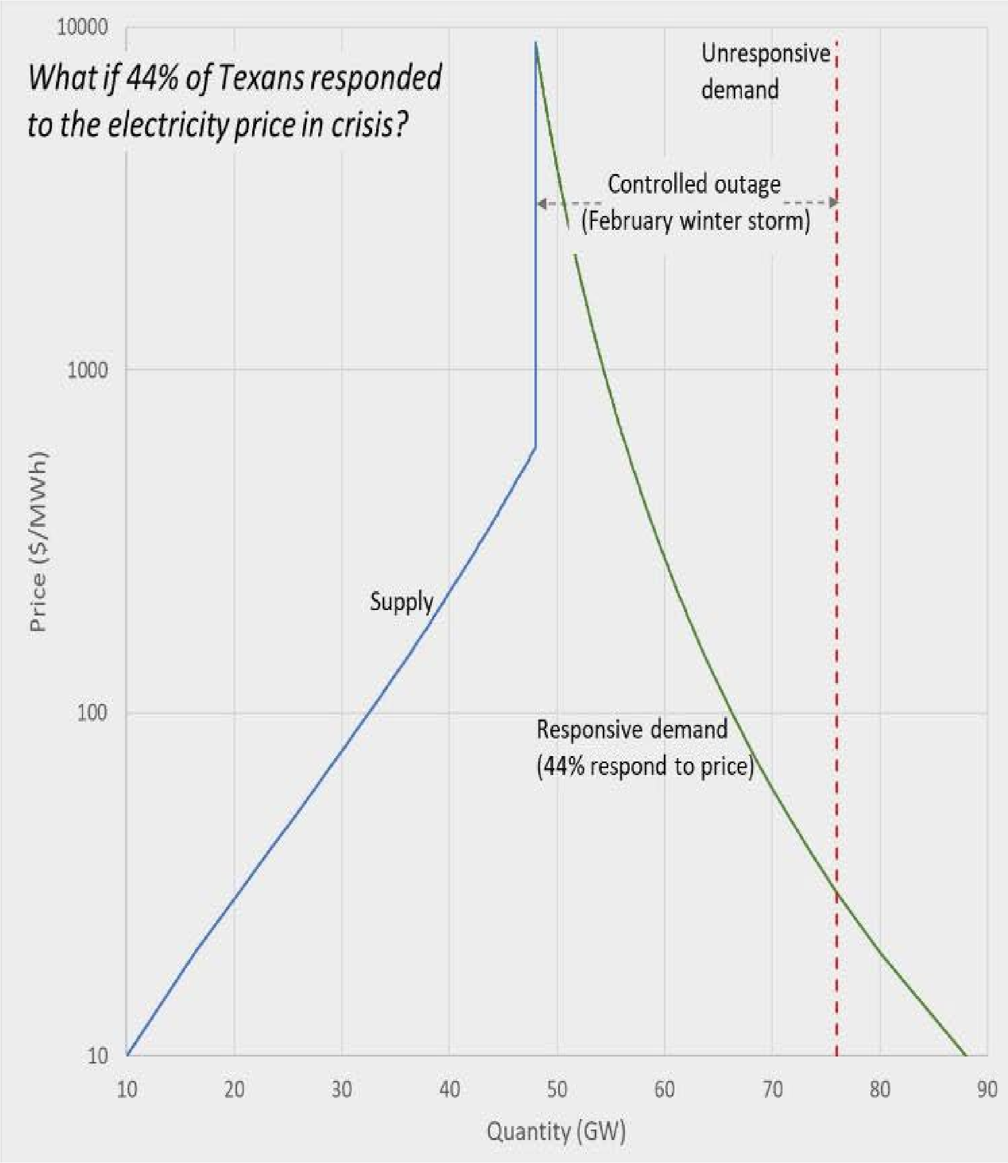


EV ownership increases price response by a factor of three

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





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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

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 expected demand increases from 0% 48 months ahead to 100% 1 month ahead
- 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

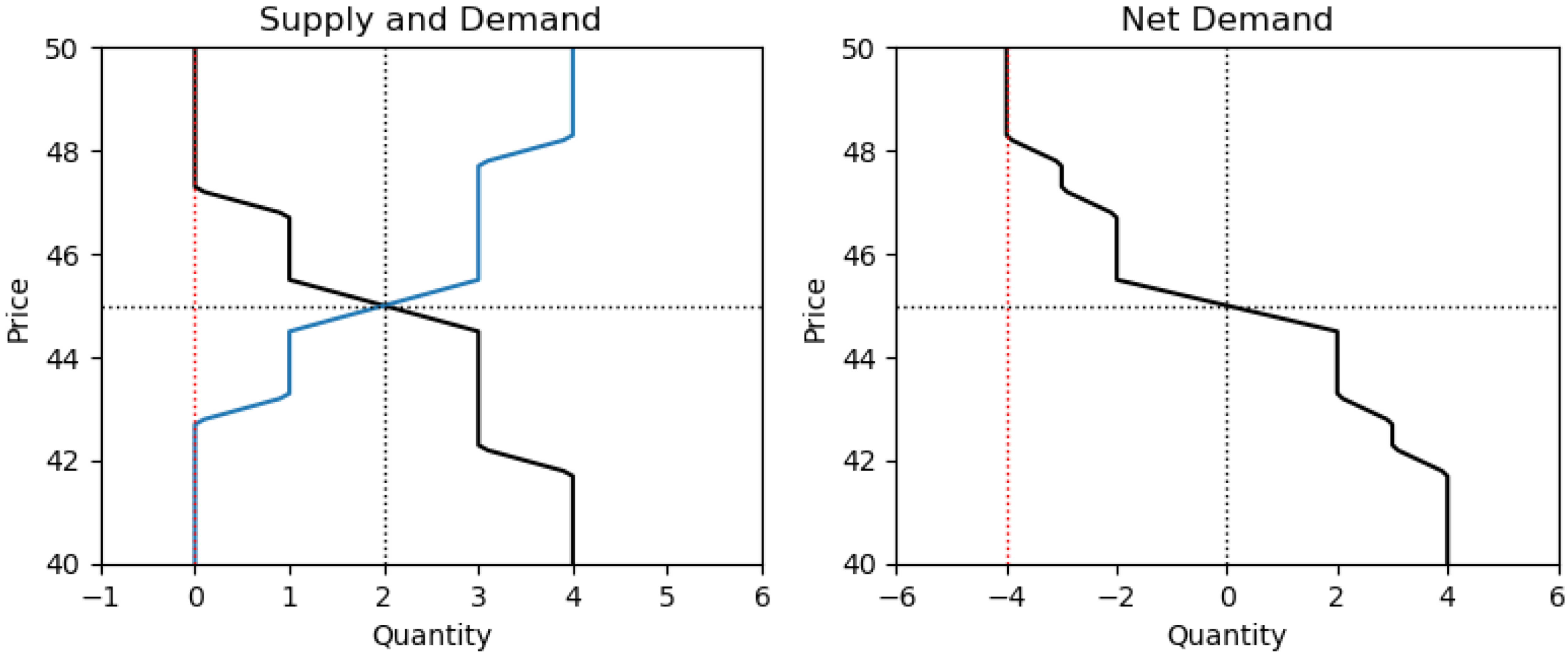
Many benefits

- Transparent and efficient forward prices to guide investment and operation of resources
- Flow trading allows fine granularity of time and space, encouraging resource flexibility when and where needed
- Finer product granularity works from computation, liquidity, and behavioral perspective
- *Renewable Energy Certificates allow efficient management of jurisdictional renewable requirements*
- *Replaces contentious capacity auctions and capacity requirements with better instrument*
- *Estimates of capacity value used for resource adequacy assessments, not for administrative accreditation of resources, encouraging resource innovation and avoiding costly accreditation fights*
- Embraces rapid resource innovation through technology-neutral rules and payments
- Resources are rewarded for their system value; the playing field is level and transparent

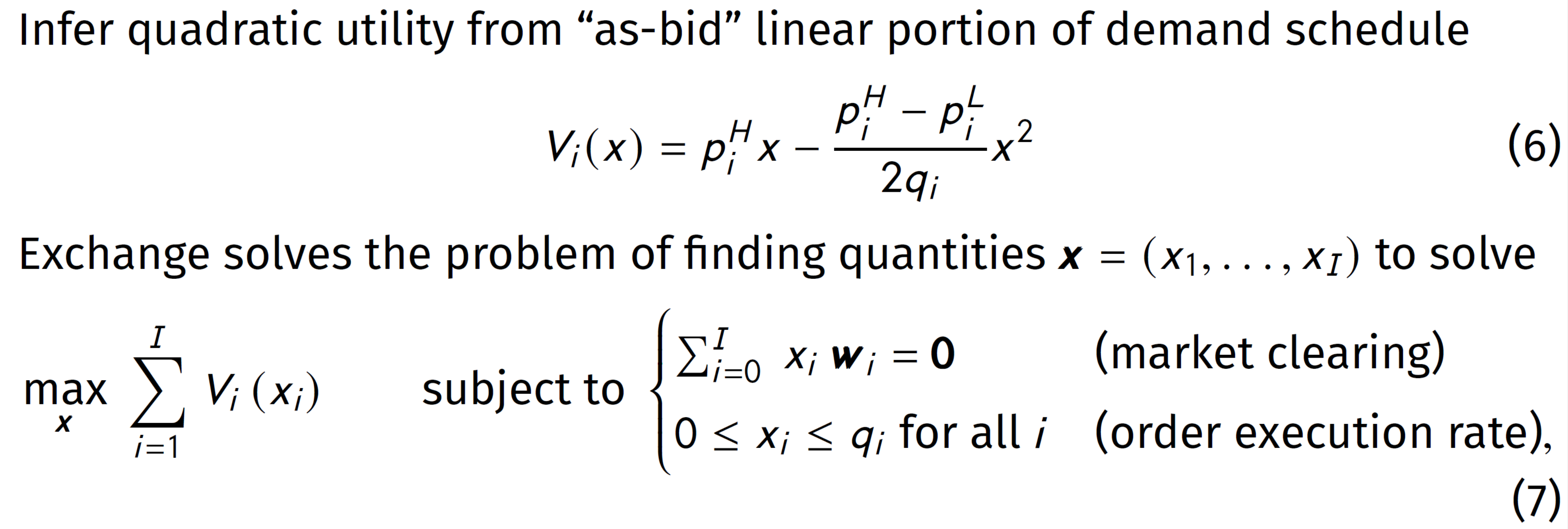
Many benefits

- *Few administrative parameters; the key parameter is the value of lost load, a parameter that becomes less critical as improved flexibility reduces shortages*
- Detailed information to better understand and manage resource adequacy; forward price information improves analysis in resource adequacy assessments
- *Readily extended to intraday (rolling settlement) to improve operational incentives and efficiency*
- Participants express preferences and trade in a way consistent with interests to efficiently manage risk, create value, and avoid adverse price impact
- Transparency of positions enables regulators to understand and manage market power
- *Position transparency lets system operator optimize collateral to reduce counterparty risk and reduce participants' collateral costs*

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]

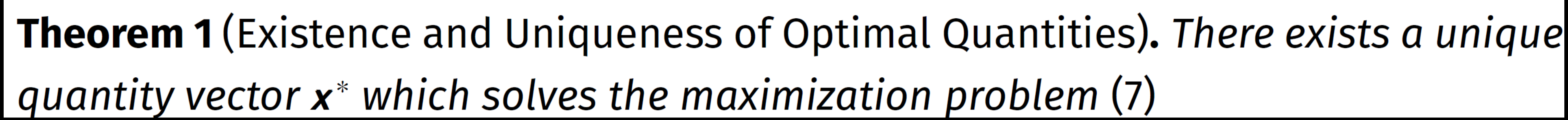


Infer quadratic utility from “as-bid” linear portion of demand schedule

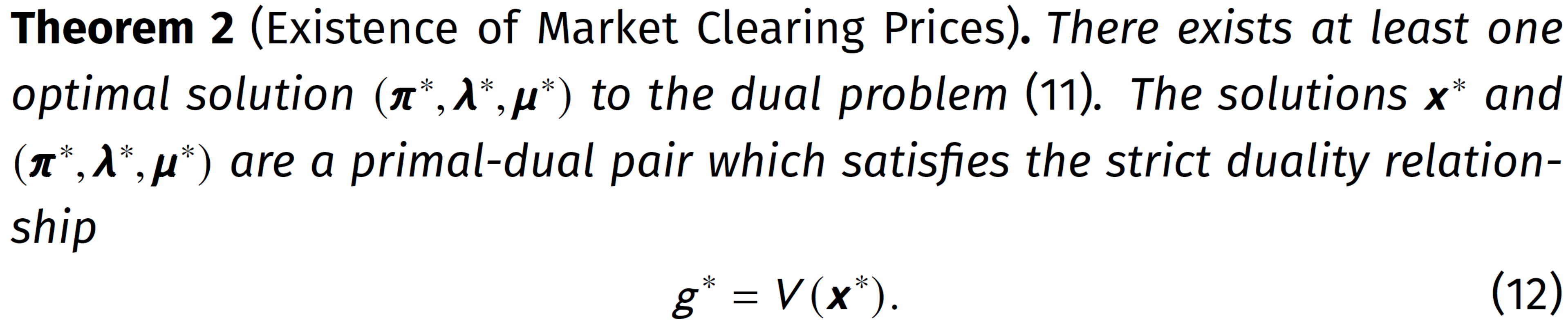
$$V_i(x) = p_i^H x - \frac{p_i^H - p_i^L}{2q_i} x^2 \tag{6}$$

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

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



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*

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

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
  - 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)?

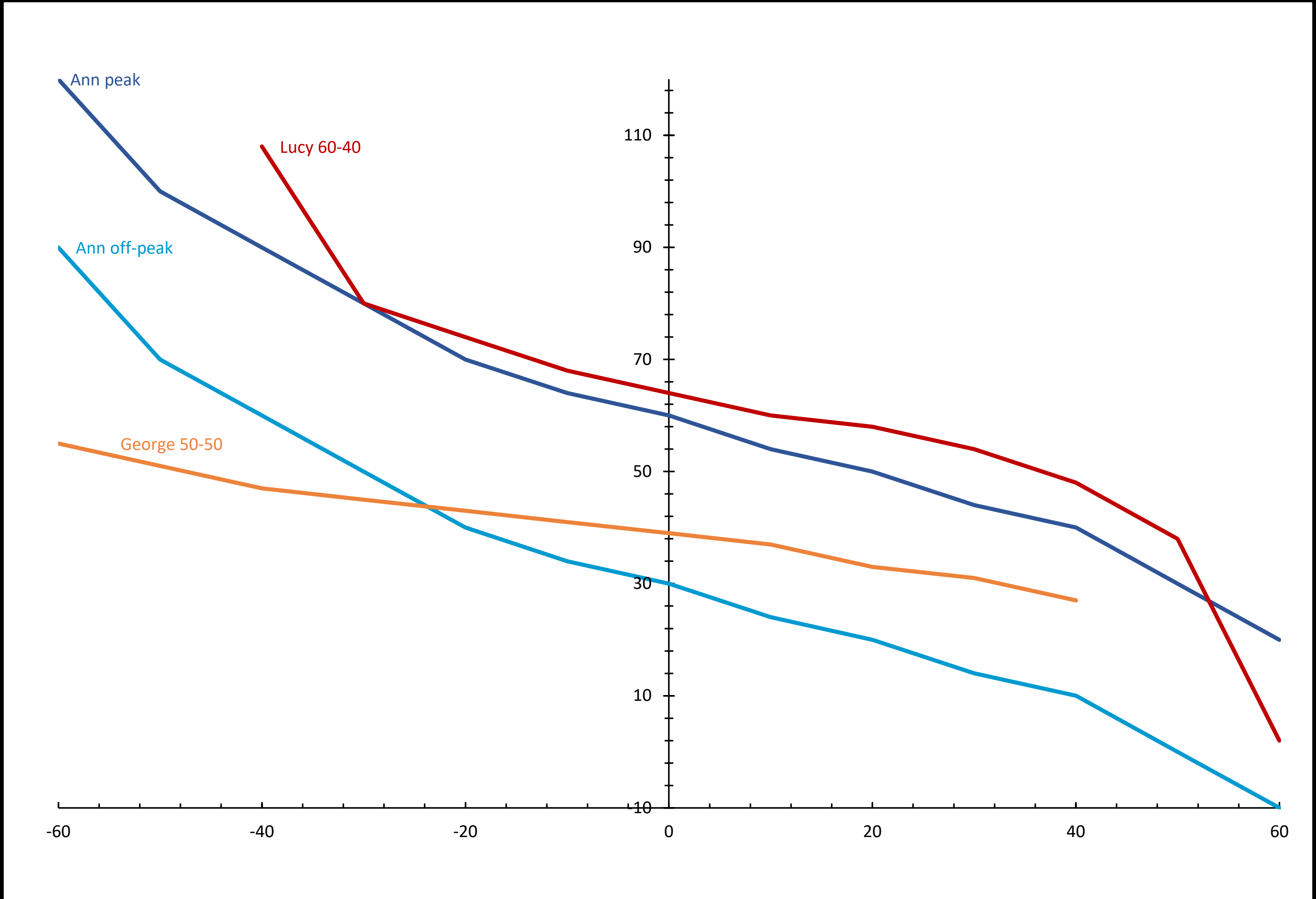
An example:
2 products,
3 participants

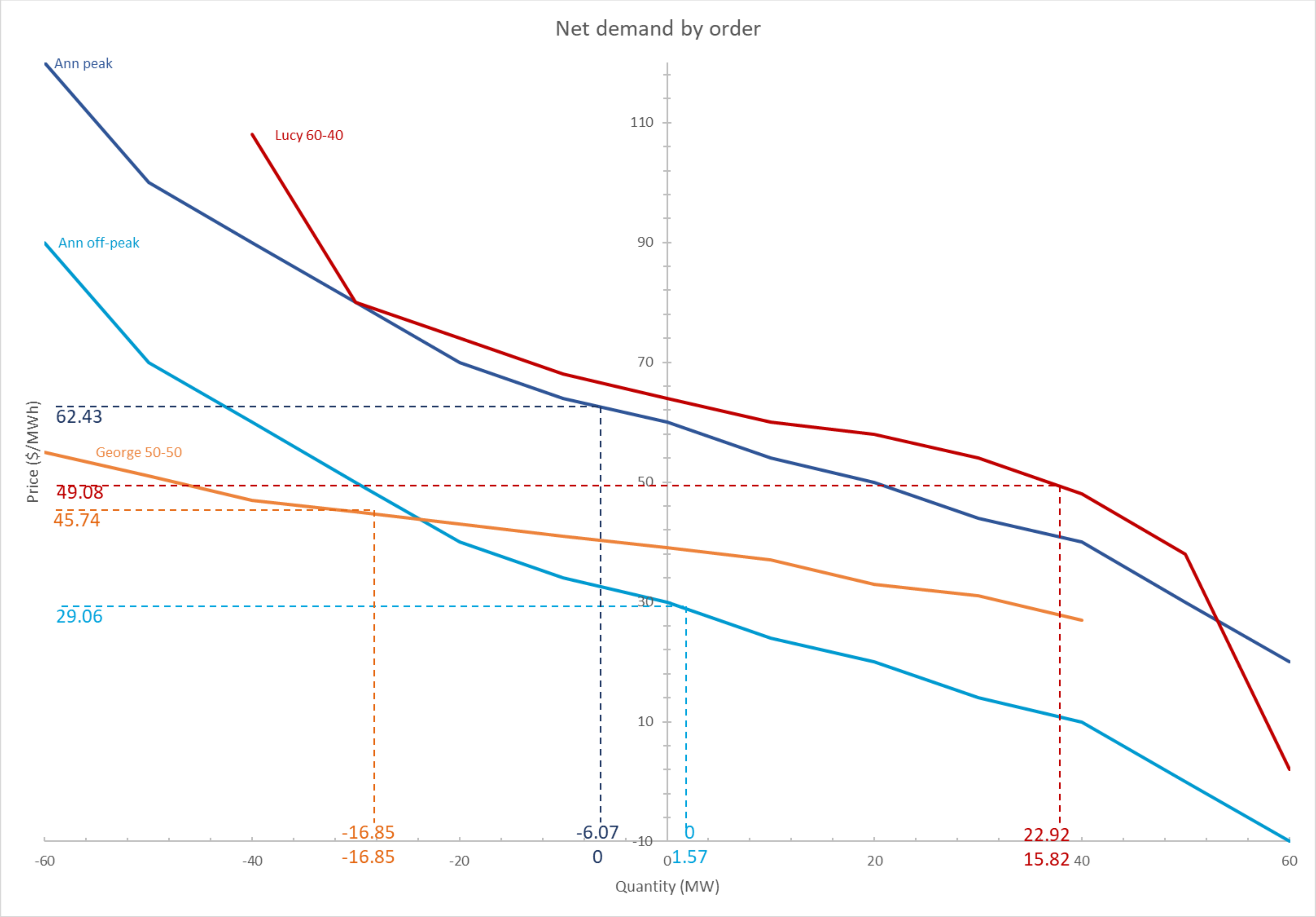
Sell

	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

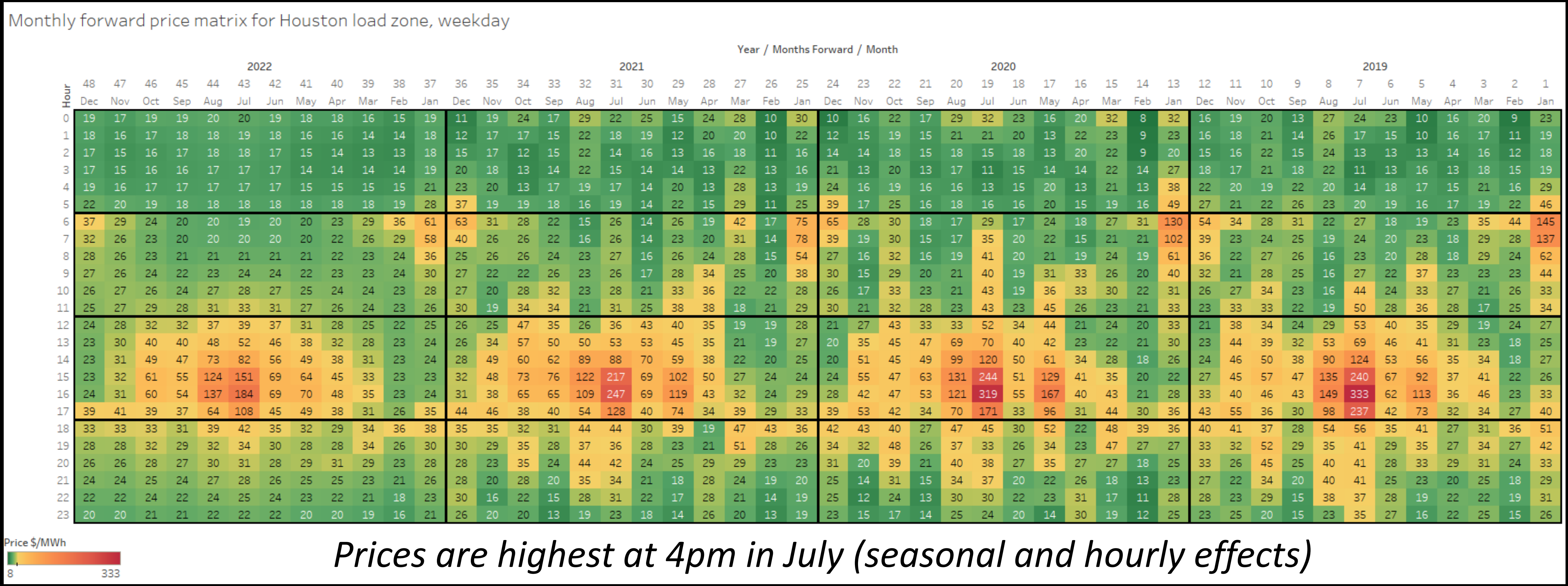
Buy

[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
Price ($/MWh)
110
90
70
50
30
10
-10
62.43
49.08
45.74
29.06
-16.85
-16.85
-6.07
0
0
1.57
22.92
15.82
-60
-40
-20
0
20
40
60
Quantity (MW)

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



Monthly forward price matrix for Houston load zone, weekday

Year / Months Forward / Month

	2022											
	48	47	46	45	44	43	42	41	40	39	38	37
Hour	Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan
0	19	17	19	19	20	20	19	18	18	16	15	19
1	18	16	17	18	18	19	18	16	16	14	14	18
2	17	15	16	17	18	18	17	15	14	13	13	18
3	17	15	16	16	17	17	17	14	14	14	14	19
4	19	16	17	17	17	17	17	15	15	15	15	21
5	22	20	19	18	18	18	18	18	18	18	19	28
6	37	29	24	20	20	19	20	20	23	29	36	61
7	32	26	23	20	20	20	20	20	22	26	29	58
8	28	26	23	21	21	21	21	21	22	23	24	36
9	27	26	24	22	23	24	24	22	23	23	24	30
10	26	27	26	24	27	28	27	25	24	24	23	28
11	25	27	29	28	31	33	31	27	26	24	23	26
12	24	28	32	32	37	39	37	31	28	25	22	25
13	23	30	40	40	48	52	46	38	32	28	23	24
14	23	31	49	47	73	82	56	49	38	31	23	24
15	23	32	61	55	124	151	69	64	45	33	23	23
16	24	31	60	54	137	184	69	70	48	35	23	24
17	39	41	39	37	64	108	45	49	38	31	26	35
18	33	33	33	31	39	42	35	32	29	34	36	38
19	28	28	32	29	32	34	30	28	28	34	26	30
20	26	26	28	27	30	31	28	29	31	29	23	28
21	24	24	25	24	27	28	26	25	25	23	21	26
22	22	22	24	22	24	25	24	23	22	21	18	23
23	20	20	21	21	22	22	22	20	20	19	16	21

	2021											
	36	35	34	33	32	31	30	29	28	27	26	25
Hour	Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan
0	11	19	24	17	29	22	25	15	24	28	10	30
1	12	17	17	15	22	18	19	12	20	20	10	22
2	15	17	12	15	22	14	16	13	16	18	11	16
3	20	18	13	14	22	15	14	14	13	22	13	16
4	23	20	13	17	19	17	14	20	13	28	13	19
5	37	19	19	18	16	19	14	22	15	29	11	25
6	63	31	28	22	15	26	14	26	19	42	17	75
7	40	26	26	22	16	26	14	23	20	31	14	78
8	25	26	26	24	23	27	16	26	24	28	15	54
9	27	22	22	26	23	26	17	28	34	25	20	38
10	27	20	28	32	23	28	21	33	36	22	22	28
11	30	19	34	34	21	31	25	38	38	18	21	29
12	26	25	47	35	26	36	43	40	35	19	19	28
13	26	34	57	50	50	53	53	45	35	21	19	27
14	28	49	60	62	89	88	70	59	38	22	20	25
15	32	48	73	76	122	217	69	102	50	27	24	24
16	31	38	65	65	109	247	69	119	43	32	24	29
17	44	46	38	40	54	128	40	74	34	39	29	33
18	35	35	32	31	44	44	30	39	19	47	43	36
19	30	29	35	28	37	36	28	23	21	51	28	26
20	28	23	35	24	44	42	24	25	29	29	23	23
21	28	20	28	20	35	34	21	18	28	24	19	20
22	30	16	22	15	28	31	22	17	28	21	14	19
23	26	20	20	13	19	23	18	14	26	20	13	19

	2020											
	24	23	22	21	20	19	18	17	16	15	14	13
Hour	Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan
0	10	16	22	17	29	32	23	16	20	32	8	32
1	12	15	19	15	21	21	20	13	22	23	9	23
2	14	14	18	15	18	15	18	13	20	22	9	20
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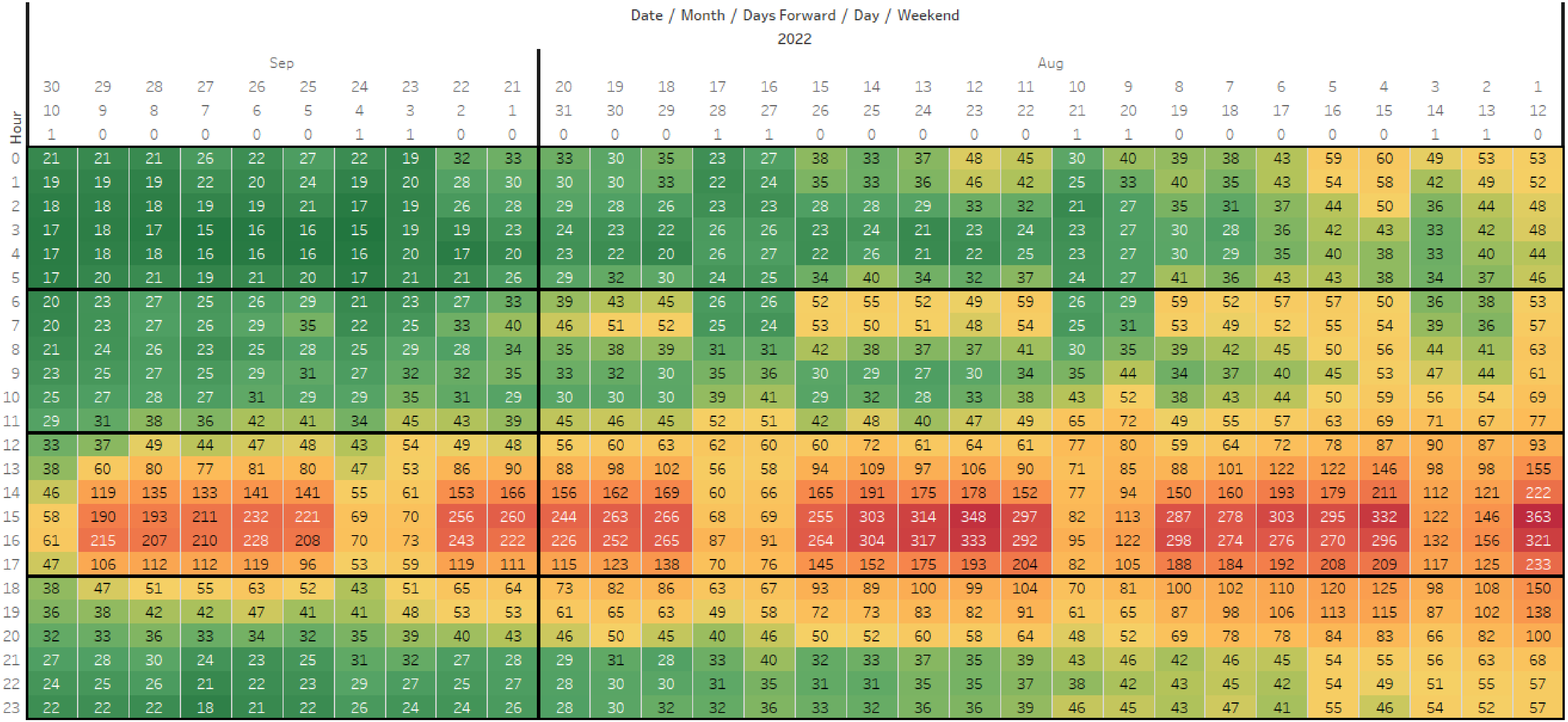
4	24	16	19	16	16	13	15	20	13	21	13	38
5	39	17	25	16	18	16	16	20	15	19	16	49
6	65	28	30	18	17	29	17	24	18	27	31	130
7	39	19	30	15	17	35	20	22	15	21	21	102
8	27	16	32	16	19	41	20	21	19	24	19	61
9	30	15	29	20	21	40	19	31	33	26	20	40
10	26	17	33	23	21	43	19	36	33	30	22	31
11	30	21	32	28	23	43	23	45	26	23	21	33
12	21	27	43	33	33	52	34	44	21	24	20	33
13	20	35	45	47	69	70	40	42	23	22	21	30
14	20	51	45	49	99	120	50	61	34	28	18	26
15	24	55	47	63	131	244	51	129	41	35	20	22
16	28	42	47	53	121	319	55	167	40	43	21	28
17	39	53	42	34	70	171	33	96	31	44	30	36
18	42	43	40	27	47	45	30	52	22	48	39	36
19	34	32	48	26	37	33	26	34	23	47	27	27
20	31	20	39	21	40	38	27	35	27	27	18	25
21	25	14	31	15	34	37	20	22	26	18	13	23
22	25	12	24	13	30	30	22	23	31	17	11	28
23	23	15	17	14	25	24	20	14	30	19	12	25

	2019											
	12	11	10	9	8	7	6	5	4	3	2	1
Hour	Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan
0	16	19	20	13	27	24	23	10	16	20	9	23
1	16	18	21	14	26	17	15	10	16	17	11	19
2	15	16	22	15	24	13	13	13	14	16	12	18
3	18	17	21	18	22	11	13	16	13	18	15	19
4	22	20	19	22	20	14	18	17	15	21	16	29
5	27	21	22	26	23	20	19	16	17	19	22	46
6	54	34	28	31	22	27	18	19	23	35	44	145
7	39	23	24	25	19	24	20	23	18	29	28	137
8	36	22	27	26	16	23	20	28	18	29	24	62
9	32	21	28	25	16	27	22	37	23	23	23	44
10	26	27	34	23	16	44	24	33	27	21	26	33
11	23	33	33	22	19	50	28	36	28	17	25	34
12	21	38	34	24	29	53	40	35	29	19	24	27
13	23	44	39	32	53	69	46	41	31	23	18	25
14	24	46	50	38	90	124	53	56	35	34	18	27
15	27	45	57	47	135	240	67	92	37	41	22	26
16	33	40	46	43	149	333	62	113	36	46	23	33
17	43	55	36	30	98	237	42	73	32	34	27	40
18	40	41	37	28	54	56	35	41	27	31	36	51
19	33	32	52	29	35	41	29	35	27	34	27	42
20	33	26	45	25	40	41	28	33	29	31	24	33
21	27	22	34	20	40	41	25	23	20	25	18	29
22	28	23	29	15	38	37	28	19	22	22	19	31
23	23	25	20	15	23	35	27	16	22	25	15	26

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

Hourly forward prices, Houston, weekday ($/MWh), 30 to 1 day ahead
(30 × 24 = 720 hourly products per load zone)

Hourly forward price matrix for the Houston load zone



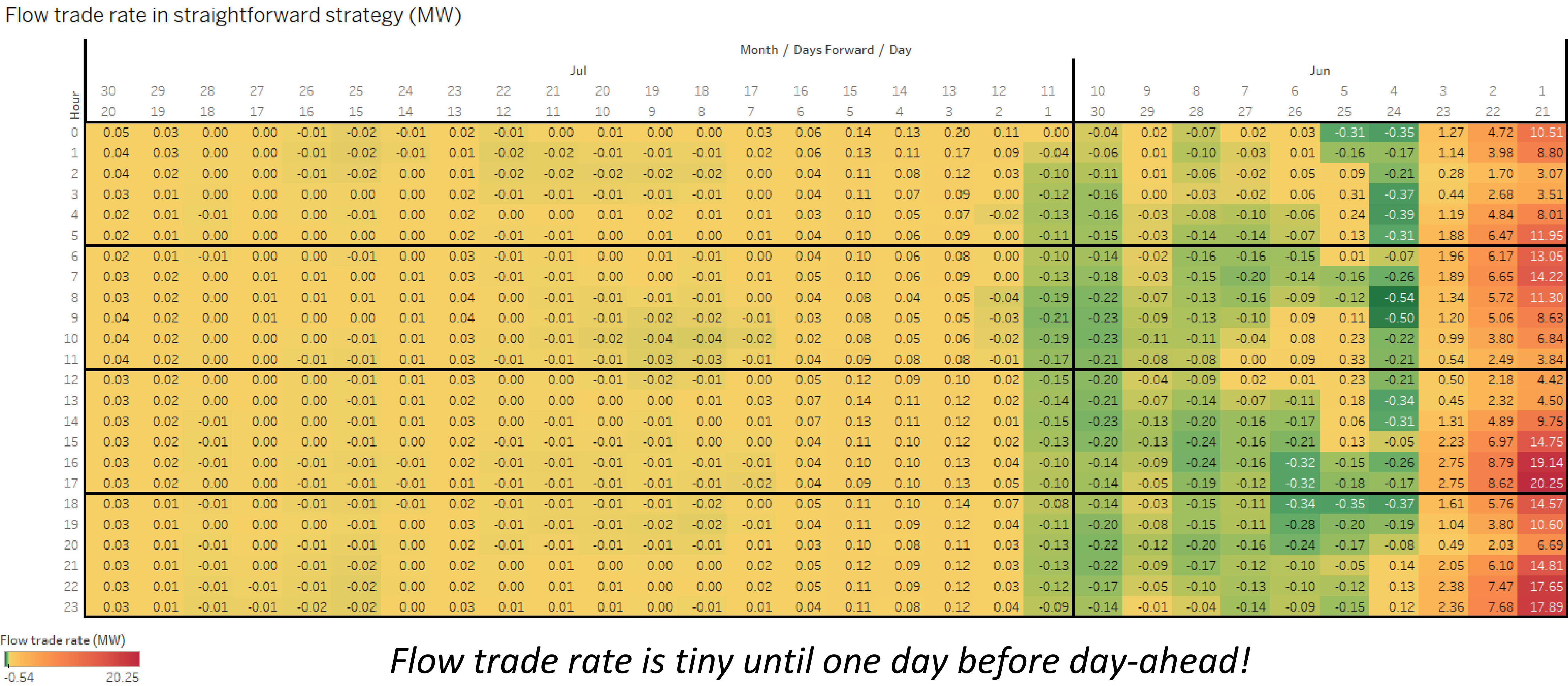
	Date / Month / Days Forward / Day / Weekend																													
	2022																													
	Sep										Aug																			
	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
	10	9	8	7	6	5	4	3	2	1	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12
Hour	1	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	0	0	0	1	1	0
0	21	21	21	26	22	27	22	19	32	33	33	30	35	23	27	38	33	37	48	45	30	40	39	38	43	59	60	49	53	53
1	19	19	19	22	20	24	19	20	28	30	30	30	33	22	24	35	33	36	46	42	25	33	40	35	43	54	58	42	49	52
2	18	18	18	19	19	21	17	19	26	28	29	28	26	23	23	28	28	29	33	32	21	27	35	31	37	44	50	36	44	48
3	17	18	17	15	16	16	15	19	19	23	24	23	22	26	26	23	24	21	23	24	23	27	30	28	36	42	43	33	42	48
4	17	18	18	16	16	16	16	20	17	20	23	22	20	26	27	22	26	21	22	25	23	27	30	29	35	40	38	33	40	44
5	17	20	21	19	21	20	17	21	21	26	29	32	30	24	25	34	40	34	32	37	24	27	41	36	43	43	38	34	37	46
6	20	23	27	25	26	29	21	23	27	33	39	43	45	26	26	52	55	52	49	59	26	29	59	52	57	57	50	36	38	53
7	20	23	27	26	29	35	22	25	33	40	46	51	52	25	24	53	50	51	48	54	25	31	53	49	52	55	54	39	36	57
8	21	24	26	23	25	28	25	29	28	34	35	38	39	31	31	42	38	37	37	41	30	35	39	42	45	50	56	44	41	63
9	23	25	27	25	29	31	27	32	32	35	33	32	30	35	36	30	29	27	30	34	35	44	34	37	40	45	53	47	44	61
10	25	27	28	27	31	29	29	35	31	29	30	30	30	39	41	29	32	28	33	38	43	52	38	43	44	50	59	56	54	69
11	29	31	38	36	42	41	34	45	43	39	45	46	45	52	51	42	48	40	47	49	65	72	49	55	57	63	69	71	67	77
12	33	37	49	44	47	48	43	54	49	48	56	60	63	62	60	60	72	61	64	61	77	80	59	64	72	78	87	90	87	93
13	38	60	80	77	81	80	47	53	86	90	88	98	102	56	58	94	109	97	106	90	71	85	88	101	122	122	146	98	98	155
14	46	119	135	133	141	141	55	61	153	166	156	162	169	60	66	165	191	175	178	152	77	94	150	160	193	179	211	112	121	222
15	58	190	193	211	232	221	69	70	256	260	244	263	266	68	69	255	303	314	348	297	82	113	287	278	303	295	332	122	146	363
16	61	215	207	210	228	208	70	73	243	222	226	252	265	87	91	264	304	317	333	292	95	122	298	274	276	270	296	132	156	321
17	47	106	112	112	119	96	53	59	119	111	115	123	138	70	76	145	152	175	193	204	82	105	188	184	192	208	209	117	125	233
18	38	47	51	55	63	52	43	51	65	64	73	82	86	63	67	93	89	100	99	104	70	81	100	102	110	120	125	98	108	150
19	36	38	42	42	47	41	41	48	53	53	61	65	63	49	58	72	73	83	82	91	61	65	87	98	106	113	115	87	102	138
20	32	33	36	33	34	32	35	39	40	43	46	50	45	40	46	50	52	60	58	64	48	52	69	78	78	84	83	66	82	100
21	27	28	30	24	23	25	31	32	27	28	29	31	28	33	40	32	33	37	35	39	43	46	42	46	45	54	55	56	63	68
22	24	25	26	21	22	23	29	27	25	27	28	30	30	31	35	31	31	35	35	37	38	42	43	45	42	54	49	51	55	57
23	22	22	22	18	21	22	26	24	24	26	28	30	32	32	36	33	32	36	36	39	46	45	43	47	41	55	46	54	52	57

Price $/MWh

15 363

Summer hourly price impacts are large

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



Flow trade rate in straightforward strategy (MW)

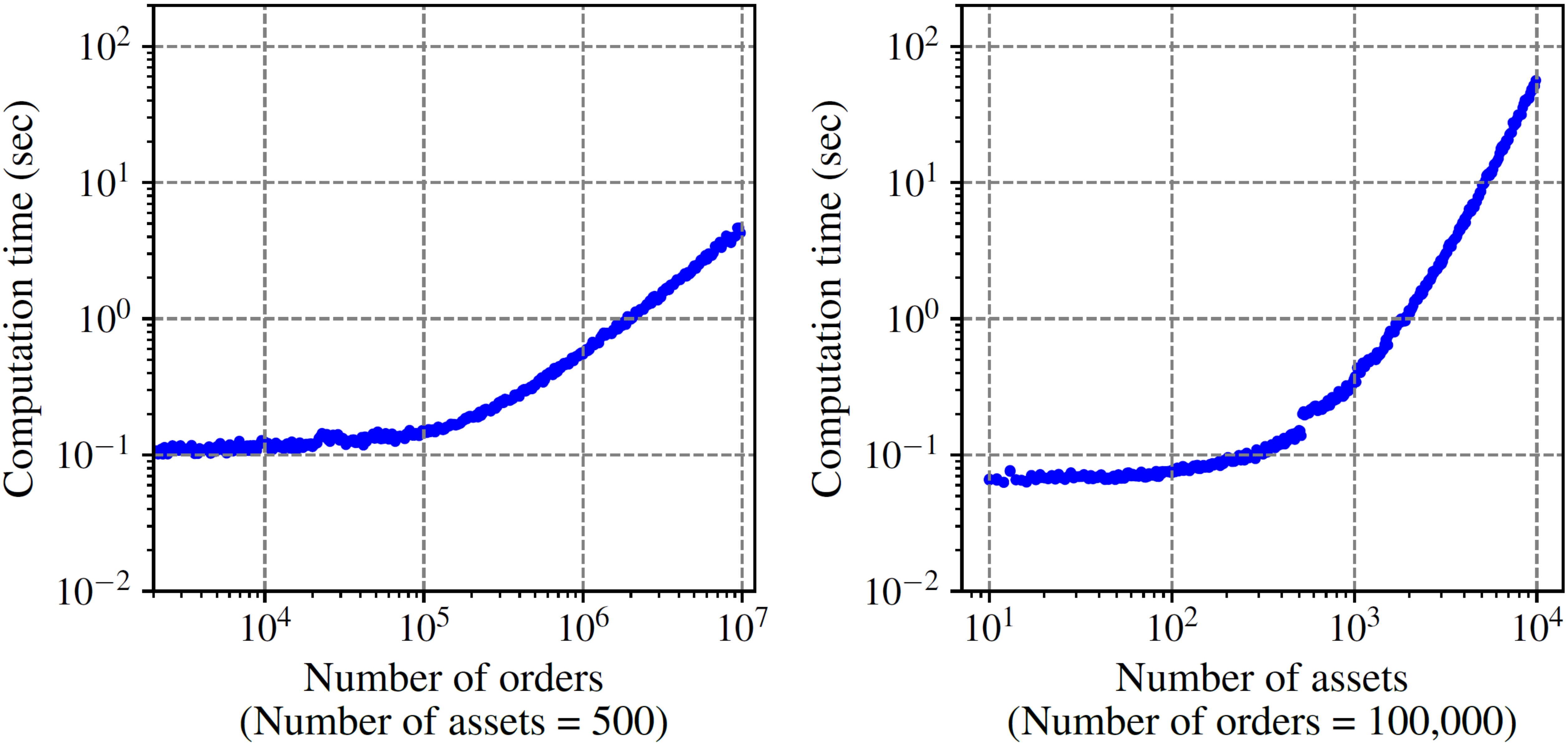
Month / Days Forward / Day

Hour	Jul																				Jun									
	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	30	29	28	27	26	25	24	23	22	21
0	0.05	0.03	0.00	0.00	-0.01	-0.02	-0.01	0.02	-0.01	0.00	0.01	0.00	0.00	0.03	0.06	0.14	0.13	0.20	0.11	0.00	-0.04	0.02	-0.07	0.02	0.03	-0.31	-0.35	1.27	4.72	10.51
1	0.04	0.03	0.00	0.00	-0.01	-0.02	-0.01	0.01	-0.02	-0.02	-0.01	-0.01	-0.01	0.02	0.06	0.13	0.11	0.17	0.09	-0.04	-0.06	0.01	-0.10	-0.03	0.01	-0.16	-0.17	1.14	3.98	8.80
2	0.04	0.02	0.00	0.00	-0.01	-0.02	0.00	0.01	-0.02	-0.02	-0.02	-0.02	-0.02	0.00	0.04	0.11	0.08	0.12	0.03	-0.10	-0.11	0.01	-0.06	-0.02	0.05	0.09	-0.21	0.28	1.70	3.07
3	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.02	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.04	0.11	0.07	0.09	0.00	-0.12	-0.16	0.00	-0.03	-0.02	0.06	0.31	-0.37	0.44	2.68	3.51
4	0.02	0.01	-0.01	0.00	0.00	-0.01	0.00	0.02	0.00	0.00	0.01	0.02	0.01	0.01	0.03	0.10	0.05	0.07	-0.02	-0.13	-0.16	-0.03	-0.08	-0.10	-0.06	0.24	-0.39	1.19	4.84	8.01
5	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.02	-0.01	-0.01	0.00	0.01	0.00	0.01	0.04	0.10	0.06	0.09	0.00	-0.11	-0.15	-0.03	-0.14	-0.14	-0.07	0.13	-0.31	1.88	6.47	11.95
6	0.02	0.01	-0.01	0.00	0.00	-0.01	0.00	0.03	-0.01	-0.01	0.00	0.01	-0.01	0.00	0.04	0.10	0.06	0.08	0.00	-0.10	-0.14	-0.02	-0.16	-0.16	-0.15	0.01	-0.07	1.96	6.17	13.05
7	0.03	0.02	0.00	0.01	0.01	0.00	0.01	0.03	-0.01	-0.01	0.00	0.00	-0.01	0.01	0.05	0.10	0.06	0.09	0.00	-0.13	-0.18	-0.03	-0.15	-0.20	-0.14	-0.16	-0.26	1.89	6.65	14.22
8	0.03	0.02	0.00	0.01	0.01	0.01	0.01	0.04	0.00	-0.01	-0.01	-0.01	-0.01	0.00	0.04	0.08	0.04	0.05	-0.04	-0.19	-0.22	-0.07	-0.13	-0.16	-0.09	-0.12	-0.54	1.34	5.72	11.30
9	0.04	0.02	0.00	0.01	0.00	0.00	0.01	0.04	0.00	-0.01	-0.01	-0.02	-0.02	-0.01	0.03	0.08	0.05	0.05	-0.03	-0.21	-0.23	-0.09	-0.13	-0.10	0.09	0.11	-0.50	1.20	5.06	8.63
10	0.04	0.02	0.00	0.00	0.00	-0.01	0.01	0.03	0.00	-0.01	-0.02	-0.04	-0.04	-0.02	0.02	0.08	0.05	0.06	-0.02	-0.19	-0.23	-0.11	-0.11	-0.04	0.08	0.23	-0.22	0.99	3.80	6.84
11	0.04	0.02	0.00	0.00	-0.01	-0.01	0.01	0.03	-0.01	-0.01	-0.01	-0.03	-0.03	-0.01	0.04	0.09	0.08	0.08	-0.01	-0.17	-0.21	-0.08	-0.08	0.00	0.09	0.33	-0.21	0.54	2.49	3.84
12	0.03	0.02	0.00	0.00	0.00	-0.01	0.01	0.03	0.00	0.00	-0.01	-0.02	-0.01	0.00	0.05	0.12	0.09	0.10	0.02	-0.15	-0.20	-0.04	-0.09	0.02	0.01	0.23	-0.21	0.50	2.18	4.42
13	0.03	0.02	0.00	0.00	0.00	-0.01	0.01	0.02	0.00	0.00	0.00	0.00	0.01	0.03	0.07	0.14	0.11	0.12	0.02	-0.14	-0.21	-0.07	-0.14	-0.07	-0.11	0.18	-0.34	0.45	2.32	4.50
14	0.03	0.02	-0.01	0.00	0.00	-0.01	0.01	0.03	0.00	-0.01	0.00	-0.01	0.00	0.01	0.07	0.13	0.11	0.12	0.01	-0.15	-0.23	-0.13	-0.20	-0.16	-0.17	0.06	-0.31	1.31	4.89	9.75
15	0.03	0.02	-0.01	0.00	0.00	-0.01	0.00	0.02	-0.01	-0.01	-0.01	-0.01	0.00	0.00	0.04	0.11	0.10	0.12	0.02	-0.13	-0.20	-0.13	-0.24	-0.16	-0.21	0.13	-0.05	2.23	6.97	14.75
16	0.03	0.02	-0.01	0.00	-0.01	-0.01	-0.01	0.02	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	0.04	0.10	0.10	0.13	0.04	-0.10	-0.14	-0.09	-0.24	-0.16	-0.32	-0.15	-0.26	2.75	8.79	19.14
17	0.03	0.02	0.00	0.00	-0.01	-0.01	-0.01	0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02	0.04	0.09	0.10	0.13	0.05	-0.10	-0.14	-0.05	-0.19	-0.12	-0.32	-0.18	-0.17	2.75	8.62	20.25
18	0.03	0.01	-0.01	0.00	-0.01	-0.01	-0.01	0.02	-0.01	-0.01	-0.01	-0.01	-0.02	0.00	0.05	0.11	0.10	0.14	0.07	-0.08	-0.14	-0.03	-0.15	-0.11	-0.34	-0.35	-0.37	1.61	5.76	14.57
19	0.03	0.01	0.00	0.00	0.00	-0.01	0.00	0.03	-0.01	-0.01	-0.01	-0.02	-0.02	-0.01	0.04	0.11	0.09	0.12	0.04	-0.11	-0.20	-0.08	-0.15	-0.11	-0.28	-0.20	-0.19	1.04	3.80	10.60
20	0.03	0.01	-0.01	0.00	-0.01	-0.01	0.00	0.02	-0.01	-0.01	-0.01	-0.01	-0.01	0.01	0.03	0.10	0.08	0.11	0.03	-0.13	-0.22	-0.12	-0.20	-0.16	-0.24	-0.17	-0.08	0.49	2.03	6.69
21	0.03	0.01	-0.01	0.00	-0.01	-0.02	0.00	0.02	0.00	0.01	0.00	0.00	0.00	0.02	0.05	0.12	0.09	0.12	0.03	-0.13	-0.22	-0.09	-0.17	-0.12	-0.10	-0.05	0.14	2.05	6.10	14.81
22	0.03	0.01	-0.01	-0.01	-0.01	-0.02	0.00	0.02	0.00	0.01	0.01	0.00	0.00	0.02	0.05	0.11	0.09	0.12	0.03	-0.12	-0.17	-0.05	-0.10	-0.13	-0.10	-0.12	0.13	2.38	7.47	17.65
23	0.03	0.01	-0.01	-0.01	-0.02	-0.02	0.00	0.03	0.01	0.01	0.01	0.00	-0.01	0.01	0.04	0.11	0.08	0.12	0.04	-0.09	-0.14	-0.01	-0.04	-0.14	-0.09	-0.15	0.12	2.36	7.68	17.89

Flow trade rate (MW)

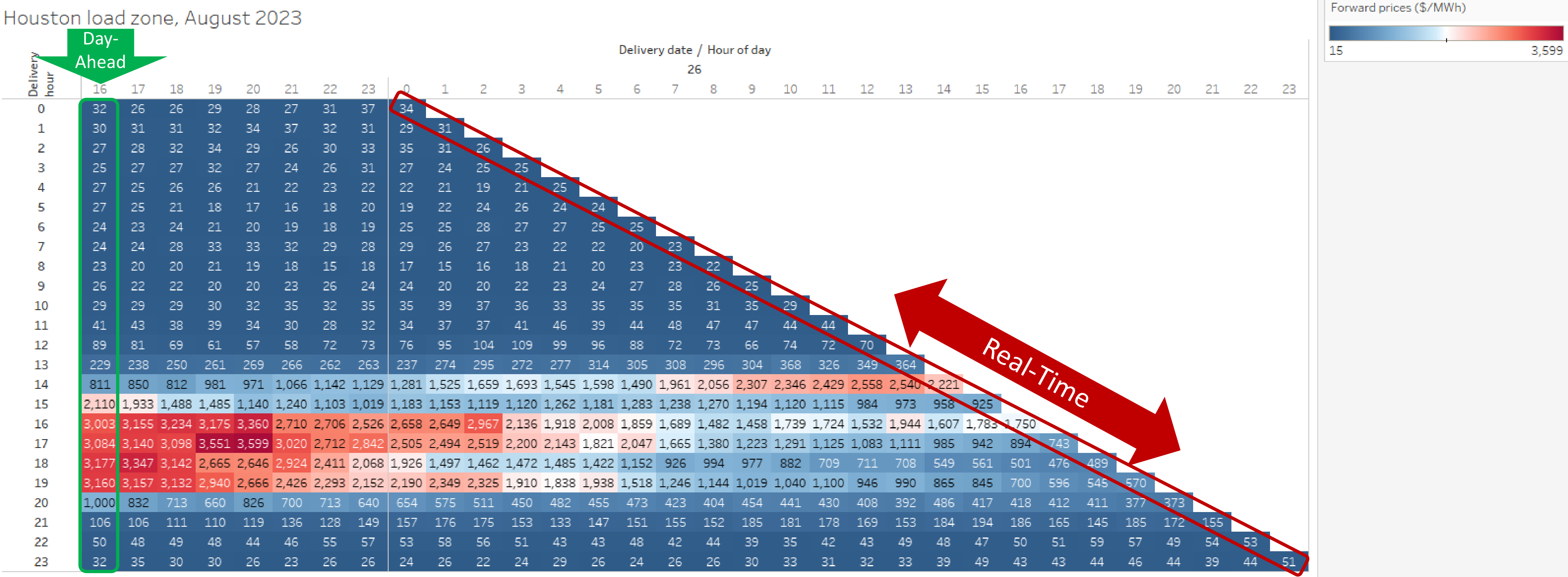
-0.54 20.25

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



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

Rolling Intraday Settlement Prices, Houston, 26 August 2023 ($/MWh)
(24 × 7 + 23 + 22 + … + 1 = 444 new prices)



Houston load zone, August 2023

Delivery date / Hour of day

26

Delivery hour	16	17	18	19	20	21	22	23	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
0	32	26	26	29	28	27	31	37	34																							
1	30	31	31	32	34	37	32	31	29	31																						
2	27	28	32	34	29	26	30	33	35	31	26																					
3	25	27	27	32	27	24	26	31	27	24	25	25																				
4	27	25	26	26	21	22	23	22	22	21	19	21	25																			
5	27	25	21	18	17	16	18	20	19	22	24	26	24	24																		
6	24	23	24	21	20	19	18	19	25	25	28	27	27	25	25																	
7	24	24	28	33	33	32	29	28	29	26	27	23	22	22	20	23																
8	23	20	20	21	19	18	15	18	17	15	16	18	21	20	23	23	22															
9	26	22	22	20	20	23	26	24	24	20	20	22	23	24	27	28	26	25														
10	29	29	29	30	32	35	32	35	35	39	37	36	33	35	35	35	31	35	29													
11	41	43	38	39	34	30	28	32	34	37	37	41	46	39	44	48	47	47	44	44												
12	89	81	69	61	57	58	72	73	76	95	104	109	99	96	88	72	73	66	74	72	70											
13	229	238	250	261	269	266	262	263	237	274	295	272	277	314	305	308	296	304	368	326	349	364										
14	811	850	812	981	971	1,066	1,142	1,129	1,281	1,525	1,659	1,693	1,545	1,598	1,490	1,961	2,056	2,307	2,346	2,429	2,558	2,540	2,221									
15	2,110	1,933	1,488	1,485	1,140	1,240	1,103	1,019	1,183	1,153	1,119	1,120	1,262	1,181	1,283	1,238	1,270	1,194	1,120	1,115	984	973	958	925								
16	3,003	3,155	3,234	3,175	3,360	2,710	2,706	2,526	2,658	2,649	2,967	2,136	1,918	2,008	1,859	1,689	1,482	1,458	1,739	1,724	1,532	1,944	1,607	1,783	1,750							
17	3,084	3,140	3,098	3,551	3,599	3,020	2,712	2,842	2,505	2,494	2,519	2,200	2,143	1,821	2,047	1,665	1,380	1,223	1,291	1,125	1,083	1,111	985	942	894	743						
18	3,177	3,347	3,142	2,665	2,646	2,924	2,411	2,068	1,926	1,497	1,462	1,472	1,485	1,422	1,152	926	994	977	882	709	711	708	549	561	501	476	489					
19	3,160	3,157	3,132	2,940	2,666	2,426	2,293	2,152	2,190	2,349	2,325	1,910	1,838	1,938	1,518	1,246	1,144	1,019	1,040	1,100	946	990	865	845	700	596	545	570				
20	1,000	832	713	660	826	700	713	640	654	575	511	450	482	455	473	423	404	454	441	430	408	392	486	417	418	412	411	377	373			
21	106	106	111	110	119	136	128	149	157	176	175	153	133	147	151	155	152	185	181	178	169	153	184	194	186	165	145	185	172	155		
22	50	48	49	48	44	46	55	57	53	58	56	51	43	43	48	42	44	39	35	42	43	49	48	47	50	51	59	57	49	54	53	
23	32	35	30	30	26	23	26	26	24	26	22	24	29	26	24	26	26	30	33	31	32	33	39	49	43	43	44	46	44	39	44	51

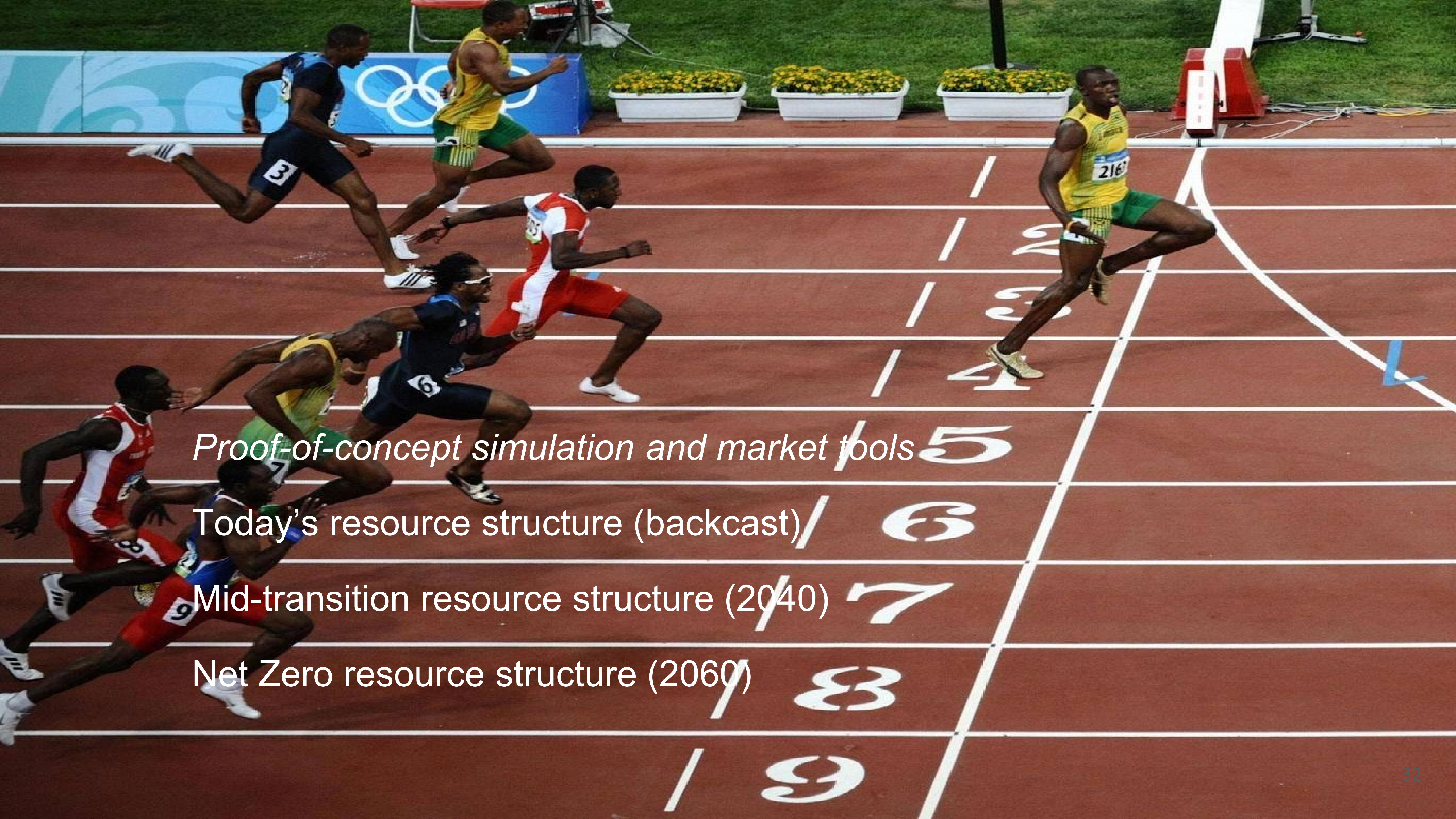
Rolling settlement especially important on summer net peak days!

Detailed market simulation (to be done)

- Backcast, for example, ISO-NE, PJM, SPP, or ERCOT
  - 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 to 1 months forward
    - LSEs deviate from target positions based on slope parameter (net demand)
    - Generators have target positions increasing from 0% to 100% from 48 to 1 months forward
    - 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 (2040)

Net Zero resource structure (2060)